Astronomers' Universe

James A. Hall III

Moons of the Solar System

From Giant Ganymede to Dainty Dactyl

Springer

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This book is dedicated to all the people who helped support me during my times of need;
Including my family and closest friends;
And to "the lovers, the dreamers and me."

Preface

Ever since the first thing that could be called "human" has first looked up at night, we have had a single eye-like orb looking back at us. However, it would take some of the greatest achievements of humankind to know what we now know about it. Hence Armstrong's famous line, "one small step for [a] man, one giant leap for mankind."

It was originally and long thought our moon was affixed to a sphere that orbited the Earth (which was naturally at the center of the universe). We now know that this is not true; current scientific thought dictates that the moon orbits the Earth, the Earth orbits the sun (Sol, by name), and that other natural objects orbiting the sun also have yet other natural objects orbiting them, under the catch-all title "satellites." Since our solar system has so many of these objects, one might want a book detailing a bit about them. Finding most such books incomplete or simply out-of-date, I found that I had to write my own book.

What Is a Moon, Anyway?

"Describe a moon." Sounds easy, doesn't it? (Fig. 1)

But some people may want a dictionary definition description, denotation only, for example, "a rock in space orbiting a planet." Others may be interested in the mythology and connotations, for example, "Pluto, named for the Roman god of the underworld, has a large moon, Charon, named for the boatman over the river Styx, which incidentally is the name of another of Pluto's moons." Others want a more elaborate description with data, for example, "the Saturnian, Gallic moon Erriapus has a mean argument of periapsis precession period of 219.9 years with a mean longitude of the ascending node precession period of 323.49 years." Here are the four elements this book prioritizes:

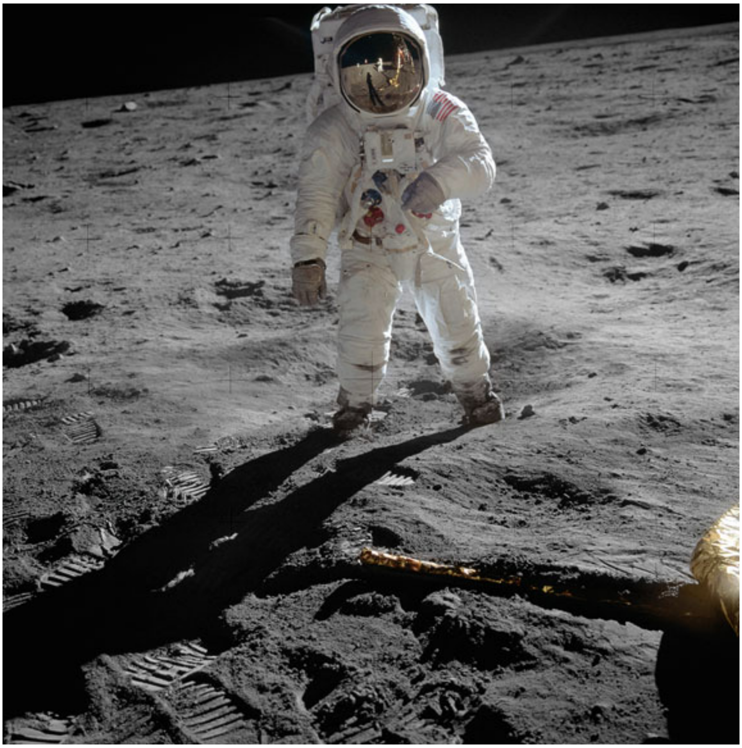

Fig. 1 Buzz Aldrin, Portrait Shot. In this picture, easily the most iconic of the space age, Edwin "Buzz" Aldrin, second man on the moon, poses for a photo op like none other, as Neil Armstrong, first man on the moon, takes his picture. In Buzz Aldrin's gold-colored visor the photographer, Armstrong, can be seen as well as the landing strut of the Eagle, the lander module of Apollo 6 (Credit: NASA)

1. Data. Pure, hard data, but about more commonplace things, such as distance, diameter, mass, and composition. Not about obscure items, such as the longitude of the ascending node, or argument of the periapsis.
2. Fresh, New Information. What do we know? And what don't we know?
3. Unusual Items. The extreme and superlative satellites are given extra attention due to what they can tell us about the behavior of the Solar System.
4. Pretty Pictures. Some of the objects within our little corner of the Galaxy are truly stunning and can be viewed in greater detail today than ever before.

What Data Is Included?

Data is ubiquitous online. Therefore I could omit that the eccentricity of Ganymede is 0.0013. But what if a reader wants to know that tidbit without going to JPL and/or NASA? Since no two people share identical interests, I tried to include a table that displays some (but not all) data in most cases. This covers the discoverer and the date of discovery, other names and designations used for the object, general orbital characteristics, physical characteristics, and atmospheric characteristics for major objects. For minor objects (such as Erriapus) less data if any will be included; 99 % of people have no clue what the argument of perihelion is or what the longitude of ascending node is, to say nothing of know-why it is important. For complete ephemeris data and information down to a dozen decimal places, JPL is really the best place to go. Only the most reliably known data is included in the book, or it is marked as unknown.

Spectral Classes

One important tool astronomers have is the spectrometer (with a telescope: spectroscope). Now, in case you do not know, a spectrometer is a tool designed to break apart light. When light from a moon or asteroid (specifically, reflected sunlight) is broken apart it creates a spectrum. Certain light types are not reflected—they are absorbed. These create absent lines in the spectra. This is called an absorption spectrum. (There are other types of spectroscopy, but these determine star properties, transiting exoplanet atmospheres, and other purposes beyond the scope of this work.) These spectra are then charted out (Figs. 2 and 3).

The dark lines in a spectroscope (like the above image of the spectrograph of our sun) are as unique as fingerprints. When what is being absorbed is known, then we can determine from that what elements are present and this gives us a clue to the moon's composition, or at least to the moon's surface composition. This can tell us about the possible origins (i.e., If XYZ has a spectrum a lot like Vesta, XYZ may be a captured asteroid of that family.)

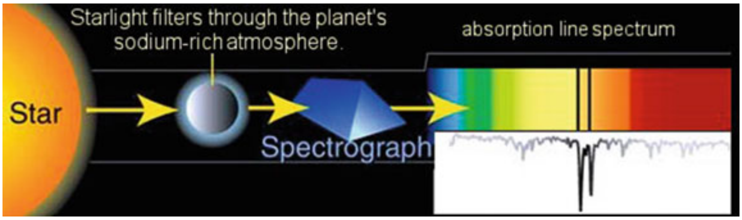

Fig. 2 Absorption spectroscope diagram (Credit: NASA/STSCI)

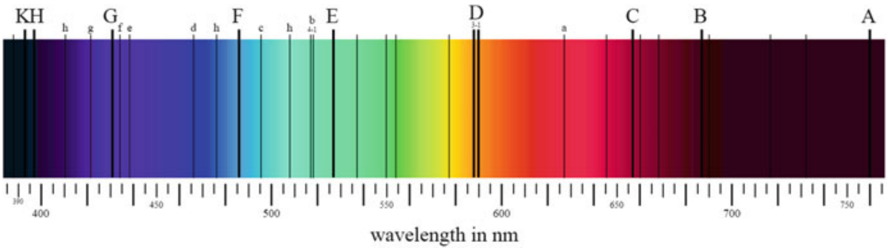

Fig. 3 Solar spectrum (Credit: Public Domain)

By using such spectroscopic techniques, we can also determine the composition of other moons (or at least their surface), by seeing what type of features shows up under spectroscopic analysis.

There are two main systems for classifying items. One is "Tholen" and the other is "SMASS."

Tholen

Tholen was defined by David J. Tholen in 1984. He designed this classification after analyzing 978 asteroids in the Eight Color Asteroid Survey (ECAS) from the 1980s. The measurements used for this survey were between 0.31 μm (microns or micrometers) and 1.06 μm.

The asteroids were then classified into 14 types (not including "U"), with three main groupings and a number of minor classes.

- C-group: These asteroids are dark (the albedo typically ranges from 0.03 up to 0.1) and carboniferous. These include the types B, C, F, and G. The C asteroids are similar to C meteorites (carbonaceous chondrites). There are few volatiles (such as hydrogen and helium), but are otherwise similar to the sun/solar nebula in composition. There are some water-containing (or hydrated) minerals. 324 Bamberga may be the most bright, but with its eccentric orbit it is hard to be certain (since it never gets close enough to Earth to get very bright). This class makes up about 75 % of all known asteroids. They absorb UV spectra in the range of 0.4–0.5 μm, but above that are mostly reddish. They also absorb light around 3 μm which indicates water.

– B-type: Similar to the C-type, however, the UV absorption below 0.5 μm is absent, and the spectrum is more bluish than reddish. Albedo is also higher. Surface minerals usually include anhydrous silicates, hydrated clay minerals, organic polymers, magnetite, and sulfides. 2 Pallas is the largest B-type asteroid.
– C-type: This is the textbook C-type, as above. It includes all C-group object types that are not B, F, or G-types. The largest is 10 Hygiea, although 1 Ceres could be a C-type asteroid (it could also be a G).
– F-type: These have spectra generally similar to those of the B-type asteroids, but the "water" absorption feature around 3 μm indicative of hydrated minerals is absent, and the ultraviolet spectrum feature is present, but below 0.4 μm. The largest is 704 Interamnia.
– G-type: Also similar to the C-type objects, but with a strong ultraviolet absorption feature below 0.5 μm. An absorption feature around 0.7 μm may also be present—this indicates phyllosilicate minerals such as clays or mica.

- S-group/type: A group and a type, these asteroids are bright (the albedo typically ranges from 0.1 up to 0.22) and siliceous. The S asteroids are similar to S meteorites (stony). The materials are mostly iron and magnesium silicates. 7 Iris is an S-type and unusually reflective, making it the second brightest of any asteroid (the brightest being 4 Vesta). They have a steep spectrum shorter than 0.7 μm and have a weak absorption feature around 1 and 2 μm. 1 μm indicates silicates. A broad shallow absorption feature at 0.63 μm is often present. 15 Eunomia and 3 Juno are both S-types.

- X-group: These asteroids are usually metallic. These include the types E, M, and P, but otherwise have little in common.

  – E-type: These asteroids have a high albedo and are siliceous. The albedos are typically at least 0.3. The S asteroids are similar to S meteorites (stony). The materials are mostly Enstatite ($MgSiO_3$) achondrites. They have a rather featureless, flat red spectrum. E-types are tiny—in fact only three are known to have diameter in excess of 50 km (44 Nysa, 55 Pandora, and 64 Angelina). The Hungaria asteroids are E-type (see Chap. 3)
  – M-type: These asteroids are not very bright; the albedo typically ranges from 0.1 up to 0.2. Some are nickel-iron and give rise to iron meteorites. Others have unknown compositions (such as 22 Kalliope). They have a rather flat red spectrum. Subtle absorption feature(s) longward of 0.75 μm and shortward of 0.55 μm are sometimes present. 16 Psyche is M-type.
  – P-type: These objects are very dark objects, with albedos not exceeding 0.1. They are similar in composition to a mix between the M-type and C-type. They are redder than S-types, and show no spectral features.

- Minor Classes: There are a number of classes that do not fit into the C, S of X group:

  – A-type: These have a strong, broad 1 μm feature that indicates Olivine feature (a common magnesium-iron silicate with the formula $(Mg^{2+}, Fe^{2+})_2SiO_4$) and a very reddish spectrum shortwards of 0.7 μm. Their origin is likely the completely differentiated mantle of an asteroid. These asteroids are rare. As of 2015, there are 17 asteroids known to be A-type, the largest of which is 246 Asporina.
  – D-type: These objects have a very low albedo and have a featureless reddish electromagnetic spectrum. The composition is a mixture between silicates, carbon, and anhydrous silicates. Water ice may also be common. 152 Atala and 944 Hidalgo are D-type; the Jupiter Trojan 624 Hektor (which we know has a moon) is the largest D-type asteroid known. Many Trojans may in fact be D-type.
  – Q-type: These are uncommon objects with strong, broad Olivine ($(Mg^{2+}, Fe^{2+})_2SiO_4$) and Pyroxene features (Pyroxene is

a mixture of |Ca, Na, Fe^{2+}, Mg, Zn, Mn, or Li||Cr, Al, Fe^{3+}, Mg, Mn, Sc, Ti, V, or Fe^{2+}|$(Si,Al)_2O_6$). (Olivine and Pyroxene together comprise most of the upper mantle of Earth—they are very common.) A steep slope indicates the presence of metal. There are absorption features shortwards and longwards of 0.7 μm. It is similar to S-types and V-types.
- R-type: These objects are moderately bright and relatively uncommon. They bridge the gap between A-type and V-types. There are Olivine and Pyroxene features at 1 and 2 μm. There is a possibility of Plagioclase as well (a feldspar of $NaAlSi_3O_8$ or $CaAl_2Si_2O_8$). Shortwards of 0.7 μm the spectrum is very reddish. 4 Vesta was the prototype R-type but it has been reclassified as a V-type, and indeed is now the prototype (and progenitor) of that class. 349 Dembowska is recognized as being type R when all wavelengths are taken into account.
- T-type: These are rare objects of unknown composition with dark, featureless and moderately red spectra. There is a moderate absorption feature shortwards of 0.85 μm. They may be related to D or P-types, or possibly a modified C-type. Samples are 96 Aegle, or 114 Kassandra.
- U-type: Miscellaneous (these items do not fit neatly into any category. U is almost universally assigned with another letter (see below).)
- V-type: These are moderately bright and similar to the more common S-type. These are stony irons and ordinary chondrites. These are rare and contain more Pyroxene than the S-type. The electromagnetic spectrum has a very strong absorption feature longward of 0.75 μm, another feature around 1 μm and is very red shortwards of 0.7 μm. 4 Vesta is the prototype.

Many items are a mixture of one or more of the above (i.e., 53 Kalypso is an "XC" with features of both, 273 Atropos is SCTU, and 343 Ostara is CSGU).

SMASS

SMASS is a newer system. SMASS was defined by Schelte J. Bus and Richard P. Binzel in 2002. They designed this classification after analyzing 1447 asteroids in the Small Main-belt Asteroid

Spectroscopic Survey (the eponymous SMASS). The measurements used for this survey were between 0.44 and 0.92 μm. This different range of measurements revealed different data, which tended to lead to different results. The resolution was also much greater. They also ignored albedo which was a major part of determining the Tholen type.

The asteroids were then classified into 26 types; however, the scientists did attempt to keep the Tholen classification as much as possible, so they appear similar.

- C-group:
  - B-type: Tholen B-types and F-types
  - C-type: Tholen C-types
  - Cg-types and Cgh-types: Tholen G-types
  - Ch-types: C-types with an absorption feature around 0.7 μm
  - Cb-types: Objects between SMASS C and B-types
- S-group:
  - A-type: Tholen A-types
  - K-type: These asteroids were "featureless S-types" under Tholen classification. These objects have a particularly shallow 1 μm absorption feature, and lack a 2 μm absorption. These were found during studies of the Eos family of asteroids.
  - L-type: These asteroids were "featureless S-types" under Tholen classification. These objects have a strong reddish spectrum shortwards of 0.75 μm, and are flat longward of this.

    Ld-type: See below
  - Q-type: Tholen Q-types
  - R-type: Tholen R-types
  - S-type: "typical" Tholen S-types
  - Sa, Sk, Sl, Sq, Sr-types: Transitional objects between S and their respective classes.
- X-group:
  - X-type: "typical" Tholen X-types
  - Xc, Xe, and Xk-types: Transitional objects between X and their respective classes.

- Other classes:
  - T-type: Tholen T-type
  - D-type: Tholen D-type
  - Ld-type: This group has an L-like flat spectrum longwards of 0.75 μm, but even redder in visible wavelengths. Tholen called these D-types usually but some were also listed as A-type (i.e., 728 Leonis)
  - O-type: This is best defined as having a spectrum similar to the unusual asteroid 3628 Boznemcová. Their spectra have a deep absorption feature longward of 0.75 μm. This definition is due to the fact that until just recently, only one such asteroid has the O-type—the aforementioned 3628 Boznemcová! Now, there are seven listed in the JPL database.
  - T-type: Tholen T-types
  - V-type: Tholen V-types

How Many Moons?

The question of how many moons are in our Solar System has undergone a lot of flux. As an example, Venus has no conventional moons, but has a co-orbital body and two smaller bodies (asteroids) related to its orbit. And while no book could really detail these three objects, due to the small amount known about them, no book even mentions them in passing. Just like no book mentions that 4 of the 5000+ Jupiter Trojans are known to have moonlets, or that there must be 1000 or more that have moonlets that we are unaware of.

According to one source published in 1958 (a book which also clearly shows that Pluto is considerable larger than Mercury, almost the size of Mars), there were 31 moons in the Solar System (and since Pluto was bigger than Mercury, I think we can understand why it showed no moons around Pluto). A later source in 1963, which was revised in 1977, showed there were 34 moons. According to a 1993 book there were 61 for the giant planets, plus 3 for the Earth and Mars and 1 for Pluto (still a planet in 1993). Moving ahead to 2006, it was 163 (with pluses after Jupiter and Saturn), including little Dactyl (which orbits an asteroid), and minus 1 since Pluto was not a planet any more, but an ice dwarf planet/trans-Neptunian object, and Charon's definition was fuzzy too. In 2011, it was 7 major, 8 medium, and 166 as a mix of minor and very minor (a four-part distinction which will be used extensively throughout the organization of the book.)

Now it is 2015, so it is time for a new count. When the book was completed, 164 moons could be found around planets, 8 around dwarf planets in the asteroid belt, 96 around smaller asteroids, 3 as Venus co-orbitals, with an additional 4 Jupiter Trojans, 51 Near-earth objects, 20 Mars-crossing objects, and 87 TNO satellites. There are also 150 or more "possible" satellites in Saturn's rings (few of which are included in this volume due to minimal information about said objects). But be forewarned, this information changes practically on a day-to-day basis. However, through using Information Clearing House wikis, an exhaustive list of reputable sites can be found. One such list is an exhaustive list of asteroids with moon, and while it would not be practical to call the any such Earth-made list complete, it is exhaustive of what is currently known, even as that knowledge is continually being revised.

Finally, this book tends to concentrate mainly on this solar system, since there is no positive information on any moons outside of it (even though it can be safely assumed they exist).

How to Use This Book

The first part of the book starts with an introduction of the subject, covering the planets and their moons in increasing distance from the sun. The chapters are organized by planet or regions, starting with Mercury and Venus and moving outward. Only asteroids that stay within the asteroid belt are covered in their own chapter. More are described by the planet(s) that they seem most tied to, so that Jupiter Trojans are dealt with in Chap. 5, and Venus' co-orbitals in the Chap. 1 (although few are covered in any detail). This initial listing talks briefly about the objects, and the number and type of moons known to exist around each planet. Each major moon is highlighted with some spotlight information and photos.

The more significant the moon, the more that is said about it. The "major" moons (diameters to exceed 2400 km) are covered extensively, all of the moderate moons (diameters in excess of 1000 km) are discussed in somewhat less detail, and while not covering every one of the myriad minor moons (some with diameter of only about a km), their families are mentioned, as well as listing all of the notable/family-less ones.

The last part of the book focuses on projects targeted on moons and satellites. Some of these anybody with time and either a four-function calculator or lots of paper and a pencil and some extra free time can do; some require observing equipment; some require a solid mathematical background; and some require a moderately advanced knowledge of physics, math, and "how things work." I tried to keep most of them simple, everyman projects.

Above all, remember when reading this book…

Enjoy it.

Crystal River, FL, USA James A. Hall III

Acknowledgments

I would like to thank the use of some ideas from GoldenBooks *Skyguide* which, even though it is a basic book, is most useful for many common and a few obscure star names, and constellation border lines.

I would also thank the use of the venerable *Burnham's Celestial Handbook* which is really a seminal work from which I got the idea of how to incorporate the tables. Even 30 years after its 1977 revision, and 50 years after its 1963 initial edition, it is still a useful guide (and it has even the most obscure star names if there are any records known to exist). Readers of that book (whether you read the whole 2138 pages, thumbed through it as needed, or read about two volumes of it finishing through Orion like I did) I hope you will find this book to be a comfortable return to the familiarity of quality data, even if it does go out of date.

I would also like to thank *The Star Guide* for some up-close maps of the moon when Google could not find the item I was looking for, *NightWatch*, well, because it is *NightWatch*! (And if you have this book, you know why I do not need to say more than that. I would be hard pressed to try…)

I would also like to thank my magazine, but they insist that I not use anything I found in the magazine, so obviously I cannot thank them. It would be rude to name them now, so this is the last mention of them.

I also wanted to include some comics here and there to add visual interest to dry chapters, but when I saw how much money they wanted—well, now I know why they are called "syndicates."

Notes on the Text

The terms asteroids and minor planets are used interchangeably, especially by JPL whose data is used extensively in this book.

If a minor planet's orbit enters the parent planet's orbit from inside, but does not cross the orbit, it is an **inner-grazer**. If a minor planet's orbit enters the parent planet's from outside without crossing, it is then an **outer-grazer**. If the minor planet's orbit causes it to cross the orbit, it is a **<planet>-crossing** asteroid/minor-planet. If a minor planet orbits in the same orbit as its planet (and may share a 1:1 orbital resonance), then it becomes a **near <planet> object**. If an object crosses multiple gas giant planet orbits, it is a **centaur**.

If the object is either 60° ahead of or behind its planet's orbit in the L_4 or L_5 Lagrangian point (2 of the 5 points where gravity of various objects balance and cancel each other out and where (an) object(s) can be in a stable/semi-stable position), then it is a **Trojan**.

The last category is **co-orbital satellites**, and **quasi-satellites**, a subclass. Co-orbital satellites share some of the same orbital characteristics of another object and a variety of these exist including satellites that are similar, satellites that swap characteristics (including possibly position), and so on. Co-orbitals also include quasi-satellites—co-orbitals that share an orbit with their planet and near the same area (i.e., close to 0°) even though most such objects are unstable (unless also highly eccentric). These are not discussed in many cases unless it is a bona fide moon like Janus and Epimetheus, two of Saturn's satellites which are co-orbital and which swap orbit every few years. (There is little that can be said about a quasi-satellite that is barely a kilometer in diameter, except that it exists, and it has unusual orbital properties.)

Since I don't intend for anyone to use this book to launch space probes nor do any other type of highly technical work with my data, I have had to make a judgment call about how accurate the data should be. Some of my source data has 16 decimal places! Rather than say that something has an inclination of 32.6773542378542° (or 32°40′38.4757627512″), I think that 32.68° (or 32°40′48″) is more than sufficient, and as you can see the introduced error is only about 10 arc seconds! In all cases, I aimed for practicability.

For numerals, the books uses **e notation** (which is similar to scientific notation and based on it). Many computer programs and calculators use e notation to denote large and small number. For instance, if someone wanted to tell a calculator or programming language 6.02×10^{23}, they would tell the calculator 6.02E23, 6.02E23, or 6.02e23. Spreadsheets often will use 6.02E+23. I will use "e". In all such cases it means "$\times 10^{e}$" (i.e., 6.02e23 is actually 602,000,000,000,000,000,000,000.)

Lastly, the number of moons and what we know about them changes continually and will continue to do so; this book is accurate as of its writing, but the terrain is always changing.

About the Author

James A. Hall III is a substitute teacher (specializing in middle and high schools) living in Central Florida. In addition to writing "The Moons of the Solar System" for Springer, he has also written freelance since the late 1990s. He has volunteered in libraries and he interned at MOSI, the Museum of Science and Industry, in Tampa, at the Saunders Planetarium, rewriting their planetarium shows. He desires to get a permanent position at a library, museum, or school media center.

He holds an AA in Liberal Arts from Central Florida Community College (now Central Florida College), a BA in English in Creative Writing (and a minor in Theater) from the University of South Florida, and earned his MA in Library and Information Sciences (MLIS), as well as a Graduate Certificate in Museum Studies.

He is the author of, and has self-published, two novels; "The Distant Suns" and "The Yesterday with No Tomorrow" (available at Smashwords.com, its affiliates, and Amazon.com). He also intends to publish "The Flare Lance" and his epic series "Atlantis 2" when they are done being edited. He also wants to revise and update "The Moons of the Solar System," and write other books for Springer (if they are interested in his ideas).

He is also active in the American Library Association, Relay for Life, and occasional University Functions. His interests include astronomy, origami, wolves, tabletop role-playing games, computers, and writing.

Contents

I. Moons

1. Mercury and Venus

Why No Real Moons?

For a book about the moons of the Solar System, the two planets closest to the Sun are rather deflating. Mercury and Venus have no moons, but it could be asked *why* Mercury and Venus have no moons. This should be handled on a case-by-case basis.

Mercury

Generally planets have moons that mass equal to about 0.1 % of their own mass or 0.001 planets. Earth's moon is an exception at 1.23 % and so is Charon at 11.82 %, but many astronomers don't consider Charon a moon at all. More about this later on.

Mercury has a total mass of 3.301e23 kg. Therefore a "typical" moon of Mercury would have a mass of only 3.301e20 kg. With an item so light, at less than 58 million km, there is a high probability that the moon would not orbit Mercury at all; it would very likely become co-orbital with Mercury around the much more massive sun.

Suffice it to say, such a moon would be very insignificant in the scale of things.

Mercury does see guests in its orbit, however—according to the JPL Solar System Dynamics database there are 207 asteroids which are Mercury-crossers and 453 Mercury-grazers (as of October, 2013).

The Tale of the "Mercurial Moon"

When *Mariner 10* investigated Mercury, it found ultraviolet radiation in an area where it "had no right to be there." It was thought to possibly be a moon. It later vanished. After a few days it was back again. From this a speed was measured which was 4 km/sec;

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about correct for what else was observed. It was eventually found to be from 31 Crateris, an eclipsing binary star which happened to be in the right direction. (Due to this, astronomers discovered that ultraviolet radiation from distant stars can pierce the interstellar medium—which at the time was thought impossible.)

Venus

Venus also has no natural satellite. But with a greater distance from the sun and a heavier mass than Mercury, the same reasoning to explain why does not work so well, unless the theoretical satellite was something like a low mass asteroid—something with a size under 1 km (0.6 miles). In that case the object might be coorbital.

But did it never have a moon? One theory is the Venus may have, at one time, *had* a moon. Earth's atmosphere is much thinner than Venus'. Venus' surface pressure is 90 times our own, and the atmosphere is 100 km thick. So anything plummeting through Venus' atmosphere, even a large body, would suffer greater burn, and more drag (resistance) than the same object plummeting through Earth's atmosphere. According to the leading theory of moon formation, such an event did occur on Earth (and a planetesimal called Theia), and that is how our own moon formed. More on this later.

Venus rotates backwards—the only planet in the solar system to do so—which could have occurred if a large object struck it in the direction opposite "normal" planetary spin (and in agreement with its current spin). Retrograde moons are not at all rare; in fact, they may be as common as prograde ones. This new retrograde spin would then be reinforced by the Earth since, like two rollers or two gears, they rotate in opposite directions (Mercury could too in theory, but Mercury is likely too small, of too low of mass, and too far away to have much of an effect, but if it had any effect it would be a reinforcing one since its spin too is prograde). Venus and Earth are nearly the same size (Venus is about 0.87 Earth volumes and 0.82 Earth masses). In addition to this similarity, 5 Venusian solar days (about 116.75 Earth days each, 5 equaling 583.75) almost equals 1 synodic period (about 584 days).

This would seem to indicate that there is some kind of gravitational interaction between Earth and Venus.

Additional evidence for this includes the fact that, of the 1000 craters observable on Venus' surface, none seem older than about 500 million years. If something as massive as a moon hit the planet, it could very likely melt the crust back into molten magma erasing any prior evidence of cratering (which the thick atmosphere Venus currently has makes difficult to begin with). Of course, if a moon hit its planet, massive out gassing can occur, and may have. (Here though, I am using lack of evidence for evidence, which leads to a scientific fallacy; however, the basic statement—that the crust would be melted, and gasses may have been released—is still true.) So at one time, Venus may have had a moon. Regardless, it does not have one now.

These things being said, asteroids 2001 CK_{32}, 2002 VE_{68}, and 2012 XE_{133} all share Venus' orbit. These will not be expanded on, as they are not technically moons of Venus (as they orbit the Sun, or they follow complex and exotic orbits, being gravitationally bound between the two objects), and none of them have moons in their own right. There is also little to say about them other than the most basic of information or complex orbital ephemeris.

Neith

Venus was thought to have an extant moon quite recently. Giovanni Cassini first claimed to see it in 1672, but made small note if it. He then claimed to see it again in 1686 and made a formal announcement. Other astronomers claimed to see it as well; James Short (1740), Joseph Louis Lagrange (1761), Andreas Mayer (1759), 18 separate "sightings" in 1761, 8 in 1764, and Christian Horrebow (1768).

But proof was not to be had. William Herschel never found it. Cassini and Lagrange claimed two separate orbits. Neither one had any location predictions proved. The name Neith was suggested by Jean-Charles Houzeau, who believed it was a planet, with a 283-day orbit, and which came into conjunction every 1080 days. Again no predicted appearances were proven.

In 1887, a thorough study was done of every recorded "sighting" by the Belgian Academy of Sciences. In a published paper they determined that most of the sightings could be explained away. Chi Orionis, M Tauri, 71 Orionis, Nu Geminorum, Theta Librae, or some combination thereof (any of which could be seen in the vicinity of Venus) were found to be the most likely culprits.

2. Earth and Luna

Luna

Luna is the proper name given to Earth's own moon, hence the word Lunar. (These terms are used interchangeably in this chapter, and Appendix B only, as this rest of this book refers to other moons). Luna is tidally locked to the Earth so that one side always faces us, but due to a slight rocking motion called libration, we can actually see about 59 % of the total surface area of the moon (not all at once, of course). Many other moons exhibit tidal locking with their own planet. Still, the far side (often incorrectly referred to as the dark side, as it is spends as much time lit as the close side) remained mostly hidden until 1959. In 1959, the Soviet Luna 3 probe photographed this mysterious side (Figs. 2.1, 2.2, 2.3, 2.4, and 2.5).

Formation and Origin

Luna, our moon, is quite unusual.

The leading theory of our moon's formation is called the Giant Impact Theory. About 4.4–4.45 billion years ago (give or take a few millennia), a large body, a planetesimal often referred to as Theia, and thought to be about the size of Mars, smashed into Earth. This destroyed the crust of our planet, turning the whole planet to magma and a large ball of this material was jettisoned from the surface. This magma spun itself into a ball, attaining hydrostatic equilibrium, cooled, and solidified into Luna. It settled into an orbit near Earth, not fast enough to escape, nor so close as to crash into it, nor so slow as to decay considerably in the short-term. It is therefore in a somewhat stable if unusual orbit.

Most other major moons orbit along the equator of their planet. Our moon does not; rather it follows a margin along either side of the ecliptic, of about 5°.

J.A. Hall III, *Moons of the Solar System*, Astronomers' Universe,
DOI 10.1007/978-3-319-20636-3_2

Fig. 2.1 Lunar near side (Credit: NASA)

It is also almost perfectly round. The moon's roundness exceeds that of every planet (or at least every superior planet. Mercury is also very round.) Visually, it looks unusually flat. Most planets from our viewpoint are brighter near their center than at their limbs. It is also important to note that many other moons appear equally fuzzy at the edge from their own planets. Luna is different. The full moon is evenly lit at all parts, which was noticed by, and puzzled, the ancient Greeks.

Continuing onward, Earth and the Moon spin in similar orientations. Moon samples indicate the surface of the Moon was once liquid rock, or magma. The Moon is believed to have a relatively small iron core (but comparable to the Earth's core by percentage of total mass and volume, accounting for density). Its density is lower than Earth's own, but only slightly. Stable mineral isotopes of lunar and terrestrial rock are identical, implying a common origin.

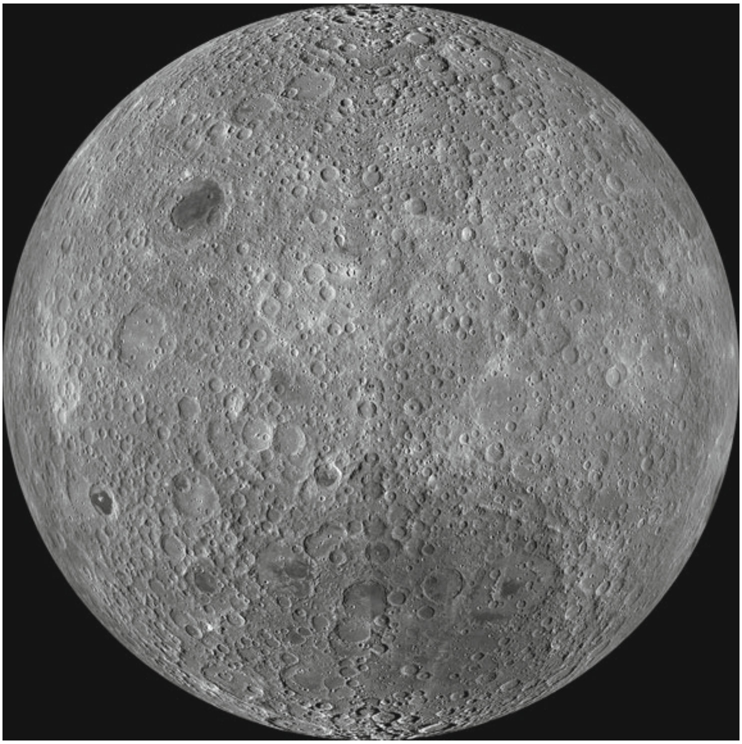

Fig. 2.2 Lunar far side (Credit: NASA)

Finally, until 2015, our moon was considered unique in having an electromagnetic field of its own. Recently Hyperion was found to have one as well, but much weaker than our moon, which has the strongest electromagnetic field found around a moon. In March of 2015 Ganymede was found to also have its own magnetic field.

Not all questions have been answered though. Lengthy scientific debates over the problems surrounding the Giant Impact Theory are still ongoing; however, this is still far and away the leading theory of formation. The Solar System has been host to a number of cataclysmic events. Shortly after the end of the planetary formation epoch, theories state there may have been 50–100 Moon-to-Mars-sized objects. Some such objects would be ejected from the system, and some would smash into other objects (both each other and more well-known objects, like Earth, Luna, and other moons). About four billion years ago, 500–600 million years after the formation of the solar system was a period known as the

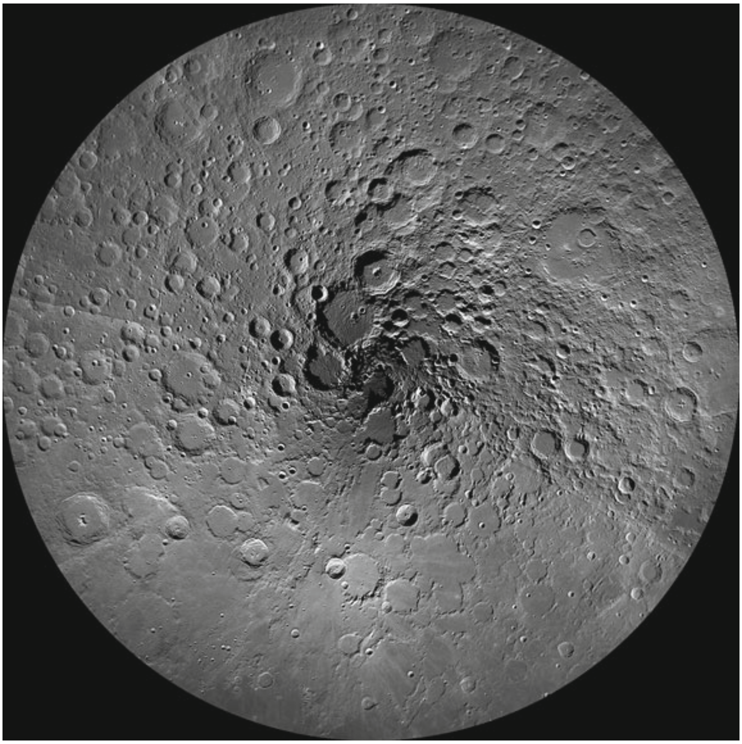

Fig. 2.3 Lunar north pole (Credit: NASA)

"Late Heavy Bombardment." Incidentally life seems to have first formed on Earth about 200 million years later in 3.8 Gya. If any life formed during or before this tumultuous period we have (as we should) no evidence of it, and it would have had a hard time surviving these events. This late heavy bombardment period left scars on most of the worlds in the solar system, including the Moon. There are 1609 named craters that can be defined; older ones get erased by newer ones, and this not including satellite craters. Some sources indicate there may be over 300,000 in all. Luna is much thicker on the far side than on the near side, the result of the heat of a still-hot Earth pushing the Moon's concentrations of aluminum and calcium to the faster-cooling side of the tidally locked Moon.

Impact on Earth

Ever since humanity can recall, Luna has been in our sky by night and by day. For some it is a simple source of light, to others it is

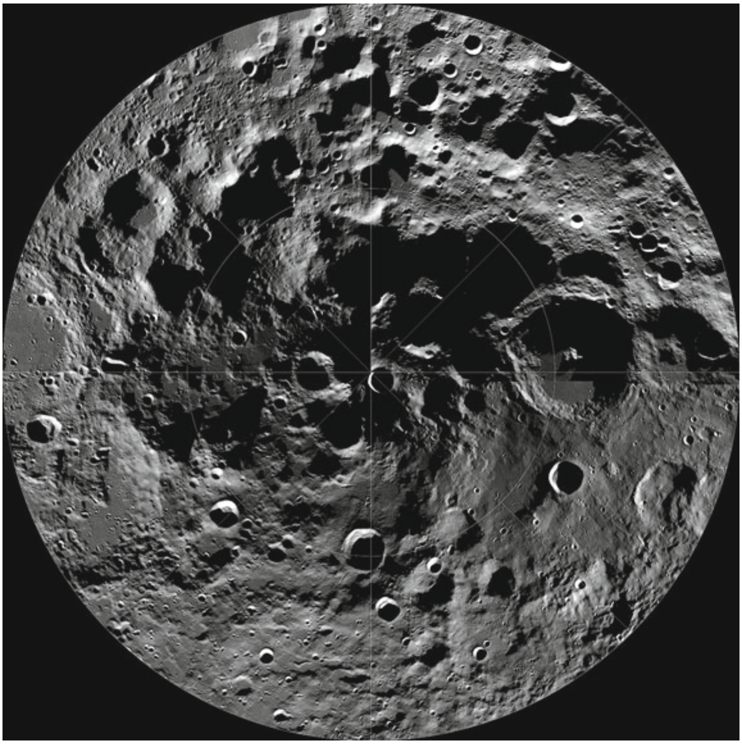

Fig. 2.4 Lunar south pole (Credit: NASA)

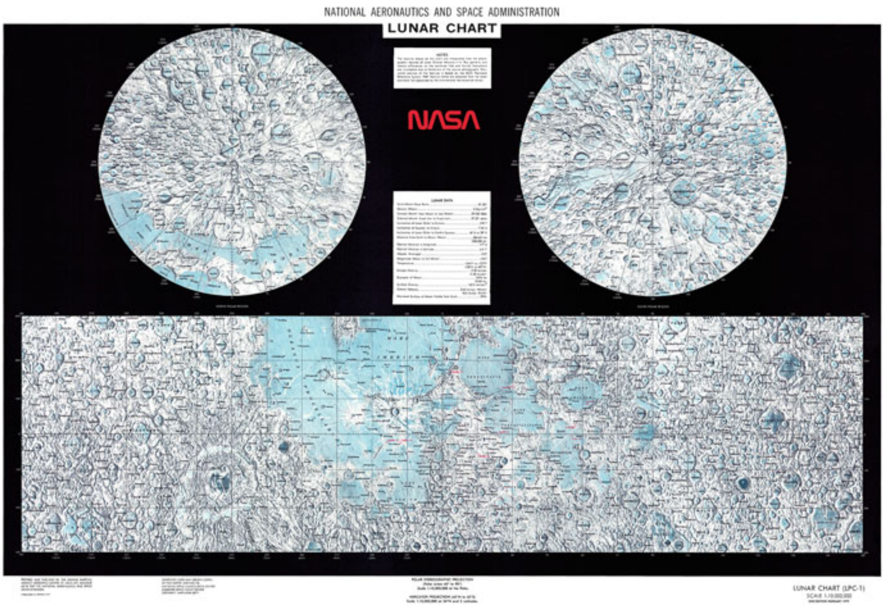

Fig. 2.5 NASA lunar chart. This chart is produced by NASA and many of the larger features can be found on it. It shows most of the surface and both polar regions. (Credit: NASA)

seen as a source of protection or inspiration and it causes superstition among others. Recent generations made it a goal to reach the surface. Regardless, for almost everyone, it holds a special place in our hearts and souls.

Light is one of the most obvious effects of the moon. During the day, the Earth has a seemingly unending source of light, the Sun. While the Sun does have a finite life span, few other than cosmologists concern themselves with such factors. For most it is enough that it exists now, and can be depended on until their dying day, as well as the dying day of the next 100 generations (which is considered long even in the astronomical timescale, though the cosmologists consider this rather shortsighted.) Light affects all functions through the circadian cycle which governs our day and night, various biological functions that slow down at night (like waste processing) which is based in part on light, and seasonal affective disorder is also based on day length/daylight length, and some treatments are based on light therapy. There are even people who study the effects of light on life; the terms scotobiologist and photobiologist have surfaced in recent years. The moon's brightness is enough that in times before electricity it could aid in navigation, and it is still manipulated in the fishing techniques for certain fish. Even navigation would be impacted since the moon is one of the many objects which ship navigators have historically used to chart their path.

Beyond the practical, just listing the works of fiction about Luna, poetry and music about the moon, and people inspired by it would be a full-time job. If someone thinks the moon controls their life, they might look into this and discover the pseudo-science of astrology. Or they may use the older term for this belief and coin themselves a **luna**tic. The moon is astronomy for the everyman.

It may even have been a factor in the existence of life at all. A number of theories indicate there was a primordial soup on Earth. All reputable theories first evolve life in some sort of liquid medium. And the moon is certainly one of the primary factors of tides. Therefore the argument follows this short line: life requires tides; significant tides require the moon. Without the moon, tides would be much weaker (driven mostly by the sun) and with weaker tides and less mixing of this soup, life may never have arisen on Earth. Geodynamicists theorize that the ocean's tidal flow, caused by the moon, may have made the climate more hospitable for speciation. Some molecular biologists even speculate that fast lunar tidal oscillation could have created an environment where protonucleic acid fragments might have benefited from the high salinity of the frequent low-tide periods. That cycle of rapidly forming and dissolving molecules in the rapidly rising and receding tidal waters could have eventually led to the development of DNA. This debate rages on.

Our moon is a big place. According what the IAU has recognized and named it has:

- 12 Vallis (valleys)
- 22 Maria (sea)
- Oceanus Procellarum (ocean)
- 20 Lacus (lakes)
- 3 Palus (marshes)
- 11 Sinus (bays)
- 30 Mons (mountains)
- 18 Montes (mountain ranges)
- Reiner Gamma (an albedo feature)
- 20 Catena (chains of craters)
- 18 Dorsa and 21 Dorsum (wrinkle-ridge system and wrinkle-ridges)
- 9 Promontorium (capes)
- 52 Rima and 53 Rimae (rilles (ridges) and rille systems)
- 8 Rupes (escarpments)
- 1609 known, named craters (older ones were erased and this does not include satellite craters, which do not have independent names.)

And when things the IAU does not recognize are added:

- 5 Ex-Seas
- 1 Unrecognized Marsh (Palus Nebularum)
- Private/personal identification systems

Selected Lunar Features

Notes (Table 2.1):

1. Asterisks have a full description under the descriptive notes that follow. Double asterisks include a picture. Triple asterisks include multiple photos.

Table 2.1 Selected lunar features

	Type of feature	Name	Latitude Deg	Latitude Min	Longitude Deg	Longitude Min	Size (km)	Notes
*	Crater	Albategnius	–11°	42′	4°	18′	114	
*	Crater	Aliacensis	–30°	36′	5°	12′	79	
	Crater	Alpetragius	–16°		–4°	30′	30	
*	Crater	Alphonsus	–13°	42′	–3°	12′	108	
	Crater	Anaxagoras	73°	24′	–10°	6′	50	
FS	Crater	Apollo	–36°	6′	**–151°**	**48′**	537	
	Crater	Arago	6°	12′	21°	24′	26	
*	Crater	Archimedes	29°	42′	–4°		82	
	Crater	Ariadaeus	4°	36′	17°	18′	11	
	Crater	Aristarchus	23°	42′	–47°	24′	40	
*	Crater	Aristillus	33°	54′	1°	12′	55	
*	Crater	Aristoteles	50°	12′	17°	24′	87	
	Crater	Arzachel	–18°	12′	–1°	54′	96	
*	Crater	Atlas	46°	42′	44°	24′	87	
*	Crater	Autolycus	30°	42′	1°	30′	39	
*	Crater	Bailly	–66°	30′	–69°	6′	26	
*	Crater	Bessel	21°	48′	17°	54′	15	
	Crater	Bianchini	48°	42′	–34°	18′	38	
	Crater	Birt	–22°	24′	–8°	30′	16	
*	Crater	Bullialdus	–20°	42′	–22°	12′	60	
	Crater	Bürg	45°		28°	12′	39	
	Crater	Byrd	85°	18′	9°	48′	93	
	Crater	Cassini	40°	12′	4°	36′	56	

*	Crater	Catharina	–18°	6′	23°	24′	104
	Crater	Challis	79°	30′	9°	12′	55
**	Crater	Clavius	–58°	48′	–14°	6′	245
*	Crater	Cleomedes	27°	42′	56°		125
	Crater	Cook	–17°	30′	48°	54′	46
**	Crater	Copernicus	9°	42′	–20°	6′	93
	Crater	Cyrillus	–13°	12′	24°		98
FS**	Crater	Daedales	–5°	54′	**179°**	**24**′	93
	Crater	Delambre	–1°	54′	17°	30′	51
	Crater	Encke	4°	36′	–36°	36′	28
	Crater	Endymion	53°	54′	57°		123
	Crater	Epigenes	57°	30′	–4°	36′	55
**	Crater	Eratosthenes	14°	30′	–11°	18′	58
*	Crater	Eudoxus	44°	18′	17°	18′	67
*	Crater	Fabricius	–42°	54′	42°		78
*	Crater	Fracastorius	–21°	30′	33°	21′	112
	Crater	Furnerius	–36°		60°	36′	135
FS	Crater	Gagarin	–20°	12′	**149°**	**12**′	265
*	Crater	Gassendi	–17°	36′	–40°	6′	101
*	Crater	Gauss	35°	42′	79°		177
	Crater	Gemma Frisius	–34°	12′	13°	18′	87
	Crater	Goclenius	–10°		45°		72
	Crater	Goldschmidt	73°	12′	–3°	48′	113
*	Crater	Grimaldi	–5°	30′	–68°	18′	172
	Crater	Halley	–8°		5°	42′	36
	Crater	Henry	–24°		–56°	48′	41

(continued)

Table 2.1 (continued)

	Type of feature	Name	Latitude		Longitude		Size (km)	Notes
			Deg	Min	Deg	Min		
	Crater	Henry Frères	–23°	30′	–58°	54′	42	
*	Crater	Hercules	46°	42′	39°	6′	69	
	Crater	Herodotus	23°	12′	–49°	32′	34	
**	Crater	Herschel	–5°	42′	–2°	6′	40	
FS	Crater	Hertzsprung	2°	36′	**129°**	**12′**	591	
	Crater	Hevelius	2°	12′	–67°	36′	115	
*	Crater	Hipparchus	–5°	6′	5°	12′	138	
	Crater	Horrocks	–4°		5°	54′	30	
*	Crater	Hyginus	7°	48′	6°	18′	9	Descirptive note under: "R" for Rima
	Crater	J. Herchel	52°		–42°		165	
	Crater	Julius Caesar	9°		15°	24′	90	
**	Crater	Kepler	8°	6′	–38°		31	
	Crater	Klein	–12°		2°	12′	44	
FS	Crater	Korolev	–4°		**–157°**	**24′**	437	
**	Crater	Lalande	–4°	24′	**–8°**	**36′**	24	
	Crater	Lambart	25°	42′	–21°		30	
	Crater	Lamont	4°	24′	23°	42′	106	
**	Crater	Langrenus	–8°	54′	61°	6′	127	
*	Crater	Lansberg	0°	–18′	–26°	36′	38	
FS	Crater	Leibnitz	–38°	18′	**179°**	**12′**	245	
	Crater	Liebig	–24°	18′	–38°	12′	37	
*	Crater	Longomontanus	–49°	36′	–21°	42′	157	
	Crater	Macrobius	21°	18′	46°		64	

*	Crater	Maginus	–50°	30′	–6°	18′	194
	Crater	Main	80°	42′	10°	6′	46
*	Crater	Manilius	14°	30′	9°	6′	38
	Crater	Maskelyne	2°	12′	30°	6′	23
*	Crater	Maurolycus	–42°		14°		114
FS	Crater	Mendeleev	5°	42′	**140°**	**54**′	313
*	Crater	Menelaus	16°	18′	16°		26
	Crater	Mersenius	–21°	30′	–49°	12′	84
	Crater	Messier	–1°	54′	47°	36′	11
	Crater	Nansen	80°	54′	95°	18′	104
	Crater	Neper	8°	30′	84°	36′	137
	Crater	Newcomb	29°	54′	43°	48′	41
	Crater	Pallas	5°	30′	–1°	30′	46
	Crater	Peary	88°	36′	33°		73
*	Crater	Petavius	–25°	6′	60°	24′	188
*	Crater	Piccolomini	–29°	42′	32°	12′	87
*	Crater	Pitatus	–29°	56′	–13°	30′	106
*	Crater	Plato	51°	36′	–9°	24′	109
	Crater	Plinius	15°	24′	23°	42′	43
*	Crater	Posidonius	31°	48′	29°	54′	95
	Crater	Protagoras	56°		7°	18′	21
**	Crater	Ptolemaeus	–9°	18′	–1°	54′	164
	Crater	Reiner	7°		–54°	54′	29
*	Crater	Reinhold	3°	18′	–22°	48′	42
	Crater	Rheita	–37°	6′	47°	12′	70
*	Crater	Riccioli	–3°	18′	–74°	36′	139

(continued)

Table 2.1 (continued)

	Type of feature	Name	Latitude Deg	Latitude Min	Longitude Deg	Longitude Min	Size (km)	Notes
	Crater	Ross	11°	42′	21°	42′	24	
*	Crater	Schickard	–44°	18′	–55°	18′	206	
	Crater	Schiller	–51°	54′	–39°		180	
FS	Crater	Schrodinger	–75°	0′	**132°**	**24′**	312	
	Crater	Scoresby	77°	42′	14°	6′	55	
	Crater	Snellius	–29°	18′	55°	42′	82	
	Crater	Stevinus	–32°	30′	54°	12′	74	
	Crater	Stöfler	–41°	6′	6°		126	
*	Crater	Struve	22°	24′	–77°	6′	164	
	Crater	Taruntius	5°	36′	46°	30′	56	
*	Crater	Theophilus	–11°	42′	26°	24′	110	
	Crater	Timocharis	26°	42′	–13°	6′	33	
	Crater	Torricelli	–4°	36′	28°	30′	22	
	Crater	Triesnecker	2°	12′	3°	36′	26	
FS	Crater	Tsiolkovskiy	–21°	12′	**128°**	**54′**	185	
***	Crater	Tycho	–43°	24′	–11°	6′	102	
*	Crater	Vandelinus	–16°	24′	61°	36′	131	
*	Crater	Walther	–33°	6′	1°		128	
	Crater	Werner	–28°		3°	18′	70	
	Crater	Wilhelm	–43°	24′	–20°	24′	106	
	Crater	Young	–41°	30′	50°	54′	71	
	Cliff/Ridge	Dorsum Zirkel	28°	6′	–23°	30′	193	
*	Cliff/Ridge	Rupes Altai	–24°	18′	22°	36′	427	
	Cliff/Ridge	Rupes Liebig	–25°		–46°		180	

*	Cliff/Ridge	Rupes Recta	–22°	6′	–7°	48′	134	
*	Lacus	Lacus Mortis	45°		27°	12′	376	"Lake of Death"
*	Lacus	Lacus Somniorum	38°		29°	12′	384	"Lake of Dreams"
*	Mare	Mare Australe	–38°	54′	93°		603	"Southern Sea"
*	Mare	Mare Congitum	–10°		–23°	6′	376	"Sea that has become known"
*	Mare	Mare Crisium	17°		59°	6′	418	"Sea of Crises"
*	Mare	Mare Fecunditatis	–7°	48′	51°	18′	909	"Sea of Fecundity" (Or Sea of Fertility)
*	Mare	Mare Frigoris	56°		1°	24′	1598	"Sea of Cold"
	Mare	Mare Humboldtianum	56°	48′	81°	30′	273	
*	Mare	Mare Humorum	–24°	24′	–38°	36′	389	"Sea of Moisture"
*	Mare	Mare Imbrium	32°	48′	15°	36′	1123	"Sea of Showers" (Or Sea of Rains)
FS***	Mare	Mare Moscoviense	27°	18′	**147°**	**54**′	277	"Sea of Muscovy"
*	Mare	Mare Nectaris	–15°	12′	35°	30′	333	"Sea of Nectar"
*	Mare	Mare Nubium	–21°	18′	–16°	36′	715	"Sea of Clouds"
FS	Mare	Mare Orientale	–19°	24′	–**92°**	**48**′	327	"Eastern Sea" While this is limb, I say far side since no detail can ever be seen
*	Mare	Mare Serenitatis	28°		17°	30′	707	"Sea of Serenity"
*	Mare	Mare Smythii	2°	18′	87°	30′	373	
	Mare	Mare Spumans	1°	6′	65°	6′	139	"Foaming Sea"
***	Mare	Mare Tranquillitatis	8°	30′	31°	24′	873	"Sea of Tranquility"
	Mare	Mare Undarum	6°	48′	68°	24′	243	"Sea of Waves"
*	Mare	Mare Vaporum	13°	30′	3°	60′	245	"Sea of Vapors"
	Mountain	Mons La Hire	27°	48′	–25°	30′	25	

(continued)

Table 2.1 (continued)

	Type of feature	Name	Latitude Deg	Latitude Min	Longitude Deg	Longitude Min	Size (km)	Notes
*	Mountain	Mons Pico	45°	42′	–8°	54′	25	"Mount Peak"
	Mountain	Mons Piton	40°	36′	–1°	6′	25	After a mountain on the Tenerife Islands
	Mountain	Mons Rümker	40°	48′	–58°	6′	70	
*	Mountains	Montes Alpes	46°	24′	0°	–48′	281	Named from terrestrial Alps
**	Mountains	Montes Apenninus	18°	54′	–3°	42′	401	Named from terrestrial Apennines
*	Mountains	Montes Carpatus	14°	30′	–24°	24′	361	Named from terrestrial Carpathians
*	Mountains	Montes Caucasus	38°	24′	10°		445	Named from terrestrial Caucus
*	Mountains	Montes Haemus	19°	54′	9°	12′	560	Named for range in the Balkans
	Mountains	Montes Harbinger	27°		–41°		89	This refers to "Harbinger of dawn on Crater Aristoteles"
*	Mountains	Montes Jura	47°	6′	–34°		422	Named from terrestrial Jura Mountains
	Mountains	Montes Pyrenaeus	–15°	36′	41°	12′	164	Named from terrestrial Pyrenees
*	Mountains	Montes Recti	48°		–20°		90	Straight Rdige
	Mountains	Montes Riphaeus	–7°	42′	–28°	6′	189	Named from range in Asia (now Ural Mountains)
	Mountains	Montes Spitzbergen	35°		–5°		60	German for "sharp peaks" and named for resemblance to the terrestrial island group

	Mountains	Montes Taurus	28°	24′	41°	6′	172	Named from terrestrial Taurus Mts
	Mountains	Montes Teneriffe	47°	6′	–11°	48′	182	Named from terrestrial island
*	Oceanus	Oceanus Procellarum	18°	24′	–57°	24′	2568	"Ocean of Storms."
	Palus	Palis Putredinis	26°	39′	0°	24′	161	Marsh of Decay
	Palus	Palus Somnii	14°	6′	45°		143	Marsh of Sleep
	Rille	Rima Adriadaeus	5°	24′	14°		250	
	Rille	Rima Birt	–21°		–9°		50	
*	Rille	Rima Hyginus	7°	24′	7°	48′	219	
	Rille	Rimae Triesnecker	4°	18′	4°	36′	215	
	Sinus	Sinus Aestuum	10°	56′	–8°	48′	290	"Seething Bay"
	Sinus	Sinus Asperitatis	–3°	48′	27°	24′	206	"Bay of Roughness"
*	Sinus	Sinus Iridum	44°	6′	–31°	30′	236	"Bay of Rainbows"
*	Sinus	Sinus Medii	2°	24′	1°	42′	335	"Bay of the center" (Or Central Bay)
*	Sinus	Sinus Roris	54°		–56°	36′	202	"Bay of Dew"
	Vallis (Valley)	Rheita Valley	–42°	30′	51°	30′	445	
***	Vallis (Valley)	Taurus–Littrow Valley	20°	6′	30°	48′		This is an underdefined area. I list it as a valley only due to the name. Size undefined
**	Vallis (Valley)	Vallis Alpes	48°	30′	3°	12′	166	"Alpine Valley"
*	Vallis (Valley)	Vallis Rheita	–42°	30′	51°	30′	445	

These are all far side objects (FS). Bold reinforces the longitude value since due to longitude these object cannot be seen from Earth under any conditions

2. The type of feature, name, location of the center, and size and included. There are also translations, when the item is not named after a person or a crater/another crater. Under descriptive notes below is the source of all names for the selected described items.
3. The location of the center down to a 6′ resolution is given—south and west are negative numbers. Eleven non near-side items (marked with an FS) are included. The rest are, at least in part, observable even if within the libration zones.
4. All this data is from the "Gazetteer of Planetary Nomenclature," credited to the USGS and the IAU.
5. The best time to view features is when there are shadows to work with. That means that for anything other than naked eye viewing features have the most definition when the lunar terminator, the line between day and night, lies very near them. They are then well-lit, yet provide long shadows. Full moon observing is therefore the second most difficult (second to only new moon) due to the factor that there are no shadows, and thus subjects are near impossible to find, and not very detailed due to glare. The brightness can be modified by using a neutral moon filter.

Descriptions

For each item the (usually) Latin name (and if different, the English name), type, and size are noted. In italics, the source of the name is included. Then a short descriptive note.

As for the name, the last name is usually the name given to the crater, and is omitted. If the last name is different from the crater name, it is included in parenthesis.

Albategnius (Crater, 114 km)

Named for Muhammed Ben Geber (Al-Battānī), an Arab astronomer and mathematician (858–929).

This is an ancient walled plain. To the north is Hipparchus. The north wall was crushed by another crater, and the west wall was destroyed in the formation of Klein (44 km).

Aliacensis (Crater, 79 km)

Named for Pierre D'Ally, a French geographer (1350–1420).

This crater is the largest of a chain of craters. To the NNW is Werner (a nice crater, deep with nice walls, but not exceptionally notable, 70 km), then Blanchinus (61 km), then La Caille (67 km.) Only the first entry is in the table.

Alphonsus (Crater, 108 km)

Named for a Spanish astronomer, (Alfonso X (El Sabio) (1221–1284).)

Near 0° longitude, this is the center of three walled plains (with Ptolemaeus to the north and Arzachel to the south, with a smaller crater Alperagius between this and Arzachel). Rilles and small mountains litter the floor of this crater. Ranger 9 impacted here.

Archimedes (Crater, 82 km)

A Greek physicist and mathematician c.287–212 BCE.

The largest of the trio of notable "A" craters; Archimedes, Autolycus, and Aristillus. These feature flat floors with a lava base.

Aristarchus (Crater, 40 km)

A Greek astronomer c.310–230 BCE.

Small but bright. Near Schroter's Valley (Vallis Schröteri).

Aristillus (Crater, 55 km)

A Greek astronomer c.280 BCE.

The largest of the trio of notable "A" crater; Archimedes. Autolycus, and Aristillus. These feature flat floors with a lava base. It has a deep floor and a central peak.

Aristoteles (Crater, 87 km)

A Greek astronomer and philosopher 383–322 BCE.

Not one of the larger craters but one with concentric, multi-level walls

Atlas (Crater, 87 km)

Named for the mythological Greek Titan.

This crater has numerous other (younger) features cutting across its floor, both craters and rimae. It makes a nice pair with the crater Hercules, just to the west.

Autolycus (Crater, 39 km)

A Greek astronomer (*Autolycus of Pitane*), *c.310 BCE.*
Another of the trio notable "A" craters; Archimedes, Autolycus, and Aristillus, this is easily the smallest. All three feature flat floors with a lava base. Luna 2 impacted near here.

Bailly (Crater, 287 km)

Named for Jean Sylvain, a French astronomer, (*1736–1793*).
The largest known lunar crater, which is a pity since it is so far on the western limb it is difficult to see under the best of conditions. The floor of this crater is littered with so many other unnamed craters it is also difficult to see the original Bailly.

Bessel (Crater, 15 km)

Named for Friedrich Wilhelm, a German astronomer, (*1784–1845*).
This crater is a small one, but one of the few (and easily the largest) wholly within Mare Serenitatis (even though Menelaus and Posidonius are larger, they are both on the edge). The floor is flat and the sloped walls appear visually perfect with a nice slope inside and out (but a powerful instrument is required to see it at all.)

Bullialdus (Crater, 60 km)

Named for Ismael Bolliau, a French astronomer, (*1605–1694*).
This small crater is right on the edge of Mare Nubium is well formed, has intact walls and an intact central peak

Catharina (Crater, 104 km)

Named for St. Catherine of Alexandria, a Greek theologian and philosopher, died c.307 CE.
This is not a particularly noteworthy crater, and it lies to the southwest of Mare Nectaris. The north parts of this crater have taken significant damage from a much younger impact.

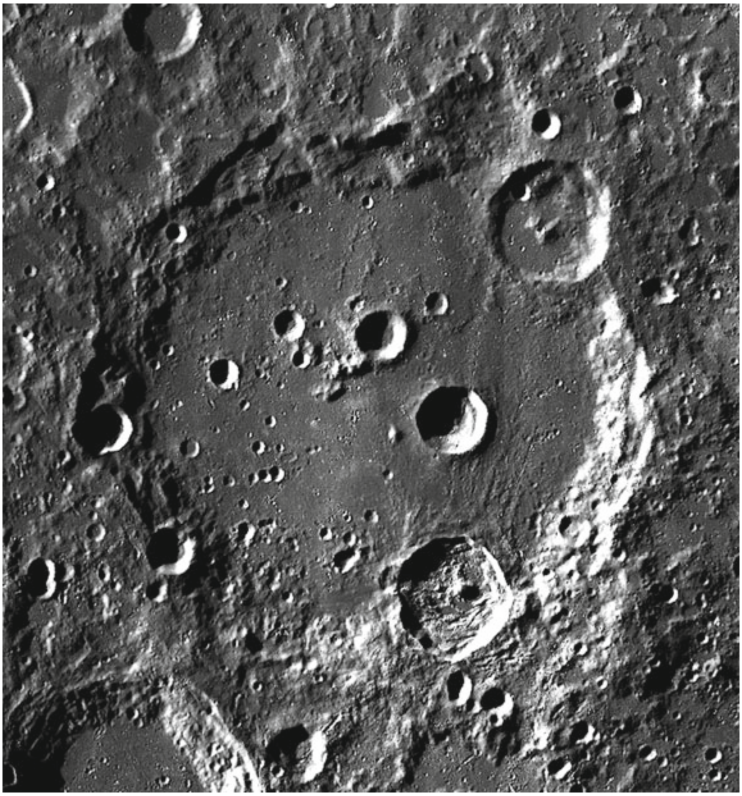

Fig. 2.6 Clavius Crater**.** This is one of the more southerly craters on the moon. It is also where the base from Arthur C. Clark's "2001: A Space Odyssey" was located. (Credit: NASA)

Clavius (Crater, 245 km)

Named for Christopher Klau, a German mathematician (1537–1612).

Clavius has 85 % the diameter of Bailly but is infinitely easier to see due to its prime location. Dozen of craters cover the site of Clavius; the largest is named Rutherford and is in the southeast corner and the second is Porter in the northeast. One of the more notable features is that there are a series of craters progressing counterclockwise from Rutherford. Some suggest that this is a good way to test a telescope's resolution (Fig. 2.6).

Cleomedes (Crater 125 km)

Named for a Greek astronomer, died c.50 BCE.

This is a bigger crater, just north of Mare Crisium. Nearby are Geminus and Messala. A number of other features are on its floor, the north wall is less of a slope than the other three, and part of its west-northwest wall was consumed when the crater Tralles (43 km) was formed.

Copernicus (Crater, 93 km)

If you cannot figure out who this is named after you may be in the wrong book, but this is named for the famed Polish astronomer, Nicolaus, (1473–1543).

One of the finest and most conspicuous lunar carters. A "classic" crater with high terraced walls and a central peak. At full moon a bright ray system becomes visible (Fig. 2.7).

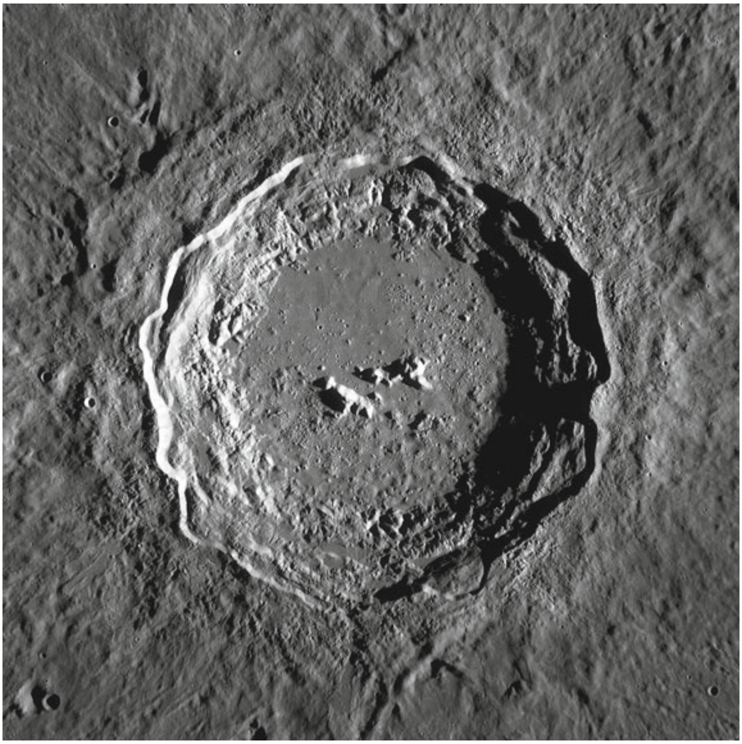

Fig. 2.7 Copernicus Crater. One of the two best craters in the northwest. Terraced wall are clearly visible. (Credit: NASA)

Fig. 2.8 Daedalus Carter (far side crater). This is another wonderful crater on the moon; unfortunately its beauty was hidden from Earth until the Soviet Luna 3 mission photographed the far side. And its beauty remained hidden even longer since the Luna 3 probes pictures were (understandbly) inferior to later imagery. (Credit: NASA)

Daedalus (Carter, 93 km) (far side)

Named for the Greek mythological character.

This is a very fine carter with terraced walls, and a central peak. Even the Apollo 11 astronauts appreciated the size and beauty of this crater photographing it, and commenting on "Crater 308" (as it may appear in some older sources) (Fig. 2.8).

Eratosthenes (Crater, 58 km)

A Greek astronomer and geographer c.276–196 BCE.

Similar to Copernicus at only two-thirds its size. This marks the end of the Apennine mountain chain (Fig. 2.9).

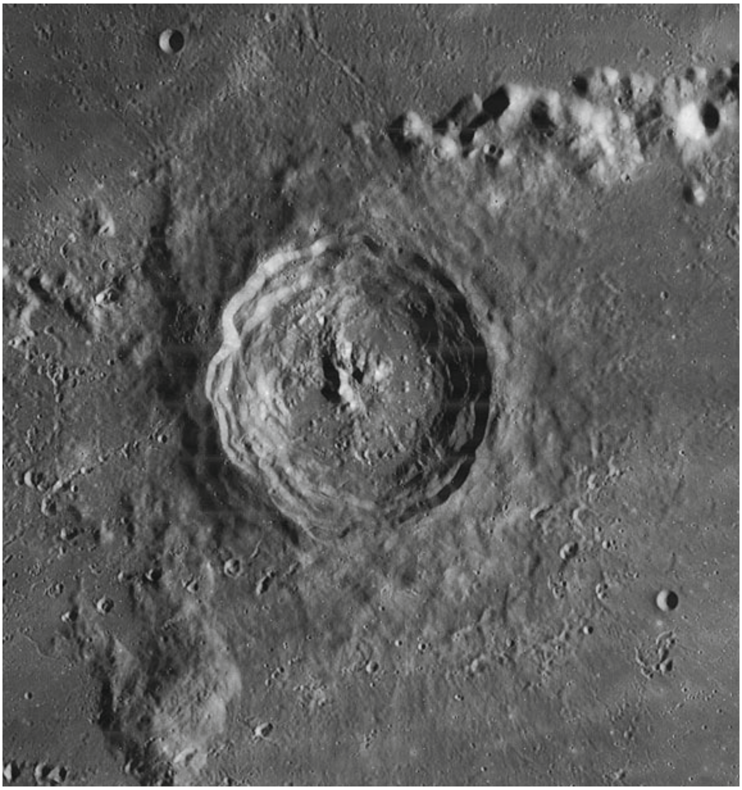

Fig. 2.9 Eratosthenes Crater**.** One of the two best craters in the northwest. Terraced walls are clearly visible. (License: CC0)

Eudoxus (Crater, 67 km)

A Greek astronomer, c.408–355 BCE.

This crater has well formed walls, but the floor is anything but flat. It is covered with very rugged plains visible on high-resolution imagery. This crater is a bit smaller than Aristoteles, but forms a nice pair with it. Both lay between Mare Serenitatis, and Mare Frigoris.

Fabricius (aka Fabricus, Crater, 78 km)

Some sources (USGS, IAU, and Gazetteer of Planetary Nomenclature) use "Fabicius," while other sources name this "Fabricus." As it is named after the Dutch astronomer David Goldschmidt ***Fabricius****, and as the IAU is the final arbiter of* *such things, I suggest the former spelling to be correct. As the issue is not settled I used the latter as it is the man's name.*

This appears similar to the larger Metius. It is a deep crater with fine walls and a fair central peak with some other interesting formations.

Fracastorius (Crater, 112 km)

Named for Girolamo (Fracastoro), an Italian doctor and astronomer (1483–1553).

This crater was fairly destroyed when Mare Nectaris was formed. What is left of it, is (like a handful of other craters) more of a Sinus. There is a visible separation of the mare and the terrain is uplifted in the same area, but higher resolution imagery shows only some debris to mark the edge of the crater.

Gassendi (Crater, 101 km)

Named for Pierre, a French astronomer, (1592–1655).

On Mare Humorum, this is a fine crater, and has some interesting features on its floor including mountains, Rimae Gassendi (a fissure south of center), and another large crater to the north.

Gauss (Crater, 177 km)

Named for Karl Friedrich, a German mathematician, (1777–1855).

This was at one time a fairly well-formed crater, but there are multiple younger craters on the southern half of the floor which have left their own marks. It is also one of the largest in the northeast, but as it is so far on the limb it is also very hard to see (or at least to study well).

Grimaldi (Crater, 172 km)

Named for Francesco Maria, an Italian astronomer and physicist, (1618–1663).

This crater has low walls, and it is on the western limb, but it is fairly easy to see as it is large and dark. Indeed it is the darkest area on the moon due to the dark basaltic lava-base rock that covers the floor.

Hercules (Crater, 69 km)

This is named for the Greek hero Heracles (which in Latin is Hercules).

This is a fairly sized crater, of good formation. There is another fairly large crater just south of its center (a very well formed inverted cone), and another one which has erased part of its southern wall. This crater is not far form the another Greek mythology-named crater, Atlas. At only 8 km smaller these two make a nice pair as well.

Herschel (Crater, 40 km)

Named for Sir William, a German-born British astronomer (1738–1822).

This is a small crater, yet it is very well formed with nice terraced walls, and a few central peaks (Fig. 2.10).

Fig. 2.10 Herschel Crater**.** The Herschel crater is a traditional crater with nice walls and a central peak. On the *right*, the crater Ptolemaeus looms over tiny Herschel. (Credit: NASA)

Hipparchus (Crater, 138 km)

A Greek astronomer (c.140 BCE)

This ancient plain is close to the moon's center (that is the intersection of the Equator and the Lunar Prime Meridian). It is similar to Albategnius, but is in a worse state of ruin. It has low walls, and is not easy to spot except when the terminator hits it. Its eastern wall is better than the western wall (almost nonexistent) except the eastern wall has been ruined in the northeast by Horrocks (a well-formed crater with well-defined concentric walls and a central peak, 30 km)

Kepler (Crater, 31 km)

German astronomer Johannes, (1571–1630).

This is a small crater, but it stands out clearly against Oceanus Procellarum during full moon, when its full ray system comes into view (Fig. 2.11).

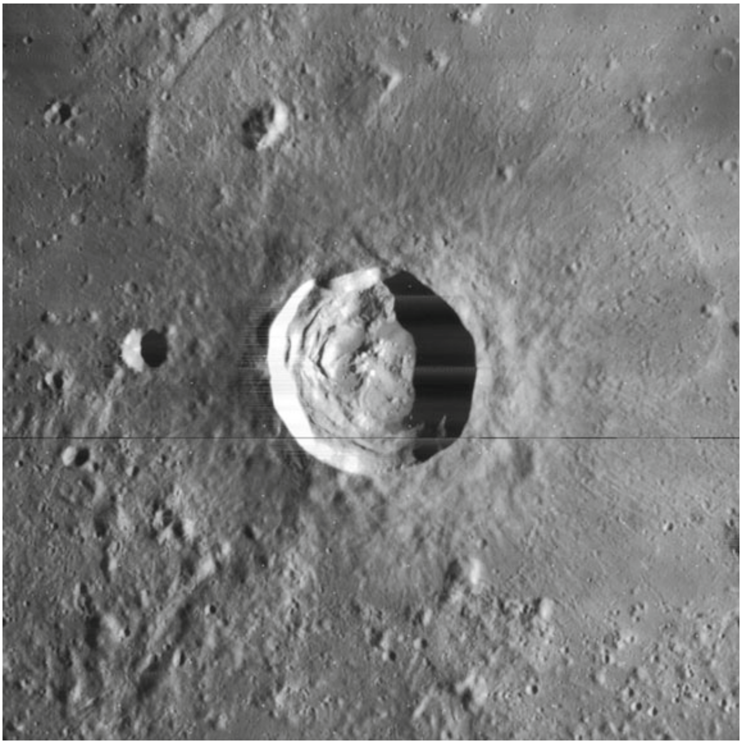

Fig. 2.11 Kepler Crater**.** A spectacular crater. Notice how smooth the area directly around Kepler is. (License: CC0)

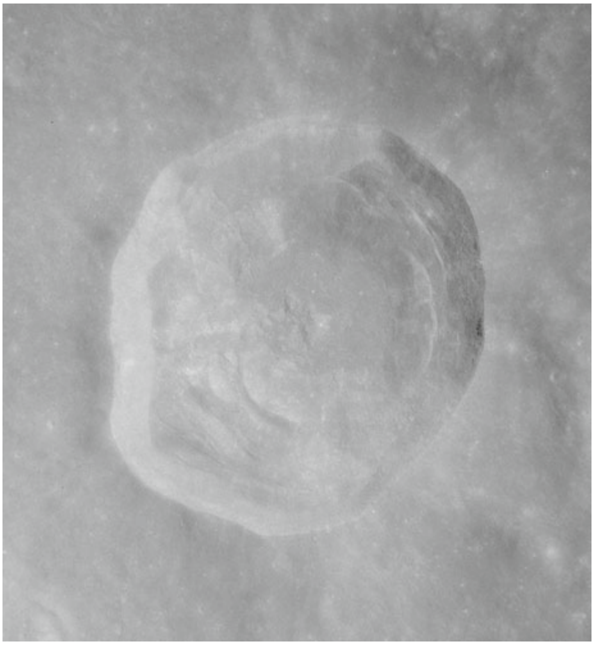

Fig. 2.12 Lalande Crater**.** This is tiny Lalande. North of this image are both Herschel and Ptolemaeus. (Credit: NASA)

Lacus Mortis (Lake, 151 km)

Latin: Lake of Death

This lake connects Mare Serentatis with Mare Frigoris, but is full of craters, including Aristoteles, Eudoxus, Bürg, and Hercules to name a few of the larger ones.

Lacus Somniorum (Lake, 384 km)

Latin: Lake of Dreams

Another lake which connects Mare Serentatis with Mare Frigoris, but with far fewer craters than Lacus Mortis.

Lalande (Crater, 24 km)

Named for Joseph Jérôme, Le François de, a French astronomer (1732–1807).

This crater is neither prominent nor large. But Surveyor 2 crashed not too far from it (Fig. 2.12).

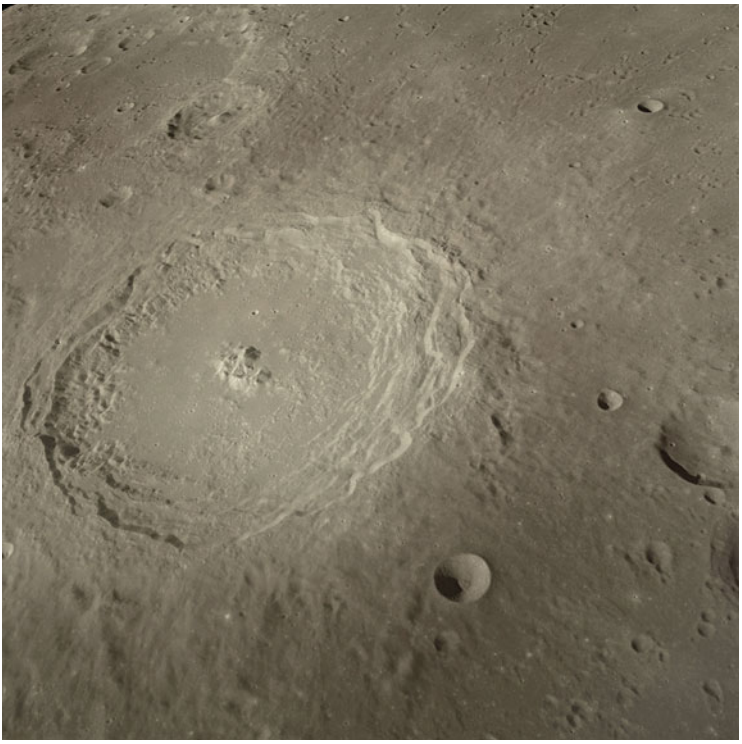

Fig. 2.13 Langrenus Crater. This crater probably takes the prize for finest crater in the southeast. High terraced wall and a small central peak are visible. The floor is noticeably lighter than many other craters. (Credit: NASA)

Langrenus (Crater, 127 km)

Named for Michel Florent van (Langren), a Belgian selenographer and engineer (c.1600–1975).

Part of the 60° east chain, which consists of Langrenus, Vendelinus, Petavius, Snellius, and Furnerius. See entries on Vandelinus and Petavius.

On its own, this is a fine crater with large, well-formed walls and a central peak (Fig. 2.13)

Lansberg (Crater, 38 km)

Named for Philippe van, a Belgian astronomer, (1561–1632).

This is a small crater, but stands out clearly against Oceanus Procellarum. Reinhold to the northeast is a near twin. Luna 5 crashed near here.

Longomontanus (Crater, 157 km)

Named for Christian Sprenson, a Danish astronomer and mathematician (1562–1647).

This is a large crater to the south (even south of Tycho), and is associated with other large craters in this area such as Clavius and Maginus.

Maginus (Crater, 194 km)

Named for Giovanni Antonio (Magini), an Italian astronomer and mathematician (1555–1617).

Again, this is a large crater to the south (even south of Tycho), and is associated with other large craters in this area such as Clavius and Longomontanus.

Manilius (Crater, 38 km)

Named for Marcus, a Roman writer, died c.50 BCE

This is a tiny crater with a small central peak. It has a floor with a few very tiny features (rugged terrain and few tiny craters). This combined with the location on the edge of Mare Vaporum (which has some fairly light colored mountains), and reflective walls means this crater's floor is relatively bright, making it one of the brightest spots in the northeast.

Mare Australe (Sea, 603 km)

Latin: "Southern Sea"

A real challenge to see, this mare is very far to both the south and the east. It is a true challenge under any conditions (and still not much to look at). The LO imagery makes it seem somewhat more rugged than other seas.

Mare Congnitum (Sea, 376 km)

Latin: Sea that has Become Known.

Mare Cognitum is named as a sea, but it often considered more of a bay of Oceanus Procellaruim. Compared to the nearby Mare Humorum, and Mare Nubium it is undefined, or under-defined at best. It lies mostly between Fra Maura (landing site of Apollo 14, and intended site of Apollo 13), and the crater Gassendi. Ranger 7 impacted here.

Mare Crisium (Sea, 418 km)

Latin: Sea of Crises

This sea is distinctly separate from places like Oceanus Procellarum, Sinus Rorum, Marge Frigorus, Lacus Mortes, Lacus Soniorum, Mare Serenitatis, Mare Tranquillitatis, and Mare Fecunditatis which are all connected. This mare is exceptionally disconnected from all of these and surrounded by some quite rugged terrain; fields and fields of craters surround it on all sides, like a land-locked sea. It is one of the largest seas, and is the landing site of Luna 23 and 24.

Mare Fecunditatis (Sea, 909 km)

Latin: Sea of Fecundity (Fertility)

A large, irregular mare; flanked by large craters including Langrenus, Vendelinus, and Petavius. It is also the landing site of Luna 16, and the (intentional) crash site of Chang'e 1.

Mare Frigoris (Sea, 1598 km)

Latin: Sea of Cold

This ocean is notably larger than Mare Imbrium, but is also significantly out-of-round. The Mare is 1598 km end-to-end, yet it is only about 300 km at the widest north–south point. In the west it merges into Oceanus Procellarum via Sinus Roris.

Mare Humorum (Sea, 389 km)

Latin: Sea of Moisture. Some sources name this as the sea of Humors. Although the Humors in ancient and medieval medicine referred to the various fluids of the body (Yellow Bile, Black Bile, Phlegm and Blood) it is likely that either translation would work. The direct meaning from Latin is Humor-um, a genitive, male noun of the third declension indicating possession or partitive use of humor which means fluid, liquid, moisture, or humor. (An alternative translation is hum-orum, which is a genitive, female noun of the second declension meaning ground, solid, earth, land or country which is not supported by any literature on the subject.)

This is one of the smaller but more circular seas on the moon.

Mare Imbrium (Sea, 1123 km)

Latin: Sea of Showers

This is the largest of the circular seas on the moons. It is bordered by the Carpathian, Apennine, Caucasus, Alps, and Jura mountain chains. Luna 17 landed here, Lunokhod 1 explored here, Cheng'e 3 landed here, and Yutu also roved about.

Mare Moscoviense (Sea, 277 km) (far side)

Latin Sea of Muscovy

This sea, shaped kind of like a fish, is the only sizable sea on the moon's far side. The reason for this is due to the fact that the far side of the moon is far thicker than the near side. Maria are where (basaltic) magma welled up from below and cooled (much like it does in Earth's ocean). Since the crust is thicker on the far side, there are less Maria. (This is visible in false color topographic maps, including the ones included with Google Earth.)

Other low lying area include Lacus Luxuriae (Lake of Luxury, but it is not as deep), Mendeleev, Korolev (but it is still somewhat highland), Hertzprung, and Mare Orintale (still not as deep or dark as Mosocviense, but 327 km in its own right) (Figs. 2.14 and 2.15).

Mare Necatris (Sea, 333 km)

Latin: Sea of Nectar

A sea, well defined by craters, including Theophilus, Catharina, and Fracastorius. It is rather flat, except for Rosse (an 11 km inverted cone type), and Daguerre (48 km, but almost flat and rarely visible).

Mare Nubium (Sea, 715 km)

Latin: Sea of Clouds.

Much larger than the nearby Mare Humroum, but not as well defined as its little brother. It does have one interesting feature, a conspicuously straight wall, appropriately named (in all astronomical originality) Rupus Recta, the "Straight Wall" (or cliff). See separate entry.

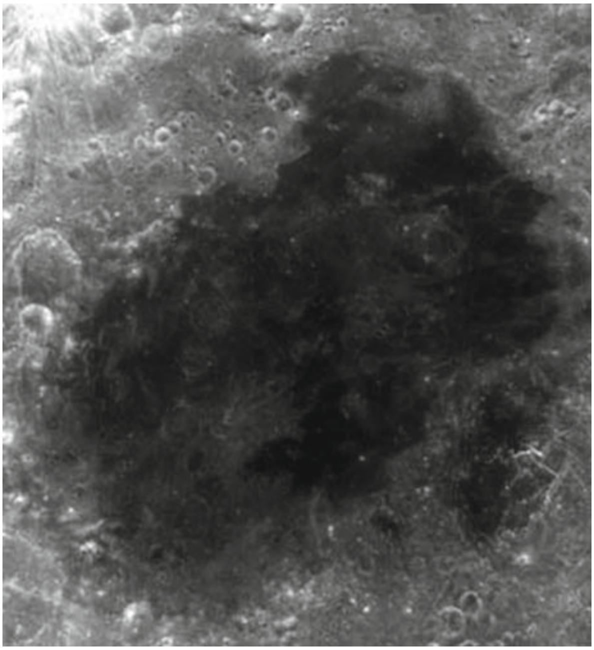

Fig. 2.14 Mare Moscoviense, Top View**.** This is the only sizable mare completely on the far side of the moon. Mare Orientale is half hidden, but this Mare would be completely unknown if not for imagery of the whole surface. (Credit: NASA)

Mare Serenitatis (Sea, 707 km)

Latin: Sea of Serenity

This mare is about 700 km in the shorter axis (NE-SW), but about 900 in the longer (NW-SE). On the north is Montes Caucasus. On the south is Montes Haemus. The Mare itself has a wrinkled appearance (with numerous faults running NE-SW, and has mostly tiny craters, except for Bessel (15 km), and Menelaus (26 km but on the very edge)). Luna 21 landed here and Lunokhod 2 explored here.

Mare Smythii (Sea, 373 km)

Latin: One of only two Maria named after a person (as well as Mare Humboldiianum); it is named after William Henry (Smyth), a British astronomer, (1788–1865).

Neither large nor prominent, this sea does have one advantage, its proximity to the limb. However, once lunar probes started to impact the far side this mare kind of slipped into obscurity.

Fig. 2.15 Mare Moscoviense, Oblique View. Rather than the mare which takes center stage in this image, notice the rugged terrain surmounting the Mare, more typical of what would be seen on the far side. (Credit: NASA)

Mare Tranquillitatis (Sea, 873 km)

Latin: Sea of Tranquility

Separated from the similar Mare Serenitatis by the low hills extending generally eastward from Montes Haumus. In the southeast, the area of Montes Secchi (a 50 km mountain range) as well as a crater (Taruntius) and three rimae (Messier, Sechhi, Tauntius), and three dorsum (ridges, Cato, Cayeux, and Cushman) separate this from Mare Fecunditatis. This is the area where Apollo 11 landed the first men on the moon. It is also the site of Surveyor 5, and Ranger 6 and 8.

The portrait shot of Aldrin, is the most iconic shot of the space age (Figs. 2.16 and 2.17).

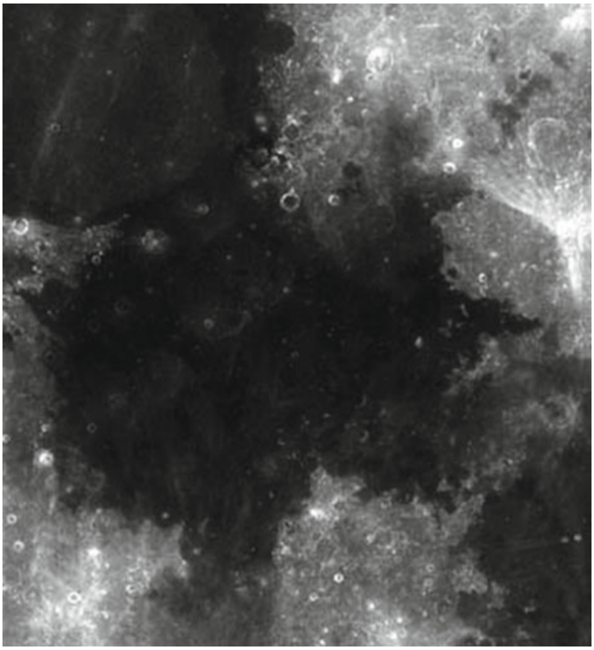

Fig. 2.16 Mare Tranquilitatis. This is the area where NASA chose for the first men to walk on the moon. Even on this image the smoothness is clear. (Credit: NASA)

Mare Vaporum (Sea, 245 km)

Latin: Sea of Vapors

This sea is located across the Haemus Range from Mare Serenitatus. Craters and Rimae intrude on this sea, most notable Rima Hyginus and the crater Hyginus in southeast and south. Mare Vaporum extends south toward Sinus Medii.

Maurolycus (Crater, 114 km)

Named after Francisco (Maurolico), an Italian mathematician (1494–1575).

Maurolycus is an ancient crater. The northwest corner of the crater was badly damaged.

It seems like another impact hit, right to the northeast of it. It is clear on the LO imagery, but the data is conflicting. (Minor lunar craters in and about major craters are lettered). One write-up suggests this is Maurolycus F. Tabled data with sizes suggest

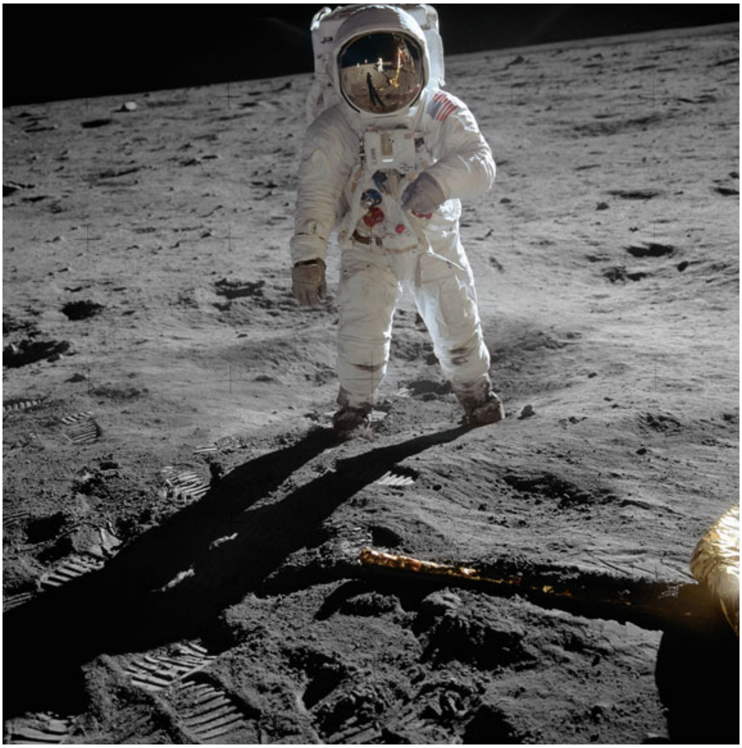

Fig. 2.17 Portrait shot. In this picture, easily the most iconic of the space age, Edwin "Buzz" Aldrin, the second man on the moon, poses for a photo op like none other, as Neil Armstrong, the first man on the moon, takes his picture. In Buzz Aldrin's gold-colored visor the photographer, Armstrong, can be seen as well as the landing strut of the Eagle, the lander module of Apollo 6. (Credit: NASA)

this is Maurolycus D, as it is almost 45 km. Meanwhile, a 1960s geology chart put out by the USGS (the most reliable source), identifies it as Maurolycus B.

The oddly triangular crater between the two, seems to be the real Maurlycus F (the write-up also suggest that, as does the tabled data and the geologic chart confirms both.) It is (roughly) 25 km, and that seem to really be where the bulk of the damage came from. The damage appears to be ejecta material from these two impacts (regolith).

Menelaus (Crater, 25 km)

Menelaus of Alexandria, a Greek geometer and astronomer, c.98 CE.

A small, but well-formed crater with high walls. It lies on the other side of Montes Haemus from Manilius, and like it, is also rather bright.

Mons Pico (Mountain, 25 km)

Spanish: Mount Peak

Mount Peak, a brilliantly unimaginative name (but not as bad as *Saturni Luna*; see "Titan"), is kind of an oddball mountain, not part of any range, which towers up over 2400 meters, just south of Plato in Mare Imbrium.

Montes Alpes (Mountain Chain, 281 km)

Latin: Named for the Alps, the familiar European mountains (which cover parts of France, much of Switzerland, much of Austria, some of Slovenia, and Northern Italy.)

Not one of the more impressive lunar mountain chains it still forms the northern part of Mare Imbrium.

Montes Apenninus (Mountain Range, 401 km)

Latin: Apennine Mountains (*Italy*)

These mountains, named for the Appenine Mountains, sport some of the most impressive mountains on the moon some soaring to 6000 meters (compare to Mount Everest at 8848 meters). This range is also where Apollo 15 landed. And while the portrait shot of Buzz Aldrin with Neil Armstrong and the Apollo Lander, *Eagle*, in his visor is the most iconic picture of the space age, this one is probably in the top five (Fig. 2.18).

Montes Carpatus (Mountain Range, 361 km)

Latin: Carpathian Mountains (*Mostly in Romania but also covering parts of Slovakia, Ukraine, Poland, Hungary, the Czech Republic, and Serbia.*)

These mountains extending northeast from the north rim of Copernicus, are 361 km long, and some peaks reach as high as 2100 meters. These form the boundary between Oceanus Procellarum and Mare Imbrium. They also separate Mare Imbrium from Mare Serenitatis.

Fig. 2.18 Salute! This image of Apollo 15's James Irwin sauting the "Stars and Stripes" on the surface of another world in front of the lunar lander with the rover beside it, and Mount Hadley in the background is certainly one of the more iconic pictures of the space age. (Credit: NASA)

Montes Caucasus (Mountain Range, 445 km)

Latin: Named for the Caucasus Mountains (between the Black and Caspian sea, at one of the borders of Europe and Asia, mostly in Georgia and Azbaijan, but also covering part of Armenia, Iran, and Turkey. Associated mountain ranges (north and south) cover many more countries.)

One of the more easily visible moon features, these form the light boundary between east and west on the north side of the moon. Through even the smallest type of visual aid, it becomes rather strikingly defined (especially when near the terminator), as the height and rugged terrain will create quite a shadow play. Like the Apennines the Caucasus sport some of the most impressive mountains on the moon, some soaring to 6000 meters (compare to Mount Everest at 8848 meters).

Montes Haemus (Mountain Chain, 560 km)

Latin: Named for the Haemus Mountains (Balkins)

This is a lower mountain chain, unlike the moons many more rugged chains. In the east they fall into hills and craters (see Plinius for a larger one). These hills serve as the indistinct border between Mare Serenitatis and the similar (in shape, size, and name) Mare Tranquillitatis.

Montes Jura (Mountain Chain, 422 km)

Latin: Named for the Juras, the European mountains which cover parts of France and Switzerland.

Like the Lunar Alps, not one of the more impressive lunar mountain chains it still forms the northwestern part of Mare Imbrium, where it also surrounds Sinus Iridum.

Montes Recti (Mountain/Mountain Range, 90 km)

Latin: Straight Range

This mountain and its range is about 90 km long and has peaks up to 1800 meters. It is on the Northern Edge of Mare Imbrium, close to Plato.

Oceanus Procellarum (Ocean, 2568 km)

Latin: Ocean of Storms

Easily the largest and most visible lunar feature, this ocean covers most of the northwest and southwest. It is the most visible feature even without aid, as it is the large dark lowland area. In the USA, people often refer to the "man in the moon," but in other areas people refer to the "rabbit of the moon," and that is due to the dark silhouette of this area. It is also the "Jill" of the Jack and Jill nursery rhyme.

Note the 2568 km is at the largest north–south measurement, and that the full area is nearly 4 million square kilometers (compare to the Mediterranean Sea of approximately 2.5 million square kilometers.)

Also of note are the missions that landed here: Apollo 12, Surveyor 1 and 3, Luna 7, 8, 9, and 13.

Petavius (Crater, 188 km)

Named for Denis (Petau), a French chronologist and astronomer (1583–1652).

Part of the 60° east chain, which consists of Langrenus, Vendelinus, Petavius, Snellius, and Furnerius.

An impressive crater with good walls, a central peak, and a rimae (Rimae Petavius) running 80 km from the wall directly NE to the peak, as straight as and as clear as could be. Other small rimae are just visible in other parts of the crater.

Piccolomini (Crater, 87 km)

Named for Alessandro, an Italian astronomer (1508–1578).
Piccolomini lies at the southern end of the Altai Mountains.

Pitatus (Crater, 106 km)

Named for Pietro (Pitati), an Italian astronomer and mathematician, (c.1500).
A smaller crater with a dark floor, and low central peak on the rim of Mare Nubium.

Plato (Crater, 109 km)

A Greek philosopher, c.428–347 BCE.
Plato, on the edge of the Lunar Alps, is a fine crater with a very dark floor.

Posidonius (Crater, 95 km)

Posidonius of Apamea, a Greek geographer c.135–51 BCE (VERY loose estimates.)
This is a large crater, well-formed on the west and with a sort of double wall on the east. There is also a crater just southwest of center, as well as crater damage to the northeastern wall (the outer). This crater is also well-placed right between Mare Serenitatis, and Lacus Somniorum, well placed for more detailed studies to be done.

Ptolemaeus (Crater, 164 km)

Named for Claudius (Ptolemy), and if you don't know who this is (again) this may be the wrong book for you; a Greek astronomer, mathematician, and geographer, (c.87–150).
A large crater and the largest of a series of such craters extending north to south from the moon's prime meridian. The craters are Lalande, small Herschel, Ptolemaeus, Alphonsus, small Alpetragius, and Arzachel. Further south on this meridian are Purbach, Regiomontanus, and Walter (Fig. 2.19).

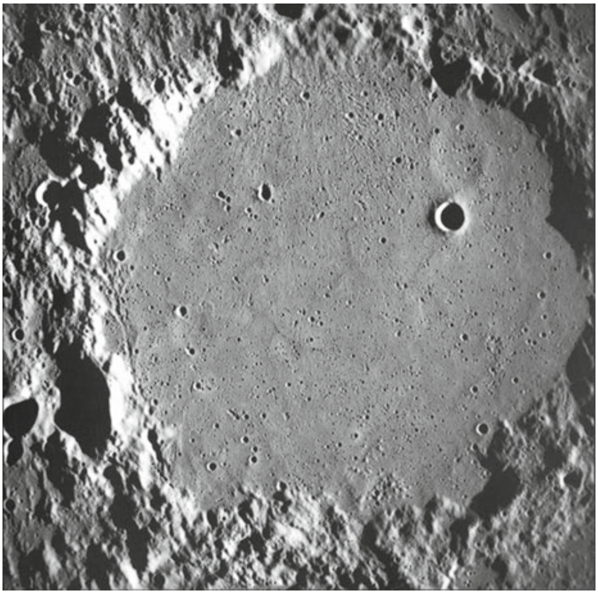

Fig. 2.19 Ptolemaeus Crater. A large stunningly beautiful crater, with only a few significant craters (and many micro-craters) marring its mirror-like surface. (Credit: NASA)

Reinhold (Crater, 42 km)

Named for Erasmus, a German astronomer, (1511–1553).

This crater, which is hard to see, lies between Copernicus and Lansberg. Like Lansberg, it has a deep floor.

Riccioli (Crater, 139 km)

Named for Giovanni Battista, an Italian astronomer, (1598–1671).

This crater lies just south of the lunar equator, and near the western limb. Like nearby Grimaldi (crater), it has an exceptionally dark floor.

Rima Hyginus and Hyginus (Fissure, 219 km long, and Crater, 9 km)

Rima Hygius is named for the crater which lies directly atop it. The crater is named for Caius Julius, a Spanish astronomer from the first century BCE.

This rime, along with Rima Airdates runs from Mare Vaporous to Mare Tanquillitatis. It is one of the most prominent such features on the moon.

Rupes Altai (Scarp/Ridge, 427 km)

Latin: Named for the Altai Mountains, in Central Asia, covering parts of Russia, China, Mongolia, and Kazakhstan.

Note: (Due to poor image quality in visible and LO imagery, if you wish to see this in Google Earth, I would advise using the colored terrain maps. It is bright yellow.)

Rupes Altai runs from Catherina to Piccolomini, about 427 km long and some up to 4 km high. It was likely formed when Mare Nectaris was formed, rippling and folding material in this area.

Rupes Recta (Scarp/Ridge, 134 km)

Latin: Straight Cliff or Straight Wall

Rupes Recta mean straight wall, so this is a straight wall (well, duh! Astronomical originality at its finest.) It is actually a fault feature, showing past geologic activity on the moon. The wall is over 100 km long, and is about 240 meters high.

Schickard (Crater, 206 km)

Named for Wilhelm, a German astronomer and mathematician, (1592–1635).

A fine plain, with low walls.

Sinus Iridum (Bay, 236 km)

Latin: Bay of Rainbows

An impressive bay, very close to round, on the northwest edge of Mare Imbrium. It is bordered by the Jura and the Straight ranges.

Sinus Medii (Bay, 335 km)

Latin: Bay of the Center

This bay is south of Mare Vaporum and includes the site of intersection between the Lunar Prime Meridian and the Lunar Equator (0° * 0°). Is is also the crash site of Surveyor 4 and the landing site of Surveyor 6 (These two landed about 750 meters apart, just about half a mile.)

Sinus Roris (Bay, 202 km)

Latin: Bay of Dew

This is a tiny bay which connects the significant Mare Frigoris with the vastly larger Oceanus Procellarum.

Struve (Crater (at least officially), 164 km)

Sometimes called Otto Struve, this crater is named for Otto Wilhelm von (Struve), a German-born Russian astronomer, (1819–1905), (Otto) (Struve), an American astronomer, (1897–1963), Friedrich Georg Wilhelm von (Struve), a German-born Russian astronomer, (1793–1864).

Author Notes: This is a tough one for even the more experienced moon watchers to see; to see it best, use Google Earth (Moon Mode), and look for Eddington and Russell (neither is on the list, but they are at 21.3 N, 72.2 W; and 26.5 N, 75.4 W respectively). These, along with Struve for a kind of "Mickey Mouse" face with Struve as the face, and the other two as ears. (In Visible Imagery it is nearly invisible due to light and dark bands of colored material on the floor, but the LO imagery makes it clearer. All three resemble more of walled plains than what comes to mind as when the word "crater" is used).

A large crater (one of a few that look more like a Sinus or a Lacus), but difficult to see on the moon due to its proximity to the western limb, and light colored material on the floor.

Taurus–Littrow Valley (Valley, Underdefined)

Montes Taurus covers 172 km, while Littrow is a crater that covers 30 km. The total EVA covers 35.74 km, so make of this what you will.

This is where the Apollo 17 landed. Harrison Schmidt working on the split boulder is also one of the top five pictures of the space age (Figs. 2.20 and 2.21).

Theophilus (Crater, 110 km)

A Greek astronomer (died c.412 CE)

An impressive crater. It sports good walls and a split central peak that would be the envy of other craters.

Tycho (Crater, 102 km)

Named for (Tycho) Brahe, a famed Danish astronomer, (1546–1601).

This is a smaller crater, but when the moon is full its full ray system comes into view, which, in many peoples eyes, make this the most spectacular crater-ray system. It is certainly spectacular,

Fig. 2.20 Taurus–Littrow Valley, Orange Soil**.** While digging in the Taurus–Littrow valley this mysterious orange soil was discovered. It was later found to be the result of beads of volcanic glass. (Credit: NASA)

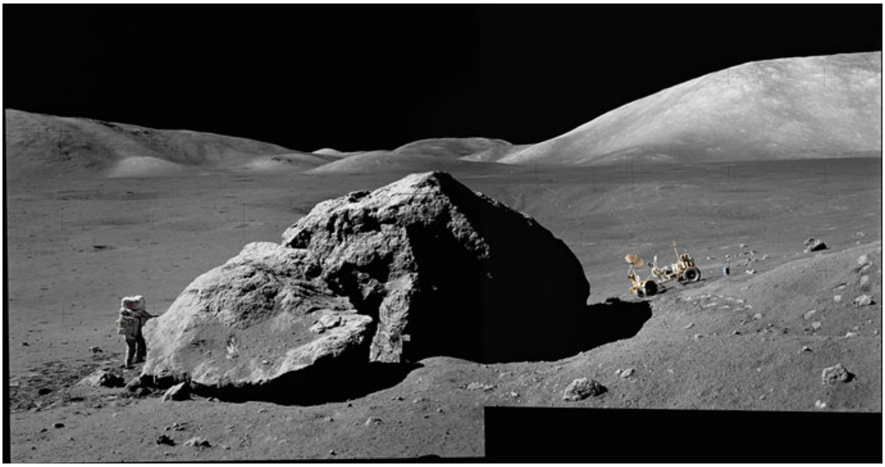

Fig. 2.21 Split Boulder. This image of Apollo 17's Harrison Schmitt working near the Split Boulder in the Taurus–Littrow Valley is also certainly one of the more iconic pictures of the space age. (Credit: NASA)

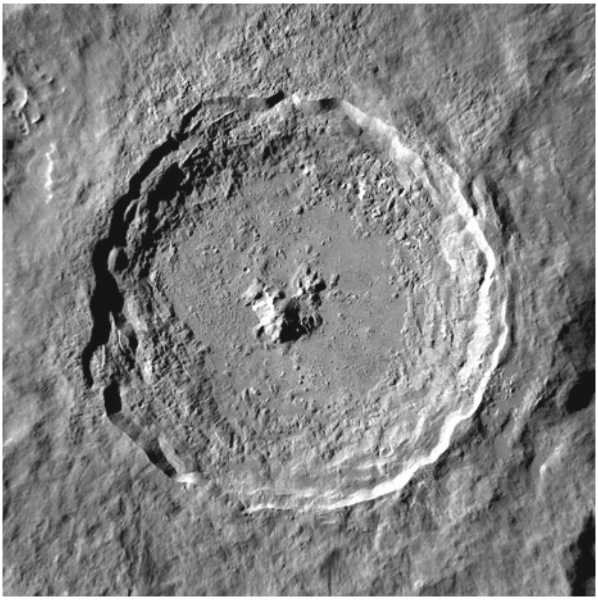

Fig. 2.22 Tycho Crater. A shot of Tycho, showing the terraced wall and central peak. (Credit: NASA)

with ejecta rays stretching as far as Oceanus Procellarum in the northwest (950 km) and Mare Nectaris in the northeast (almost 1300 km!) Surveyor 7 soft landed not far from here (Figs. 2.22 and 2.23).

Vallis Alpes (Valley, 166 km)

Latin for Alpine Valley,
This valley links Mare Imbrium and Mare Frigoris. It looks like a terrestrial river valley, but it actually a particularly straight fault (Fig. 2.24).

Vallis Rheita (Valley, 445 km)

Named for the nearby crater Rheita (no separate entry).
The crater sits at one end of a long valley system, a clear scar in the southeast.

Vendalinas (Crater, 131 km)

Named for Godefroid (Wendelin), a Belgian astronomer (1580–1667). (This is one spelling of his name, but there were many others. And the "W" in the Latinate makes a "V" sound).

Fig. 2.23 Tycho Ray System. This shot, taken during the spring 2007 lunar eclipse tends to highlight southern Tycho's extensive ray system. (License: CC0)

Part of the 60° east chain, which consists of Langrenus, Vendelinus, Petavius, Snellius, and Furnerius.

Vendelinus is a large crater, but not very impressive. It has simple walls and no peak, and there is some significant damage in the northeast from Lame (which is 84 km alone. An impressive, if tiny, chain of craters have demolished its eastside though.)

Walther (Crater, 128 km)

Named after Bernard, a German astronomer (1430–1504). Note: The crater used to be called Walter (a variant spelling). It appears as such in one source dated 1993. Walter now refers to a 1 km crater of no interest which is not visible even in probe imagery.

Fig. 2.24 Vallis Alpes. This is the Alpine Valley. It is very recognizable, cutting through the Alps on the edge of Mare Imbrium. It is 80 miles long and resembles a river bed. (Credit: NASA)

Walther lie on the Lunar Prime Median, and is the southernmost in line of craters that share this line including Ptolemaeus, Alphonsus, Azachel, Purbach, and Regiomontanus.

Other Near Earth Objects

Luna is the most notable Near Earth Object, but what about the other NEOs? (Another common term is NEA or Near Earth Asteroids). In addition to bits of spacecraft, satellites, and other artificial objects there are also over 10,000 natural objects. As of the time of this book, the following numbers of NEOs have been discovered. (As a reminder an AU or astronomical units is the Earth–Sun distance, about 150 million km or 93 million miles):

- 96 comets
- 14 Apohele or Atira asteroids (Atiras are objects whose orbits are contained entirely within that of Earth, that is, they have a maximum aphelion below 0.983 AU, i.e., 163693 Atira)
- 898 Aten asteroids (Atens are asteroid who have a semi-major axis (orbital distance) of less than 1 AU, but an aphelion greater than 0.983 AU, i.e., 2062 Aten)
- 5766 Apollo asteroids (Apollos are asteroids who have a semi-major axis (orbital distance) greater than 1 AU, but a perihelion less than that of Earth (1.017 AU), i.e., 1862 Apollo)
- 3729 Amor asteroids (Earth-outer grazers. i.e., 1221 Amor)
- 1544 total "Potentially Hazardous Objects"[1]
- 867 NEAs greater than 1 km
- 153 NEAs which are also PHAs at least 1 km.
- 10,756 total NEOs (including the above categories) (*Note:* This number is extrapolated from a February 2014 report where the report amounts are subtracted from the above amount, and then the excess added to the report number. However a number of categories yielded negative results which indicate that some objects were either removed from the number I found, removed from the list of object or in error. But this is not the subject of this book. This information can all be found in much greater depth, if one wishes to put forth the time to do so.)

There are also five asteroids which are co-orbital and with a 1:1 resonance with Earth; however, only one of them is named, 3752 Cruithne. (The rest have simple designations).

There is also one known Earth Trojan, 2010 TK_7 oscillating between the L_3 and L_4 Lagrangian points (Table 2.2).

The asteroids range in size from 120 meters (2003 SS_{84}, an Apollo) to 8.48 km (1866 Sisyphus, also an Apollo). The moonlets range in size from 40 meters (S/2009 (363067) 1, an Apollo), to 1060 meters (S/2008 (153591) 1, an Amor, and in a double moon system). Many are too hard to be measured at this time. The separation ranges from 250 meters (363599 2004 FG_{11}, and S/2012

[1] (Potentially Hazardous Asteroids are NEAs whose Minimum Orbit Intersection Distance (MOID) with the Earth is 0.05 AU or less and whose absolute magnitude (*H*) is 22.0 or brighter)

TABLE 2.2 NEO satellite data

	Class	Primary size rank	Number	Name	Type	Spectral types Th	Spectral types SMASS	Diameter (primary) (in meters)	Diameter secondary) (in meters)	Separation (km)
*	NEO	13	3671	Dionysus	Amor		Cb	1430	290	3.4
	NEO	8	5646	1990 TR	Amor		U	2580	480	5.1
*	NEO	14	7088	Ishtar	Amor			1390	580	2.8
	NEO	6	7888	1993 UC	Amor		U	2720		
	NEO	23	31345	1998 PG	Amor		Sq	900	270	1.4
*	NEO	27	65803	Didymos	Amor		Xk	750	170	1.18
	NEO	9	138095	2000 DK79	Amor			2180		
*	NEO	7	153591	2001 SN263	Amor			2600	1060/460	16.633/3.804
	NEO	5	285263	1998 QE2	Amor			3200	800	6.212
	NEO	22	385186	1994 AW1	Amor		Sa	940	460	2
	NEO	32		2002 BM26	Amor		X	600	100	1.4
	NEO	36		2002 KK8	Amor			500	100	
	NEO	10		2005 AB	Amor			>1900	460	3.4
	NEO	42		2008 DG17	Amor			380		
*	NEO	12	1862	Apollo	Apollo	Q	Q	1550	80	3.75
*	NEO	1	1866	Sisyphus	Apollo		S	8480		
*	NEO	3	5143	Heracles	Apollo		O	3600	600	4
	NEO	18	35107	1991 VH	Apollo		Sk	1040	420	3.26
*	NEO	34	69230	Hermes	Apollo			600	540	1.1

(continued)

TABLE 2.2 (continued)

	Class	Primary size rank	Number	Name	Type	Spectral types: Th	Spectral types: SMASS	Diameter (primary) (in meters)	Diameter secondary) (in meters)	Separation (km)
	NEO	40	85938	1999 DJ4	Apollo		Sq	430	210	0.8
	NEO	21	88710	2001 SL9	Apollo			960	200	1.6
*	NEO	29	136617	1994 CC	Apollo			620	113/80	1.729/6.13
	NEO	28	136993	1998 ST49	Apollo		Q	690	80	
	NEO	39	153958	2002 AM31	Apollo			450	110	1.5
	NEO	45	162000	1990 OS	*Apollo*			300	50	0.6
	NEO	16	164121	2003 YT1	Apollo			1100	210	3.93
	NEO	11	175706	1996 FG3	Apollo		C	1690	490	3
	NEO	26	185851	2000 DP107	Apollo			800	300	2.62
	NEO	4	276049	2002 CE26	Apollo	C		3460	300	4.7
	NEO	43	311066	2004 DC	Apollo			360	70	0.75
m	NEO	30	363067	2000 CO101	Apollo		Xk	620	40	0.61
m	NEO	49	363599	2004 FG11	Apollo			150	<80	0.25
	NEO	17	374851	2006 VV2	Apollo			1060	>300	1.5
	NEO	37	399774	2005 NB7	Apollo			500	200	0.6
	NEO	50		1994 CJ1	Apollo			<150	<150	0.525
	NEO	31		1994 XD	Apollo			600	>150	0.6
	NEO	48		2000 UG11	*Apollo*			260	130	0.426

m	NEO	51		*2003 SS84*	*Apollo*		120	60	0.27
	NEO	41		2006 GY2	Apollo		400	80	0.5
	NEO	46		2007 DT103	Apollo		300	>80	0.45
	NEO	38		2007 LE	Apollo		500	180	1.4
	NEO	33		2008 BT18	Apollo		600	>200	2
	NEO	19		2013 WT44	Apollo		1000		
	NEO	44		2014 WZ120	Apollo		360		
*	NEO	20	5361	Sekhmet	Aten		1000	300	1.54
	NEO	24	66063	1998 RO1	Aten		800	380	1.2
	NEO	15	66391	1999 KW4	Aten	S	1317	451	2.548
	NEO	2	*137170*	1999 HF1	*Aten*	*X*	3640	840	7.3
	NEO	35	162483	2000 PJ5	Aten		550	280	
	NEO	25	363027	1998 ST27	Aten		800	120	4.5
	NEO	47		2006 YQ96	Aten		270		

No moon names are given since they all have only provisional designations (i.e.: "S/2005 (1862) 1)." An asterisk indicates a write-up. All named asteroids have been so written. A lowercase "m" indicates a brief mention due to a notable numerical value. Blank values are unknown. In many cases the value used are assumed, derived, or estimated, but in all cases this book has tried to provide the most accurate data that could be found. Amors are Earth outer-grazers, Apollos are Earth-crossers, and Atens are Earth inner-grazers

(363599) 1, an Apollo), to 16.633 km (again 153591 2001 SN_{263} S/2008 (153591) 1, an Amor, and in a double moon system).

Note: Some of the minor moon names were not available in the data that could be found, so they had to be constructed as best as could be. The provisional designation system for these is not too hard.

1862 Apollo: This is an Apollo and the prototype of the class. It is 1550 meters, the moon is 80 meters and the separation is 3.75 km. Apollo is a Q-type (Tholen and SMASS).

1866 Sisyphus: This is an Apollo and the largest asteroid in this class. It is 8480 km, far-and-away larger then from number 2 at only 3640 km. Moon size and separation are not known at this time. Sisyphus is an S-type (SMASS).

3671 Dionysus: This is an Amor. The primary is 1430 meters. The secondary is 290 meters. The separation is 3.4 km. Dionysus is a Cb-type (SMASS).

5143 Heracles: This is an Apollo. The primary is 3600 meters. The secondary is 600 meters. The separation is 4 km. Heracles is a rare O-type (SMASS).

5381 Sekhmet: This is an Aten, The only named Aten with a moon. The primary is 1000 meters. The secondary is 300 meters. The separation is 1.54 km.

7088 Ishtar: This is an Amor. The primary is 1390 meters. The secondary is 580 meters. The separation is 2.8 km.

65803 Didymos: This is an Amor. The primary is 750 meters. The secondary is 170 meters. The separation is 1.18 km. Didymos is an Xk-type (SMASS).

69230 Hermes: This is an Apollo. The primary is 600 meters. The secondary is 90 % of that, at 540 meters. The separation is 1.1 km.

(*136617*) *1994 CC*: This is an Apollo with two moons designated Beta and Gamma (Beta is closer than Gamma). It is 620 meters, the moon sizes are 113 and 80 meters and the separations are 1.729, and 6.13 km. In this system Beta is larger than Gamma (Fig. 2.25).

(*153591*) *2001* SN_{263}: This is an Amor with two moons designated Beta and Gamma (Beta is closer than Gamma). It is 2600

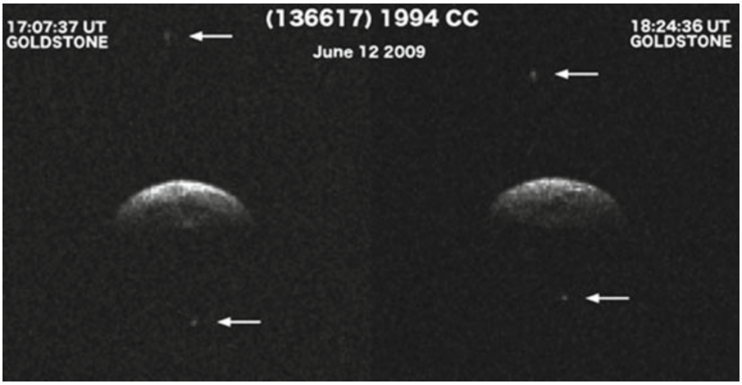

Fig. 2.25 136617 1994 CC

meters, the moon sizes are 460 meters and 1060 km, and the separations are 3.804 and 16.633 km. In this system, Gamma is more than double the diameter of Beta. 1060 meters is the largest moon in this category, and 16.633 km is the greatest separation between a primary and a moon in this category. I guess congratulations are in order?

3. Mars

While the Spirit, Opportunity and Curiosity rovers and several orbiters have done excellent science on the surface and atmosphere of Mars, it has limited objects in its orbit compared to the planets of the outer Solar System.

Mars by the numbers:

- 2 Moons
  - 1 Minor moon between 10 and 25 km (not including Eros)
  - 1 Very minor moon not exceeding 10 km
- 7 Trojan asteroids
  - 1 Possible Trojan asteroid
- 16 Inner-grazing, Earth-crossing asteroids (these asteroids stay closer to the sun than Mars' orbit, but also cross the Earth's orbit)
- 20 Inner-grazing asteroids (these asteroids stay closer to the sun than Mars' orbit, but do not cross Earth's orbit)
- 145 Asteroids, that cross both Earth and Mars orbit
- 238 Mars crossers (these do not venture close to Earth, or stay well outside of our orbit)
- 670 Outer-grazers (which travel through Mars' area (Mars' gravity) but stay slightly farther from the sun than the planet) (Table 3.1)

Note: This table also includes three asteroids from the numbers above. Eros is one of the most well known asteroids, being much larger than Diemos, and longer than even Phobos.

J.A. Hall III, *Moons of the Solar System*, Astronomers' Universe,
DOI 10.1007/978-3-319-20636-3_3

Table 3.1 Mars satellite data

	Phobos	**Deimos**	**433 Eros**	**163963 Atira**	**1221 Amor**	**1862 Apollo**	**2062 Aten**
Adjective	Phobian	Deimosian	Erotian				
Albedo	0.071	0.068	0.25	0.1?	0.15?	0.25 (geometric)	0.26
Alternative names	Mars I	Mars II	1898 DQ, 1656 PC	2003 CP20	1932 EA1	1932 HA	1976 AA
Apoapsis	9528 km	23,471 km	1.784 AU Aphelion	0.98 AU Aphelion	2.754 AU Aphelion	2.294 AU Aphelion	1.143 AU Aphelion
Apparent magnitude	11.3	12.45	7–15	16.28 Absolute	17.7 Absolute	16.25 Absolute	16.8 Absolute
Average orbital speed	2.138 km/s	1.3513 km/s	24.36 km/s	33.68 km/s	20.44 km/s	22.5 km/s	30.04 km/s
Axial tilt	0	0					
Composition (Atmosphere)							
Dimensions	27 * 22 * 17	7.8 * 6 * 5.1	34.4 * 11.2 * 11.2	2.5 km	1.5 km	1.5 km	1.1 km
Discovered by	Asaph Hall	Asaph Hall	Carl Gustav Witt	Lincoln Near-Earth Asteroid Research	Eugéne Joseph Delporte	Karl Reinmuth	Eleanor F. Helin
Discovery date	18 AUG 1877	12 AUG 1877	12 AUG 1898	11 FEB 2003	12 MAR 1932	24 APR 1932	7 JAN 1976
Eccentricity	0.0151	0.00033	0.223	0.322	0.435	0.56	0.183
Equatorial surface gravity	0.0057 m/s	0.003 m/s	0.0059 m/s	0.0003 m/s	0.00042 m/s	0.0005 m/s	0.00025 m/s

Escape velocity	11.39 m/s	5.56 m/s	0.0103 km/s	0.0005 km/s	0.00079 km/s	0.0009 km/s	0.00048 km/s
Inclination	1° 5′ 34.8″	55′ 48″	10° 49′ 44.4″	125° 37′ 4.8″	11° 52′ 44.4″	6° 21′ 18″	
Mass	1.07e16 kg	1.48e15 kg	6.69e15 kg	1e12? kg	3.5e12 kg	5.1e12 kg	7.60E+11
Mean density	1.876 gm/cm	1.471 gm/cm		2? g/cm	2? gm/cm	2? gm/cm	2? g/cm
Orbital period	7 h 39 m 12 s	30 h 18 m 43 s	643 d 5 h 15 m 22 s	233 d 33 m 7 s	971 d 15 h 14 m 24 s	651 d 13 h 1 m 28 s	347 d 4 h 1 m 55 s
Periapsis	9234 km	23,456 km	1.133 AU Perihelion	0.502 AU Perihelion	1.086 AU Perihelion	0.647 AU Perihelion	0.79 AU Perihelion
Rotation period	Synchronous	Synchronous	5 h 16 m	2 h 58 m 12 s		3 h 3 m 56 s	40 h 46 m 12 s
Satellite of	Mars	Mars	Sun	Sun	Sun	Sun	Sun
Semi-major axis	9376 km	9376 km	1.458 AU	0.741 AU	1.92 AU	1.471 AU	0.967 AU
Surface area	1548 km	495 km					
Surface pressure							
Surface temperature (temp)	233 K	233 K	227 K	323 K	198 K	222 K	275 K
Volume	5784 km	1000 km					
Notes			Amor Mars-crosser	Aten Atira/Apohele Atira/ Apohele Prototype Venus-crosser	Amor Amor Prototype Mars-Crosser	Apollo Apollo Prototype Mars/ Venus-crosser	Aten Aten Prototype

A higher degree of uncertainty then other data. You could replace it with a tilde in front (i.e.: ~0.1, or ~0.15). Use whatever is more in line with you styling guide

Fig. 3.1 Phobos (Credit: NASA/JPL, University of Arizona)

Phobos

Overview: From the Greek word for fear, a natural result of war. (Ares/Mars is the god of war.) The English cognate for Phobos is phobia. This moon is larger than Mars' outer moon and seven times as massive. Phobos is still a minor moon since it average diameter is below 25 km (Fig. 3.1).

Orbit: At 6000 km or 3700 miles, it orbits closer to Mars than any other moon to its respective planet. It has an angular diameter of 8.4–12 arcminutes which is still only a third of our moons 29–31 arcminutes, due to Phobos' small size. It is accelerated quite a bit due to this close orbit, and it moves so fast across the sky (or appears to) that each day has two moon-rises and two moon-sets (with respect to Phobos at least). Each time, the moon is in the sky for less than four and a half hours. Phobos is also closer than the Hill Sphere which means its orbit is not stable. In about 30–50 million years it will likely break up into a planetary ring. It is currently at 172 % of its Roche limit, that is the limit of how close it can be before it will likely break up due to tidal interactions. (By comparison our moon seems to be at about 4100 %, and small Mercury is over 10,000 times the suns!)

Features: It also has a large impact crater called Stickney (almost all features are named after proper names from Jonathon Swift's novel *Gulliver's Travels*, except for *Kepler Dorsum*, a ridge named after Johannes Kepler, and Stickney named for discoverer Asaph Hall's wife). Stickney's 9 km diameter would be insignificant except the moon is only (on average) 22 km in any direction. There is also a 2 km crater inside of it named Limtoc. It is thought that Stickney could be seen from the surface of Mars with the unaided eye. Measurements yield a size of 200 arcseconds and the human eye can resolve objects as small as 60 (or 1 arcminute). Next to Stickney are parallel scrapes. However studies conduced by *Mars Express* seem to show no connection between the two (Figs. 3.2 and 3.3).

Hollow Phobos: In 1958, Iosif Samuilovich Shklovsky suggested that Phobos might be hollow (a "thin sheet metal") and artificial, and suggesting that what we saw was simply the outer layer. In 1960, Fred Singer, then science advisor to President Eisenhower, suggested an error in Shklovsky's measurements. In 1969, it was found that he had used 5 cm/yr of altitude loss when the actual value was 1.8 cm/yr. Although to Shklovsky's credit the moon's density is only 1.887 g/cm, which lead some people to term this moon a rubble pile (an actual astronomical term meaning not monolithic, that is to say not "one rock"). More recent measurements suggest porosity of 30 %—but not in one spot, rather in small spots throughout.

Misc.: Phobos has one of the lowest known Bond albedos at only 0.071, meaning very little light is reflected off of its surface. Its apparent magnitude from Earth is about 11.3.

Deimos

Overview: From the Greek word for dread, another natural result of war. This moon is much smaller than Mars' inner moon, orbiting 2.5 times as far from Mars, with 17.29 % of Phobos' volume,

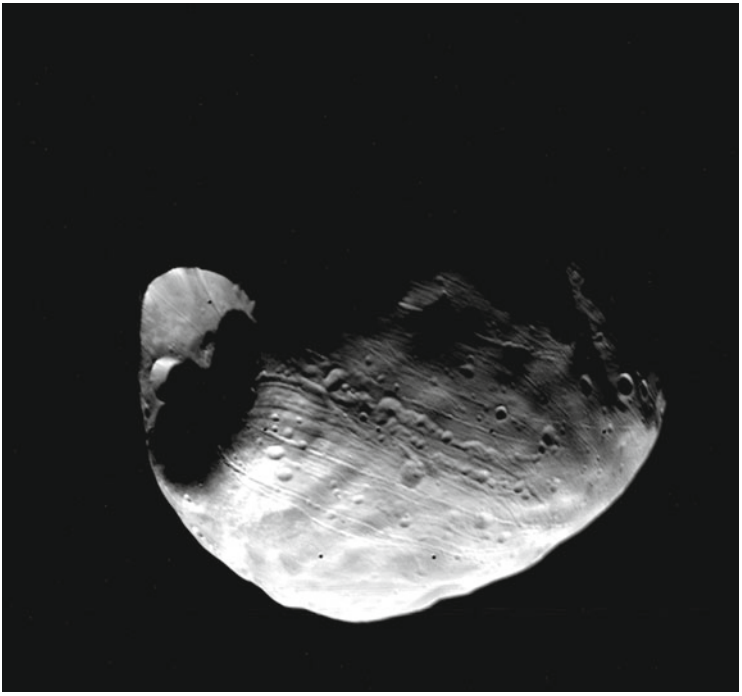

Fig. 3.2 Stickney Crater (Credit: NASA)

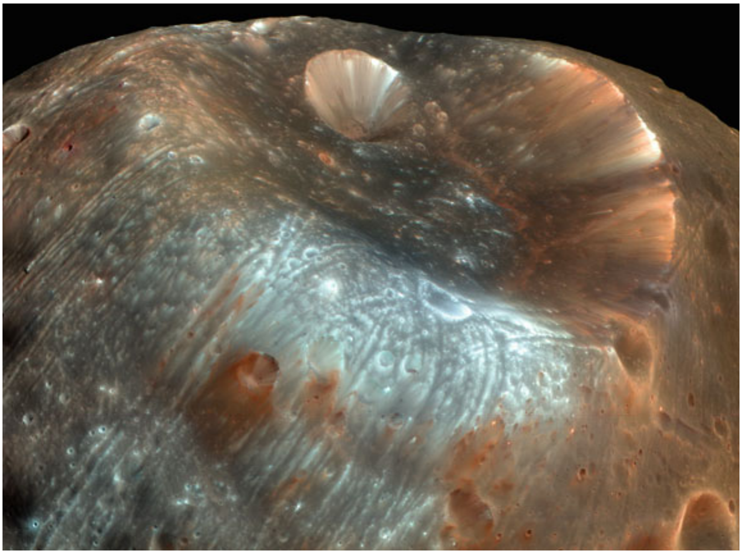

Fig. 3.3 Close-up of the Stickney Crater (Credit: NASA/JPL/University of Arizona)

Fig. 3.4 Deimos (Credit: NASA/JPL-Caltech, University of Arizona)

and about 13.85 % of its mass. Deimos is a very minor moon since it average diameter is below 10 km (average of 6.3 km) (Fig. 3.4).

Orbit: Whereas Phobos' angular diameter is (on average) 10.2 arcminutes, Deimos is only 2.5 arcminutes. It takes about 30.3 hours to complete one orbit, going though its phases in about the same time. Its orbit is, however, stable. Its density is about 78 % that of Phobos, it has a high porosity, and it can be assumed from these that the moon is even "weaker" than Phobos (less well-assembled).

Features: Only two objects on Deimos have been given names; craters named Voltaire and Swift. They are about 1.9 km and 1 km respectively.

Misc.: When Deimos is full, it is about as luminous from the surface of Mars as Venus is from the Earth. Its albedo is not much better than Phobos. Its apparent magnitude from Earth is about 12.45.

Trojans

Mars does have some Trojan asteroids, although none of these are known to have moons.

Mars Crossers/Hungaria Family

There are 20 Mars crossers/Hungarias with 21 known moons. The true Mars crossers cross, while Hungaria Family are the asteroids which orbit the sun between 1.78 and 2.00 AU and make up the innermost dense concentration of asteroids in the Solar System. The orbit of Mars marks the inner boundary, while the Kirkwood gap (2.06 AU) marks the outer boundary (Table 3.2).

The asteroids range in size from 1190 meters (5261 Eureka, and the only Mars Trojan to make the list) to 10,180 meters (1727 Mette, a Hungaria). The moonlets range in discernible size from 460 meters (also S/2011 (5261) 1, and the only Mars Trojan moonlet to make the list) to 5000 meters (S/2005 (1139) 1). The discernable separation ranges from 2.1 km (again 5261 Eureka and S/2011 (5261) 1), to 378 km (2577 Litva and S/2012 (2577) 1)!

The primary objects are generally larger than NEOs, the moons are generally larger than NEO moons, and the separations are greater than those between NEOs and their moons. This can however be just the ones we have found since these three elements would indicate the highest likeliness to have been found, and most extensively studied.

Also these tend to line up as might be expected—in general they go largest to smallest which matches up the diameter from largest to smallest (although the separations are highly variable). The Near-Earth objects display more variance at least at the small ends (which we simply may just not have discovered yet). The few that have a known spectral class tend to be S-types.

1139 Atami: This is a Mars crosser, with a primary of 6000 meters, a secondary of 5000 meters, and a separation over 15 km. Atami is an S-type (Tholen and SMASS)

1727 Mette: This is a Hungaria; with a primary of 10,180 meters, a secondary of 2140 meters, and a separation of 21 km. Mette is a S-type (Tholen).

2044 Wirt: This is a Mars crosser with a primary of 6460 meters, a secondary of 1620 meters, and a separation of 12 km.

Table 3.2 Mars crosser satellite data

	Number	Name	Type	Spectral types		Diameter (Primary) (in meters)	Diameter (Secondary) (in meters)	Separation (km)
				Th	SMASS			
*	1727	Mette	Hungaria	S		10,180	2140	21
*	2577	Litva	Hungaria	EU		4000	1400/1200	21/378
*	26074	Carlwirtz	Hungaria			3620		6.1
	26471	2000 AS152	Hungaria			2687	2050	18
*	1139	Atami	Mars Crosser	S	S	6000	5000	>15
*	2044	Wirt	Mars Crosser			6460	1620	12
*	3873	Roddy	Mars Crosser		S	7250	1960	14
	5407	1992 AX	Mars Crosser		Sk	3900	780	5.8
*	7369	Gavrilin	Mars Crosser			7540	2410	27
*	8373	Stepherngould	Mars Crosser			5290	1430	15
	15700	1987 QD	Mars Crosser			4150		
	16635	1993 QO	Mars Crosser			4610	1240	12
	32039	2000 JO23	Mars Crosser			3960	1270	53
	34706	2001 OP83	Mars Crosser			3480	980	7
	51356	2000 RY76	Mars Crosser			3230	680	13
	53432	1999 UT55	Mars Crosser			2550	590	4
	99913	1997 CZ5	Mars Crosser		S	6770	1290	11
	114319	2002 XD58	Mars Crosser			2620		
	218144	2002 RL66	Mars Crosser			3460		
*	5261	Eureka	Mars Trojan (L5)			1190	460	2.1

No moon names are given since they all have only provisional designations (i.e., “S/2005 (1139) 1).” An asterisk indicates a write-up. All named asteroids have been so written. There are no brief mentions due to a notable numerical value as all such asteroids are discussed. Blank values are unknown. In many cases the value used are assumed, derived or estimated, but in all cases this is the best information that could be found.

2577 Litva: This is a Hungaria and is a three asteroid system. The primary is 4000 meters, and it has two satellites of 1400 meters and 1200 meter at 21 km and an eye-popping 378 km distant. Litva is an unusual E-type (Tholen).

3873 Roddy: This is a Mars crosser with a primary of 7250 meters, a secondary of 1960 meters, and a separation of 14 km. Roddy is an S-type (SMASS).

5261 Eureka: This is a Mars Trojan (L_5), the only Martian one with a moon, and has a tiny primary of 1190 meters, a meager secondary of 460 meters, and a separation of a scant 2.1 km. There is little truly notable about it except that is has the smallest components and is the only Trojan listed (or only Trojan of Mars. There are four Jovian ones with moons, listed in Chap. 5).

7369 Gavrilin: This is a Mars crosser with a primary of 7540 meters, a secondary of 2410 meters, and a separation of 27 km.

8373 Stephengould: This is a Mars crosser with a primary of 5290 meters, a secondary of 1430 meters, and a separation of 15 km.

26074 Carlwirtz: This is a Hungaria with a primary of 3620 meters; the secondary diameter and the separation are as of yet undetermined.

4. The Asteroid Belt

The Main Belt

While asteroids are not moons, they share certain characteristics. The main asteroid belt is a region between Mars and Jupiter where the majority of the asteroids in the solar system are located. It is also a region which is commonly misunderstood. People hear "asteroid belt" and often thinks of a Star Wars-style region with fields of asteroids thick as the hair on a dog. This is not the case. If you were in the asteroid belt, you might not even know it since much of the zone is only sparsely populated. There are asteroids here, but on the whole they are few and far between.

The total mass of the collected material is 2.8e21 to 3.2e21 kg, or about 4 % the mass of Luna. There are hundreds of thousands to millions of asteroids, many of them less than 100 km in size. There are over 200 exceeding 100 km, and over 500,000 (possibly three times that number) over 1 km.

Half of the mass of the belt is contained within the four largest bodies, Ceres (sometimes called 1 Ceres), 4 Vesta, 2 Pallas, and 10 Hygeia (in order of decreasing size). The number before asteroid designations is serial, so obviously these were the first, second, fourth, and tenth objects discovered. All four exceed 400 km, and Ceres is about 950 km. None of these four objects have moons (as far as we know).

The largest (that is to say, the most massive, not most voluminous) asteroids are listed below (in descending mass with masses listed). Mass is much more important than volume when it comes to moons and other Solar System objects. Volume is merely a measure of how much space an object takes up, while mass (and through mass, gravity) impacts everything around it:

- 1 Ceres (945e18 kg)
- 4 Vesta (259.08e18)
- 2 Pallas (211e18)

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- 10 Hygiea (86.7e18)
- 31 Euphrosyne (58.1e18)
- 704 Interamnia (39e18)
- 511 Davida (38.4e18)
- 52 Europa (32.7e18)
- 15 Eunomia (31.2e18)
- 3 Juno (26.7e18)
- 532 Herculina (22.9e18?)
- 16 Psyche (22.7e18)
- 88 Thisbe (18.3e18)
- 48 Doris (17e18)
- 13 Eugenia (16.3e18)
- 7 Iris (16.2e18)
- 423 Diotima (16e18)
- 87 Sylvia (14.78e18)
- 29 Amphetrite (11.8e18)

Of these, 532 Herculina has a single moon and only 87 Sylvia has two. But many more of the minor planets have moons of their own. 96 main belt asteroids have a moon, and a few have two moons, one (130 Elektra) even has three moons (84 asteroids/102 moons). Jupiter has four Trojan asteroids with a moon (+4/+4). 42 near earth objects have a moon, and four more have two moons (+46/+50). 18 Mars-crossers have single moon each (+18/+18). 76 trans-Neptunian objects have a moon, two have two moons, and one has five (which is Pluto, now formally called 134340 Pluto) (+79/+85). That makes 231 objects with 259 moonlets (as of December, 2014). Not all of them are covered as little is really known, and all but the trans-Neptunian object moons (161 others) are tiny objects.

There is one really well-known binary where both companions are nearly the same size, 90 Antiope.

Comets

There are main belt comets, but none of them have any moons, which is to be expected.

Main-Belt Asteroids/Hungaria Family

There are 96 such objects with 102 moonlets (Table 4.1).

The asteroids with moonlets range in size between 1.79 km (8026 Johnmckay (Hungaria) and 15822 1994 TV_{15}) to over 231 km in each direction (87 Sylvia is 384 * 264 * 232). The measurable moonlets range in size from 320 meters (again S/2010 (15822) 1), to over 79 km in each direction (S/2000 (90) 1 is 89 * 83 * 80). The separation ranges from 3.1 km (27568 (2000 PT_6) (Hungaria), and S/2013 (25768) 1), to 3.336 km (379 Huenna and S/2003 (379) 1).

Once again the available data may be skewed, as these can just be the ones we have found with the highest likeliness to have been found.

22 Kalliope and Linus: 22 Kalliope is 231 * 175 * 148 km. It has one moon called Linus which is 28 km (the third largest), and is 1095 km from 22 Kalliope.

45 Eugenia, *Petit-Prince, and S/2004 (45) 1:* 45 Eugenia is 206 km, It has two moons called S/2004 (35) 1 and Petit-Prince. S/2004 (45) 1 is 5 km and is 610.59 km distant. Petit-Prince is 7 km, and is 1164.42 km from 45 Eugenia. This was the second triple asteroid system to be discovered. It was also one of the first to be discovered to have any moons, and the first have one discovered by ground telescope (the Canada–France–Hawaii telescope, in Mauna Kea, Hawaii). Dactyl was discovered earlier, but by the *Galileo* probe.

87 Sylvia, Remus, and Romulus: Sylvia was the first asteroid known to possess more than one moon. Both moons are close to equatorial (within 1 degree), orbit close to circular (eccentricities between 0.027 and 0.005 and between 0.002 and undetectable) and the smaller one, Remus, would have an excellent view of both Sylvia (which would take up 30×18 degrees of the sky) and Romulus which would take up about 1 degree. Due to the distances, and the size of the primary and size of the moonlets the system seems remarkable stable. 87 Sylvia is 384 * 261 * 232 km. Remus is 10.6 and 701.64 km distant. Romulus is 10.8 km and is 1351.35 km from 87 Sylvia (Fig. 4.1).

Table 4.1 MBA satellite data

	Class	Number	Name	Diameter (primary) (in km)	Moon name or designation	Diameter (secondary) (in km)	Separation (km)
	Hungaria	1453	Fennia	6.96		1.95	15
	Hungaria	1509	Esclangona	7.76		2.57	140
	Hungaria	2131	Mayall	8.28		2.15	18
	Hungaria	3169	Ostro	3.89		3.38	5.2
	Hungaria	3309	Brorfelde	4.88		1.27	9
	Hungaria	4440	Tchantches	2.03		0.51	3.8
m	Hungaria	4674	Pauling	4.46		1.41	250
	Hungaria	4765	Wasserburg	1.76		9.28	2.9
	Hungaria	5477	Holmes	2.95		1.09	6.7
	Hungaria	5899	Jedicke	2.54		0.81	4.4
	Hungaria	5905	Johnson	4.45		1.78	9.3
	Hungaria	7958	Leakey	2.82		0.85	10
m	Hungaria	8026	Johnmckay	1.69			
	Hungaria	9069	Hovland	3		0.9	7.8
m	Hungaria	27568	2000 PT6	1.82			3.1
	Hungaria	79472	1998 AX4	3.79			9
*	MBA	22	Kalliope	231 * 175 * 146	Linus	28	1095
	MBA	41	Daphne	174		<2	443
*	MBA	45	Eugenia	206	S/2004 (45) 1	5	610.59
*	MBA	45	Eugenia	206	Petit-Prince	7	1164.42
*	MBA	87	Sylvia	384 * 264 * 232	Remus	10.6	701.64
*	MBA	87	Sylvia	384 * 264 * 232	Romulus	10.8	1351.35

*	MBA	90	Antiope	93 * 87 * 84	S/2000 (90) 1	89 * 83 * 80	171
*	MBA	93	Minerva	141.6	Gorgoneion	3.2	375
*	MBA	93	Minerva	141.6	Aegis	3.6	623.5
	MBA	107	Camilla	219.37		16	1250
	MBA	121	Hermione	187		32	747
*	MBA	130	Elektra	198.93	S/2003 (130) 1	7	1318
*	MBA	130	Elektra	198.93	S/2014 (130) 1		
*	MBA	130	Elektra	198.93	S/2014 (130) 2		
*	MBA	216	Kleopatra	217 * 94 * 81	Cleoselene	6.9	454
*	MBA	216	Kleopatra	217 * 94 * 81	Alexhelios	8.9	678
*	MBA	243	Ida	59.8 * 25.4 * 18.6	Dactyl	1.6 * 1.4 * 1.2	108
	MBA	283	Emma	134.7		9	581
	MBA	317	Roxane	19.86		5.3	257
m	MBA	379	Huenna	87.47		5.8	3336
*	MBA	702	Alauda	201.96	Pichi üñëm	3.51	1227
	MBA	762	Pulcova	141.72		19	703
	MBA	809	Lundia	6.9		6.1	15.8
	MBA	854	Frostia	6.35		4.6	17
	MBA	939	Isberga	12.4		3.6	33
	MBA	1052	Belgica	9.79		3.53	34
	MBA	1089	Tama	10.7		7.33	20.7
	MBA	1313	Berna	10.6		8.37	25
	MBA	1333	Cevenola	17.15			
	MBA	1338	Duponta	7.68		1.77	14
	MBA	1717	Arlon	9.13			17
	MBA	1830	Pogson	7.89		2.52	18

(continued)

Table 4.1 (continued)

	Class	Number	Name	Diameter (primary) (in km)	Moon name or designation	Diameter (secondary) (in km)	Separation (km)
	MBA	2006	Polonskaya	4.51		0.99	8.5
	MBA	2047	Smetana	3		0.63	6.3
	MBA	2121	Sevestool	8.62		3.54	26
	MBA	2478	Tokai	8.1		5.83	21
	MBA	2486	Metsähovi	8.42			
	MBA	2623	Zech	7.92			
	MBA	2691	Sersic	5		2.15	12
	MBA	2754	Efimov	6.46		1.29	10
	MBA	2815	Soma	6.95		1.74	13
	MBA	3034	Climenhaga	9.97			19
	MBA	3073	Kursk	6.69		1.67	22
	MBA	3673	Levy	6.17		1.73	13
	MBA	3703	Volkonskaya	3.46		1.39	7.8
*	MBA	3749	Balam	4.95	S/2007 (3749) 1	1.66	20
*	MBA	3749	Balam	4.95	S/2002 (3749) 1	1.84	289
	MBA	3782	Celle	5.44		2.34	18
	MBA	3841	Dicicco	6.02		>1.67	12
	MBA	3868	Mendoza	9.13		2.01	20
	MBA	3905	Doppler	6.27		4.83	26
	MBA	3961	Zichichi	6.38		2.11	16
	MBA	3982	Kastel	6.79			
	MBA	4029	Bridges	7.8		1.87	13

	MBA	4383	Suruga	6.33	1.33	11
	MBA	4492	Debussy	14.6	9.39	31
	MBA	4607	Seildnadfarm	7.1	2.06	19
	MBA	4786	Tatianina	3.22	0.61	6.6
	MBA	4951	Iwamoto	4.39	3.34	31
	MBA	5474	Gingasen	5.05		
	MBA	5481	Kiuchi	7.52	2.48	15
	MBA	6084	Bascom	5.96	2.2	20
	MBA	6244	Okamoto	6.69	1.67	13
	MBA	6265	1985 TW3	4.81	1.16	8
	MBA	6615	Plutarchos	3.14		9.7
	MBA	6708	Bobbievaile	8.02	4.57	19
	MBA	7187	Isobe	6.05		
	MBA	7225	Huntress	6.54	1.37	10
	MBA	8116	Jeanperrin	4.53	1.49	13
	MBA	8306	Shoko	3.21	1.28	9.4
	MBA	9260	Edwardolson	3.98	1.07	7.2
	MBA	9617	Grahamchapman	2.74	0.74	5.2
	MBA	10208	Germanicus	3.23	1.48	13
	MBA	11217	1999 JC4	3.3		5.2
	MBA	11264	Claudiomaccone	<4	>1.24	6
	MBA	15268	Wendelinefroger	3.83	1.03	8.7
	MBA	15430	1998 UR31	3.74		8.2
m	MBA	15822	1994 TV15	1.69	0.32	3.3
	MBA	16525	Shumarinaiko	5.18	0.83	8.1
m	MBA	17246	2000 GL74	4.5	1	228

(continued)

Table 4.1 (continued)

Class	Number	Name	Diameter (primary) (in km)	Moon name or designation	Diameter (secondary) (in km)	Separation (km)
MBA	17260	2000 JQ85	4.62		1.2	7.4
MBA	20325	1998 HO27	4.94			
MBA	22899	1999 TO14	5.54		1.23	182
MBA	32008	2000 HM53	4.23		1.69	13
MBA	52316	1992 BD	3.26		0.52	4.9
MBA	69408	1995 SX48	3.12		0.59	5.3
MBA	76818	2000 RG79	3.6		1.33	5.6

Moon names are given only where they are names; provisional designations were (in general) not included (although some were). An asterisk indicates a write-up. All asteroids with named moons are so written. There are no brief mentions due to a notable numerical value; all such asteroids are fully discussed. Blank values are unknown. In many cases the value used are assumed, derived, or estimated, but in all cases this book tries to provide the most accurate data that could be find. Rounded whole number values for non-round object diameters are used (i.e., Kalliope is 231.4 * 175.3 * 146.1 which I rounded to 231 * 175 * 146)

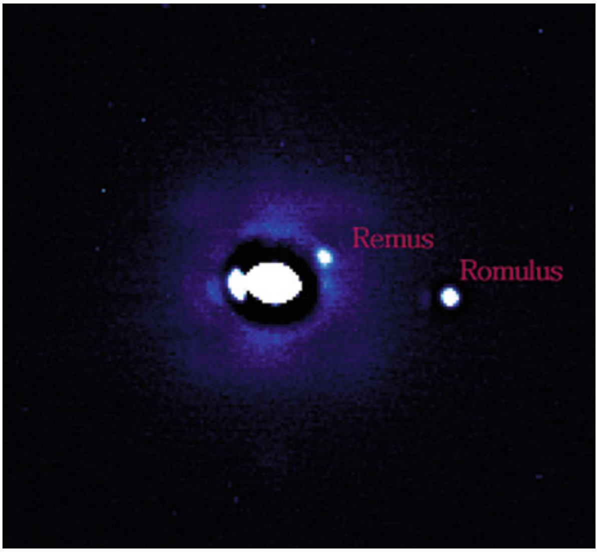

Fig. 4.1 87 Sylvia, Remus, and Romulus

90 Antiope and S/2000 (90) 1: Or is it S/2000 (90) 1 and 90 Antiope? These two bodies are inexplicable identical. The bodies are so close in size (a scant 4 km difference, on asteroids that exceed 80 km each, a difference of only 5 %, and a mass difference less than half that at only 2.5 %) that it is really difficult to tell which one is the asteroid and which one is the moon (even though they don't care what we call them). They orbit around a common spot between them (the barycenter), but the orbit is near circular. Scientists currently do not understand how the two bodies could have come to be so near-identical nor how they could end up in a co-orbit so near-circular. They have come up with a number of theories, but none of the theory work well enough to explain the situation.

93 Minerva, Aegis, and Gorgoneion: The 141.6 km Minerva has two satellites: Gorgoneion (3.2 km at 375 km) and Aegis (3.6 km at 623.5 km).

130 Elektra: As of 2014, 130 Elektra is unique among the asteroid as it is the only body with three known satellites (134340 Pluto which has 5, and at one time was thought to have 3…). One of the bodies is S/2003 (130) 1, a satellite of 7 km at 1318 km. The other two are S/2014 (130) 1 and S/2014 (130) 2, but these two are so new that we do not have any reliable data for them.

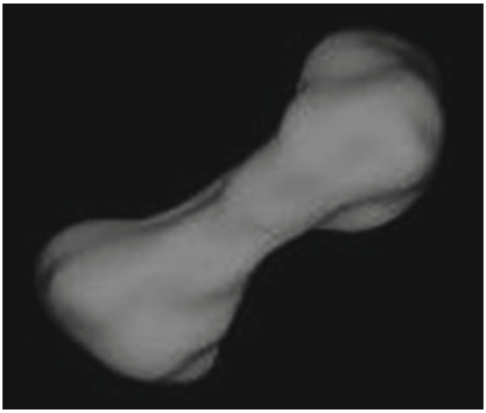

Fig. 4.2 216 Kleopatra. Alexhelios and Cleoselene are not included in the computer-generated image (Credit: NASA)

216 Kleopatra, Alexhelios, and Cleoselene: Kleopatra is 217 * 94 * 81 km, and it a contact binary and it is what astronomers call a rubble pile, consisting of 30–50 % empty space (the density is a scant 4.27 gm/cm^3). If it were spinning faster it would very likely break itself into two, becoming a true binary with two moons. Cleoselene is 6.9 km and 454 km distant. Alexhelios is 8.9 km and 678 km, which means the larger is more distant, which seems to fit the regular pattern of asteroids with multiple moons (Fig. 4.2).

243 Ida and Dactyl: Ida is one of the most well-known asteroids in our solar system. Dactyl was the very first body to be found orbiting an asteroid. It is particularly spherical measuring 1.6 * 1.4 * 1.2 km. Ida is not very spherical at all measuring 59.8 * 25.4 * 18.6. Dactyl (at 108 km away) and Ida have many shared characteristics like albedo and spectra, indicating that Dactyl may be ejecta from Ida, or maybe they both came form the same parent body (the progenitor of the Koronis family, not detailed here as it is a minor family) (Fig. 4.3).

702 Alauda and Pichi üñëm: 702 Alauda is 201.96 km, has a moonlet named Pichi üñëm (little bird in the Mapuche language) which is 3.51 km in diameter and 1227 km distant (Fig. 4.4).

3749 Balam, S/2007 (3749) 1, and S/2002 (3749) 1: 3749 Balam, is the primary of a three asteroid system. It is 4.95 km in diameter, and has two satellites with provisional designations, which measure 1.66 and 1.84, and are 20 km and 289 km distant respectively. Since it is 4.95 and has a 1.84 km satellite at 289 km (well within

Fig. 4.3 243 Ida and Dactyl (Credit: NASA/JPL)

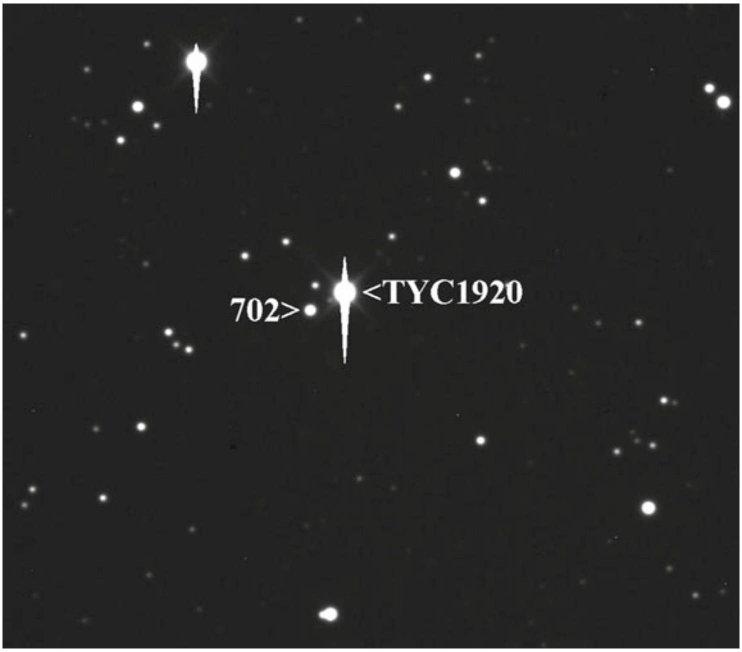

Fig. 4.4 702 Alauda (Credit: Kevin Heider, License: CC BY-SA 3.0)

the 1500 km Hill sphere), it is 116 primary radii away and thus is currently the most loosely bound binary object known. (Other ones exceeding 100 include 4674 Pauling (at 112 primary radii), and (17246) 2000 GL_{74} (at 101 primary radii).)

A Final Note

As a final note, this is an area of ongoing research. I could probably add even more objects to the table, except it does not seem worthwhile to do so, especially since these objects are mostly suggested (not confirmed) and since the data on "suggested" objects is possibly (and, in fact, likely) wrong. The most reliable data may be incorporated into later editions.

5. Jupiter

As befits the largest planet in the Solar System, Jupiter has a plethora of objects.

Jupiter by the numbers:

- 67 Definite moons
  - 4 Major moons, at least 2400 km
  - 0 Medium moon, 1000–1599 km
  - 12 Minor moons between 10 and 999 km
  - 51 Very minor moons not exceeding 10 km
- 4 Rings (not including the so-called Himalia Ring)
- 6178 Trojan asteroids (as of January 2015) with more found regularly, including 4 Jupiter Trojan asteroid with moons
- 12 Jupiter crossers
- 61 Inner grazers (Table 5.1)

The moon lists included in this chapter follow increasing orbital period. For families and groups these are ordered by the distance of the largest member of the group, and then (except for the Amalthea group) listed in descending size based on diameter. The Amalthea group is listed by increasing distance and decreasing radioactivity (see section "Io").

Rings

While not really moons, Jupiter's four main rings deserve mention as they have connections with some of the Jovian moons. The dust that comprises the majority of these rings is believed to be composed of material ejected from the moons Amalthea, Thebe, Metis, Adrastea, and other parent bodies during high-velocity impacts. It is possible that the rings have surrounded Jupiter since it became a planet.

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Table 5.1 Jupiter satellite data

	Amalthea	Io	Europa	Ganymede	Callisto	Themisto	Himalia	Carpo	S/2003 J 12	S/2011 J 1	Ananke	Carme	Pasiphae	S/2003 J 2
Represents	*Amalthea Group* (*4*)	(*Unique*)	(*Unique*)	(*Unique*)	(*Unique*)	(*Unique*)	*Himalia Group* (*4–5*)	(*Unique*)	(*Unique*)	(*Unique*)	*Ananke Group*(*14–17*)	*Carme Group*(*15–17*)	*Pasiphae Group* (*13–15*)	(*Unique*)
Adjective	**Amalthean**	**Ionian**	**Europan**	**Ganymedian**	**Callistoan**	**Themisoan**	**Himalian**							
Albedo	0.09	0.63	0.67	0.43	0.22	0.04	0.04				0.04	0.04	0.04–0.1	
Alternative names	Jupiter V	Jupiter I	Jupiter II	Jupiter III	Jupiter IV									
Apoapsis	182,840 km	423,400 km	676,938 km	1,071,600 km	1,897,000 km	8,874,300 km	13,082,000 km				29,063,500 km		31,209,300 km	
Apparent magnitude	14.1	5.02 (opposition)	5.29 (opposition)	4.61 (opposition)	5.65 (opposition)		14.6							
Average orbital speed	26.57 km/s	17.334 km/s	13.74 km/s	10.88 km/s	8.204 km/s	4.098 km/s	3.312 km/s				2.367 km/s	2.253 km/s	2.242 km/s	
Axial tilt	0°		6′	19′ 48″	0									
Composition (Atmosphere)		Sufur dioxide	Oxygen	Oxygen	98 % Oxygen									
Dimensions	131 * 73 * 67	3643 km	3122 km	5262 km	4821 km	8 km	170 km	3 km	1 km	2 km	28 km	46 km	60 km	2 km
Discovered by	E. E. Barnard	Galileo Galilei				Kowel-Roemer/ Sheppard et al.	C. D. Perrine	Sheppard et al.	Sheppard et al.	Sheppard et al.	S. B. Nicholson	S. B. Nicholson	P. J. Melotte	Sheppard, Jewitt
Discovery date	9 Sep 1892	7–8 Jan 1610				30 Sep 1975/ 21 Nov 2000	3 Dec 1904	? ? 2003	? ? 2003	27 Sep 2011	28 Sep 1951	30 Jul 1938	27 Jan 1908	4 Mar 2003
Eccentricity	0.00319	0.0041	0.009	0.0013	0.0074	0.2006	0.16	0.4316	0.492	0.2963	0.24	0.25	0.2953	0.4074
Equatorial surface gravity	0.02 m/s	1.79 m/s	1.314 m/s	1.428 m/s	1.235 m/s	0.0029 m/s	0.062 m/s				0.01 m/s	0.017 m/s	0.022 m/s	

Escape velocity	0.058 km/s	2.558 km/s	2.025 km/s	2.741 km/s	2.44 km/s	0.0048 km/s	0.1 km/s				0.017 km/s	0.028 km/s	0.036 km/s	
Inclination	0° 22′ 26.4″	3′	28′ 12″	12′	11′ 31.2″	47° 28′ 48″	29° 35′ 24″	56° (to ecliptic)	143° (to ecliptic)	162° 49′ 48″ (to ecliptic)	149° 54′	167° 31′ 48″	143° 2′ 24″	152°
Mass	2.08e18 kg	8.93e22 kg	4.7998e22 kg	1.4819e23 kg	1.0759e23 kg	6.89e14 kg	4.19–6.70e18 kg		1.5e12 kg		3e16 kg	1.3e17 kg	3e17 kg	
Mean density	0.857 gm/cm	3.528 g/cm	3.01 g/cm	1.936 g/cm	1.8344 g/cm	2.6 g/cm	1.65–2.6 g/cm				2.6 gm/cm	2.6 gm/cm	2.6 gm/cm	
Orbital period	11 h 57 m 23 s	1 d 18 h 27 m 34 s	3 d 13 h 13 m 42 s	7 d 3 h 42 m 33 s	16 d 16 h 32 m 11 s	129 d 19 h 51 m 46 s	250 d 13 h 26 m 24 s	459 d 15 h	489 d 17 h 16 m 48 s	582 d 5 h 16 m 48 s	610 d 10 m 48 m	702 d 6 h 43 m 12 s	764 d 1 h 58 m 8 s	981 d 13 h 12 m
Periapsis	181,150 km	420,000 km	664,862 km	1,069,200 km	1,869,000 km	5,909,000 km	9,782,900 km				12,567,000 km		16,890,00 km	
Rotation period	Synchronous	Synchronous	Synchronous	Synchronous	Synchronous		7 h 46 m 55 s							
Satellite of	Jupiter	Jupiter	Jupiter	Jupiter	Jupiter	Jupiter	Jupiter	Jupiter	Jupiter	Jupiter	Jupiter	Jupiter	Jupiter	Jupiter
Semi-major axis	181,365.84 km	421,700 km	670,900 km	1,070,400 km	1,882,700 km	7,391,650 km	11,460,000 km	17,146,000 km	17,883,000 km	20,155,290 km	21,280,000 km	23,400,000 km	24,094,770 km	29,500,000 km
Surface area		41.91e6 km	3.09e7 km	8.7e7 km	7.3e7 km	200 km	90,800 km				2500 km	6600 km	11,300 km	
Surface pressure		*Trace*	0.1 µPa	*Trace*	0.75 µPa									
Surface temperature (temp)	142 K	110 K	102 K	110 K	134 K	124 K	124 K				124 K	124 K	124 K	
Volume	2.43e6 km	2.53e10 km	1.593e10 km	7.8e10 km	5.9e10 km	270 km	2,570,000 km				11,500 km	51,000 km	113,000 km	
Notes	Amalthea Prototype	Galiean Moon				High uncertainty No family	Himalia Prototype	Very Litte Data Very high uncertainty	No family	No family	Ananke Prototype	Carme Prototype	Pasiphae Prototype	Very litte data No family

Note: This table includes about 14 of the 67 objects, those for which clear information is known. The other 43 are possibly a Carme, maybe an Ananke and so forth. The ones included indicate the core (or prototype) members of these groups in ascending distance.
? Missing data

Halo Ring: Extends from 92,000 to 122,500 km. Entirely dust, it's 30,500 km wide and 12,500 km thick.

Main Ring: Extends from 122,500 to 129,000 km. It's 6500 km wide and 30–300 km thick; it's only 25 % dust, with the remainder larger particles, and is bounded by Adrastea.

Amalthea Gossamer Ring: Extends from 129,000 to 182,000 km. It's 53,000 km wide, and 2000 km thick; it's entirely dust and it has an ambiguous connection with Amelthea.

Thebe Gossamer Ring: Extends from 129,000 to 226,000 km. It's 97,000 km wide, and 8400 km thick; it's entirely dust and it has an ambiguous connection with Thebe.

Amalthea (or Inner) Group

Core Members and Diameters (*in km*) (*4*): Metis (60 * 40 * 34). Adrastea (20 * 16 * 14), Amalthea (250 * 146 * 128, prototype), Thebe (116 * 98 * 84) (Figs. 5.1, 5.2, 5.3, and 5.4).

Candidate Members: None, although there are believed to be many unseen moonlets hiding in the faint and dusty rings.

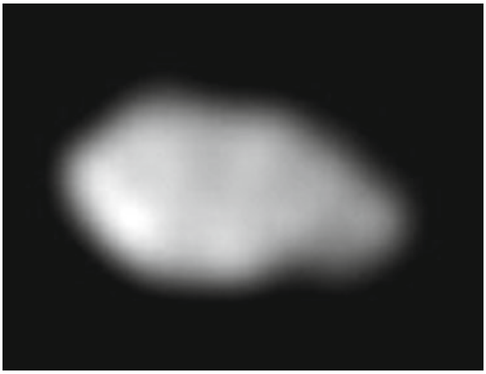

Fig. 5.1 Metis (Credit: NASA)

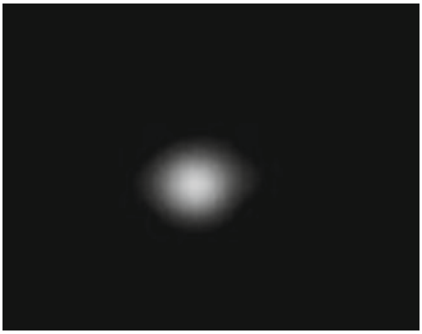

Fig. 5.2 Adrastea (Credit: NASA)

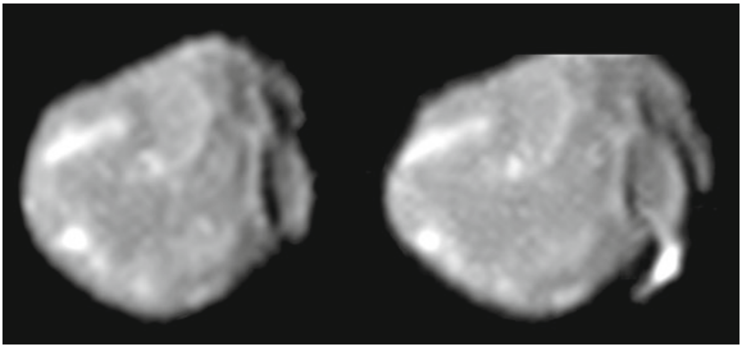

Fig. 5.3 Amalthea (Credit: NASA)

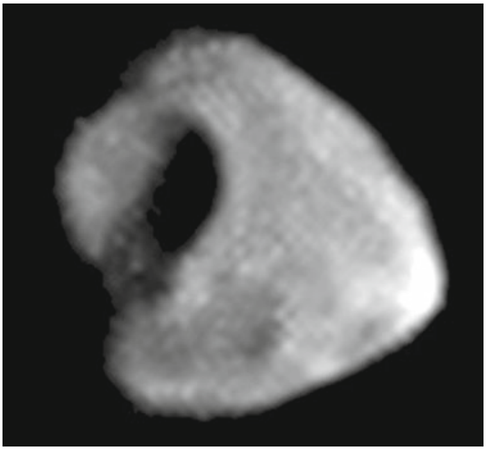

Fig. 5.4 Thebe (Credit: NASA)

Overview: These four tidally locked minor moons are named after characters in Greek mythology. Metis was the first wife of Zeus (the Greek equivalent of the Roman Jupiter); Adrastea was Zeus' foster mother, and the other two are named after nymphs. Amalthea nursed the infant Zeus with goat's milk, while Thebe was a lover of Zeus. From Metis (the closest), Jupiter takes up 67.9° of the sky! On Amalthea that number would be 46°.

Orbit: These moons are the closet to Jupiter orbiting between 127,500 and 222,000 km. The Amalthea Group includes both the fifth and seventh largest moons in the Jovian system. With masses of 0.2e16, 3.6e16, 43e16, and 208e16 (81.6 %) these moons are clearly dominated by the largest, Amalthea. The two closer ones, Metis and Adrastea, orbit in under a Jovian day, completing their circuit in less than 10 hours. They are also close to Jupiter and subject to intense radioactivity. See below under section "Io" for a full discussion on radioactivity levels.

Metis and the Rings: Metis lies within a 500 km gap in the rings, near Jupiter's Roche limit but far enough outside of this zone to have maintained its cohesion. An asymmetrical, low density object, Metis supplies the main ring with dust ejected from the impact of small satellites.

Adrastea and the Rings: Adrastea also contributes much of the material of the main ring, and its location bounds said ring, at least in front-scattered images. In back-scattered images taken to show large particles, it appears to lie just within the boundary. Discovered by photographs from *Voyager 2* in 1979, it was also observed by the *Galileo* Spacecraft, but there have not been enough direct observations to know any of the moon's surface details.

Amalthea: Amalthea was discovered 282 year after the first four moons (the Galilean satellites) of Jupiter (and it would be 12–13 years before Himalia was discovered). Amalthea is one of the reddest satellites in the solar system. Yet there are also bright patches of green of unknown nature on its surface. It has many craters. The two most notable are Pan (at 100 km wide and 8 km deep), and Gaea (at 80 km wide, but likely at least 16 km deep.) Amalthea also has two faculae identified as mountains that are 20 km high, Mons Lyctas and Mons Ida, whereas Mount Everest is only 8.85 km high. Ida and Lyctas are mountains that also appear in the stories of Zeus. From the top of Jupiter's clouds Amalthea would be about magnitude –4.7, about as bright as Venus often gets and the disc would measure 8 arc-minutes across. Amalthea's complete revolution of Jupiter takes 12 days.

Amalthea and the Rings: Amalthea supplies the Amalthea gossamer ring. There are also objects in the ring which appear to be more strongly linked to Amalthea although there is conflicting evidence of these objects existence and the impact of them on Amalthea.

Thebe and the Rings: The fourth closest moon to Jupiter, Thebes was found in images from the *Voyager 1* probe. It orbits at 2,220,000 km and has an especially high eccentricity of 1.018, most likely due to orbital excitations caused by Io. Thebe supplies the Thebe gossamer ring with its dust. Like the other inner moons, it is tidally locked and has a small escape velocity, and has asymmetrical hemispheres. Its largest feature is a 40 km crater, Zethus, on the far side of the moon.

The Galilean Moons

Overview: The four Galilean moons are named for Galileo Galilei who discovered them in 1609–1610. The names of the individual moons were first used by Simon Marius, who discovered them independently at about the same time as Galileo, discussed them with Johannes Kepler, and announced his findings in 1614. There were many other suggestions for the names of the moons, by Galileo and others who wanted to name them after Cosimo de' Medici, or the entire de' Medici family, in order to retain their patronage to fund further study.

Members: Io, Europa, Ganymede, and Callisto.

Connections: These moons are locked into some very specific orbital resonances, except for distant Callisto. Io, Europa, and Ganymede are locked in a 4:2:1 orbital resonance, that is to say, for each orbit of Ganymede, Europa makes exactly 2 orbits, and Io makes exactly 4.

Visibility: These four Jovian satellites have a visibility bright enough that they could be (theoretically) seen with the naked eye. See Chap. 12 for a full discussion on this subject.

Io

Overview: Io is named for Io, a priestess of Hera and one of Zeus' many lovers. It is the fourth largest moon in the solar system. Io has over 400 active volcanos, and over 100 mountains exceeding Mount Everest in height. It is the most geologically active body in the solar system, and the gas from its many volcanoes is ionized in its atmosphere to create the Io plasma torus. An increase in Io's volcanic activity causes a reduced degree of auroral activity on Jupiter. This is due to a plasma sheet created in Jupiter's equatorial plane. As this sheet rotates synchronously with Jupiter it deforms of the Jovian dipole. Io may have its own magnetosphere but as of yet the data is inconclusive. It would be hard to detect due to Jupiter's massive magnetosphere (see below). It has a thin atmosphere, which is mostly sulfur dioxide. It is also the most changing body in the solar system as each probe sent to or past Io sees a different face (see two images). Some of the lava flows on Io are over 500 km long, and some of the eruptions are over 500 km high and easily detectable from orbit. Io also boasts a vast lava lake, known as a patera, named Loki, spotted by the Large Binocular Telescope Observatory. This 200 km diameter volcanic depression has heating and cooling cycles that follow the formation and sinking of a thick lava crust, whose radiating heat may be observed from Earth (Figs. 5.5 and 5.6).

Orbit: Io orbits Jupiter at over 421,000 km from the orbital barycenter (at the core of Jupiter) and over 350,000 km from the tops of its clouds. Between Ganymede pulling on it during the four close passes, Europa pulling on it during its two close passes and Jupiter constantly pulling on it from the other side, the interior heat source is tidal. This is the same type of tidal effect that the moon and sun exert on Earth's oceans, except far greater, which is visible in all the active volcanism on Io (Fig. 5.7).

Interaction with Jupiter: Io has a significant role on Jupiter's magnetosphere. Io orbits completely within Jupiter's most powerful magnetic field lines. Jupiter captures a ton of material (gas and dust) from Io every second which causes Io to orbit in a plasma torus consisting of ionized sulfur, oxygen, sodium and chlorine. Io crosses Jupiter's magnetosphere field line and this creates what is called the Io Flux Tube. These effects profoundly affect Io. Jupiter

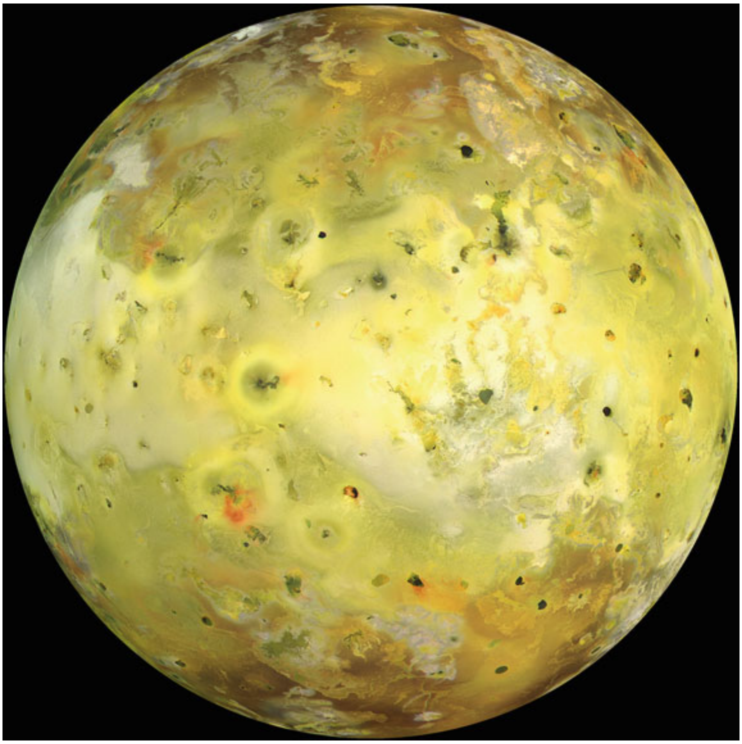

Fig. 5.5 Io. Taken with the *Galileo* probe 3 July 1999. (Credit: NASA)

captures the material ejected from Io, which includes the above particles, accelerates this material between the Jovian north and south poles to a highly accelerated state, and then it is sent back to Io with super velocity. This bathes the moon in 3600 rems of radiation per day, 3.6–5 times the human lethal dose!

For comparison, Io receives 3600 rem/day; Europa 540 rem/day; the three villages (1000 people total) nearest the Kyshtyn disaster (USSR, 1957, Level 6 disaster) received 52 rem (average total per person); people within 30 km of Chernobyl (USSR, 1986, Level 7 disaster) received up to 15 rem total; Ganymede receives 8 rem/day; an average US citizen *yearly* dose (due to cosmic gamma rays) is 360 mrem; people 20 km northwest of the Fukishima Daiichi nuclear accident (Japan, 2011, Level 7 disaster) were exposed to up to 12.5 mrem; Callisto receives 10 mrem/day; and people within 16 km of the Three Mile Island accident (US, 1979, Level 5 disaster) received 8 mrem. Compare these numbers

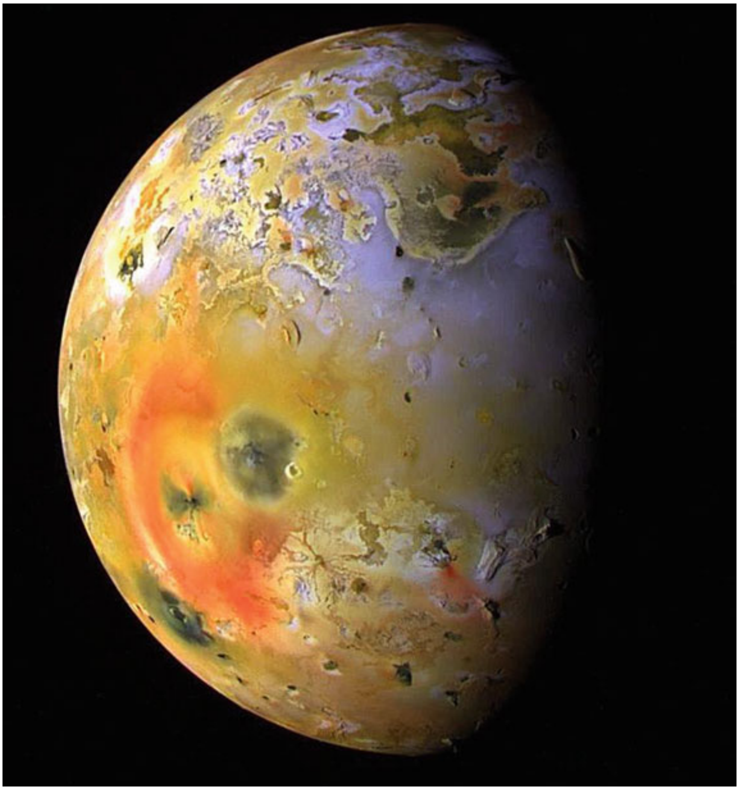

Fig. 5.6 Io. Taken with the *Galileo* probe on 19 September 1997. Even with color enhanced notice the major differences. (Credit: NASA)

to the lethal dose of 1000 rems. Europa would give a visitor enough radiation in 2 days, and Io is about 7 hours. Thebes and the other inner moons have been measured at about 18,000 rem/day!

Io's interaction with Jupiter is interesting in another way. A pulsar is a neutron star which sends out regular pulses of EM radiation as it spins (hence the name). Jupiter was at one time thought to be a brown dwarf, at the time called a "failed star", even though we no longer classify Jupiter as such an object. We do get EM pulses from Jupiter, blocked not by its own spin, but by Io's revolution about it. Therefore, the two together can be seen as a sort of pulsar in its own right.

History: As a final note it should be noted how important Io was to the development of astronomy, in its fledgling beginnings in the seventeenth century in Europe. This, of course, refers to the helio-

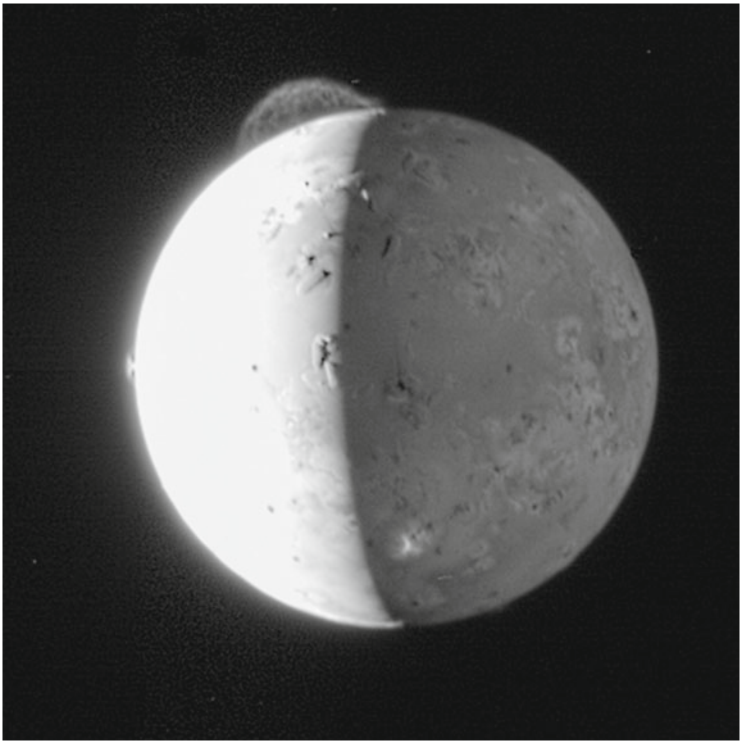

Fig. 5.7 Eruption! This image of Io was obtained by the *New Horizons* probe on 1 March, 2002. The volcano Tvashtar Paterae (name from Tvashtrim, the Hindu (Vedic) first born creator of the universe) was erupting. The lava was clearly visible from space. This plume was about 330 km high. (Credit: NASA)

centric model of astronomy, which places the sun at the center of the solar system.

The heliocentric model in Europe was first suggested by Aristarchus of Samos (c. 270 BCE), brought up time and time again by various people in both faith and science, revolutionized by Nicolaus Copernicus, and then Galileo wrote to various important people and taught his views on the heliocentric theory publically, to his great peril. The discovery of Io was vital to the development of the heliocentric theory as well as Kepler's laws of motion, and the first measurement of the speed of light (discussed further in the projects section).

In the meantime, Indian astronomers first suspected the heliocentric nature of the Solar System in Aryahata's 499 *Aryabhatiya* and it was well accepted by the 1500s according to Somayaji's *Tantrasangraha*. Islamic astronomers suggested the heliocentric model in 973 (but it was not published by Abu Rayhan Niruni) and it was repeatedly discussed but Mid-Eastern astronomers never accepted it in one big leap as did other places.

Europa

Overview: Europa is named for Europa, a Phoenician noblewoman who was courted by Zeus. It is the smallest of the four Galilean moons, but the sixth largest moon known. Its most notable features are the *linae* (Latin for lines) that cross the surface like so many pick-up-sticks, and the vast ocean that lies beneath the surface. Europa has a thin atmosphere consisting primarily of oxygen (Fig. 5.8).

Orbit: Europa orbits Jupiter at over 660,000 km from its barycenter. Between Jupiter, Ganymede, and Io pulling on its orbit (and

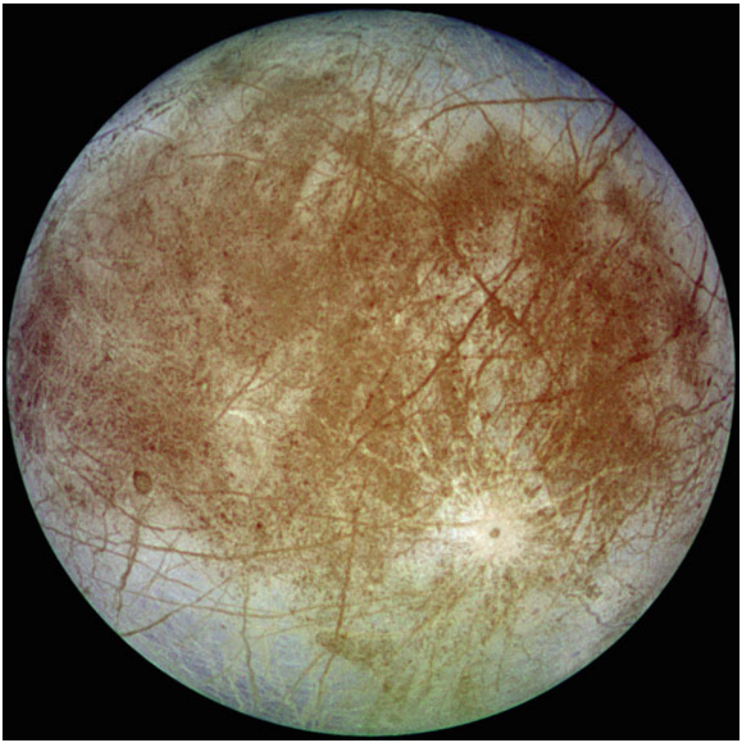

Fig. 5.8 Europa. Notice the linae covering the world ocean. (Credit: NASA)

the fact that it is smaller than Luna), Europa may have as much heat as does Io.

Interaction with Jupiter: Europa's effects on Jupiter are far less than those of Io. Europa receives 540 rem/day, which is enough to kill a human in 2 days, though other, worse effects would occur much, much sooner.

Linae: The linae are lines that cross the surface. These dark streaks cross the globe in every direction, and seem to occur when warm ice breaks open, due to surface flexing. The water beneath comes out and then is frozen. This process includes subduction and ridge spreading, just like Earth's ocean floor and this is considered extra-terrestrial plate tectonic activity.

Chaos features: There are other features present on Europa's surface. There are domes, pits and spots (in Latin, *lenticulae*, or freckles) which are believed to have formed when the older ice sheets around them were pushed up onto the surface.

Ocean: Scientists have reached a consensus that beneath 200 meters to 30 km of ice lies an ocean over 100 km deep. (Scientists disagree on how thick the ice sheet is—some think there is no water, just lots of ice, but the consensus is there must be water.) More recent evidence shows the chaos terrain features may indicate lakes detached from the main ocean surrounded by ice on all sides. Additional studies revealed phyllosilicates (a clay-like mineral) which often indicates organic matter.

Life: One of the areas which is intriguing many scientists now is the possibility that Europa's ocean may have life. Many scientists believe that life may exist in the form of extremophiles or floating in Europa's ocean. Some scientists are more optimistic and have put forth the hypothesis that Europa could have hydrothermal vents, "black smokers" similar to the undersea volcanic features found on Earth. Hypothesis have been put forth saying that if Europa had such features the ocean could support extraterrestrial life including microbes, giant tube worms, clams, crustaceans, mussels, bacteria, Achaean life, endoliths, halophytes (only if excessively salty), or some other type of as-of-yet unknown life forms. NASA is planning a robotic mission in the mid-2020s but are not yet sure whether they should build a Europa clipping, Jupiter-orbiter mission, a probe to actually orbit Europa, a Europa Lander, or some sort of hybrid mission (like the Cassini–Huygens orbiter/lander mission). ESA is planning the Jupiter Icy Moon Explorer, JUICE to launch in 2022, which can study Europa, but its primary mission would focus on larger Ganymede.

Ganymede

Overview: Ganymede is named for a divine hero from Troy, and one of Zeus' many lovers—as a side note this is the only Galilean moon named after a male. It is the largest moon in the solar system (with 2.3 % more diameter, 8.9 % more volume, and 10.2 % more mass than Titan, the second largest moon by any count). It exceeds both Titan and Mercury, but has less density than Mercury by a wide margin. Ganymede does have a magnetosphere but, as its orbit is so entrenched within Jupiter's field, it is hard to detect as more than a perturbation. It has a trace atmosphere, which is mostly various forms of oxygen (O, O_2, and O_3). There is also some atomic hydrogen, but this is a minor component even for Ganymede's thin atmosphere (Fig. 5.9).

Orbit: Ganymede takes 7 days and 3 hours to complete one orbit. It is the third component of the 4:2:1 orbital resonance between Io, Europa and Ganymede (and which Callisto is not a part of).

Ocean: Scientists believe that Ganymede has a vast amount of interior saltwater in a subterranean ocean, believed to hold more water than that is on all of Earth's surface. The ocean was suspected in the 1970s, and it was confirmed by the *Galileo* probe in the 1990s. In 2014, it was suggested that Ganymede may have a "stacked" ocean 60 miles deep with many layers of ice, water, and various types of snows and slushes. This, of course, makes it possible for life to exist in the ocean, but further study is clearly called for. The *JUICE* mission should answer some of the questions. In March, 2015, scientists studying the Jovian and Ganymedean aurorae have discovered that Ganymede does have a 100 km deep ocean, beneath 150 km of hexagonal ice, and over a layer of tetragonal ice.

Core: The presence of a magnetosphere makes an argument for the existence of an iron-rich liquid core. The magnetosphere is likely caused by convection occurring in this core.

Radiation: Ganymede receives 8 rem/day.

Fig. 5.9 Ganymede. This image come from the *Galileo* probe. (Credit: NASA)

Callisto

Overview: Callisto is named for a nymph and one of Zeus' many lovers. It is the second largest moon in the Jovian system (Fig. 5.10).

Orbit: Callisto orbits significantly further from Jupiter than Ganymede does—its semi-major orbital distance is 59.5 % greater than that of Ganymede. Due to the great distance, Callisto does not form part of the orbital resonance pattern of the other three moons and is tidally locked with Jupiter. Callisto is notably different from the other moons as its distance means that the tidal heating which affects the other three has little effect on Callisto, and the radiation received by this moon is a tiny 10 mrem/day, a fact which makes Callisto a tempting place to build a base for further colonization or exploration of the solar system.

Fig. 5.10 Callisto. This image come from the *Galileo* probe. (Credit: NASA)

Ocean: Callisto is still a bit of a mystery. It may have an ocean, but scientists are not sure. If it does have an ocean it is beneath 80–150 km of rocky ice, and does not exceed 200 km in depth. By studying how Callisto responds to Jupiter's magnetosphere it is believed to have a liquid layer at least 10 km deep. Where Io, Europa and Ganymede all have fully differentiated cores, it appears that the interior of Callisto is largely a homogenous ice-rock mixture, much like its surface. Due to having an undifferentiated interior, it may not have convection and thus may not be liquid. It is unlikely that an ocean here could support life, even if it is liquid.

Surface and Craters: Callisto's most notable visible features are its many craters. The surface is saturated with craters, to the point where there is no place on Callisto where a new crater could be formed, without erasing an older one. It is the most heavily pockmarked body in the solar system. Beyond that the surface geology is

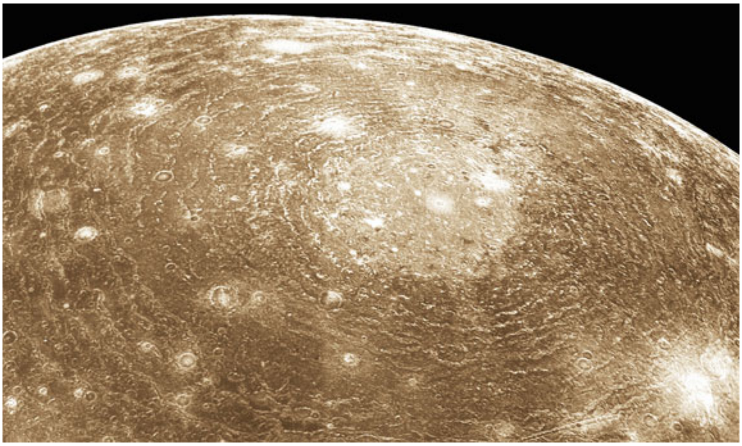

Fig. 5.11 Valhalla Crater. Notice the extensive multi-ring structure of this crater. This is one of the largest impact craters in the solar system, and the stress on the moon must have been truly intense. (Credit: NASA)

rather simple with little in the way of tectonic activity, mountains, volcanoes or anything unusual and unique to this world (Fig. 5.11).

There are a few multi-ring structures, evidence of extremely heavy impacts in its history. But what happens after a crater is formed is dependant (mostly) on size. Craters smaller than 5 km are usually simple craters and are bowl-shaped or have a flat floor. Beyond that size up to 40 km they often have a central peak. At 25–100 they may have a central pit. And any crater beyond 60 km may have a geologic dome (evidence of some sort of activity for large impacts). The largest craters, those beyond 100 km, can have any type of features. Many of the craters have Norse names such as Asgard, Burr, Doh, Har, Lofn, Tindr, and Valhalla to name a few. Asgard and Valhalla are the largest, creating these multi-ring structures. Asgard is 1600 km when all the rings are included, and Valhalla extends out to 1800 km, with a 600 km center ring.

Colonization: NASA studied Callisto in 2003, believing it to be a suitable target for colonization and exploration in the outer solar system. The program was called Human Outer Planet Exploration or HOPE. The report said Callisto was a good target (with low radiation and geologic stability) and the report said that if proper funding were given such a manned mission could happen by 2040.

Themisto

Themisto is not part of any group.

Themisto is a prograde, irregular moon of Jupiter. It was initially discovered in 1975, lost not much later (as enough observations were not made to determine its orbit), and rediscovered in 2000. It was determined that the two observations were of the same object, which was then named after the lover of Zeus and the daughter of the river god Inachus. The very fact that Themisto is not part of a family makes it somewhat interesting. Unfortunately for Themisto, that is the only thing that makes this 8 km moon interesting.

Himalia Group

Core Members and Diameters (*in km*) (*4 + 1*): Himalia (170, prototype), Elara (86), Lysithea (36), Leda (16–20) (Figs. 5.12 and 5.13)

Candidate Members: Dia (4)

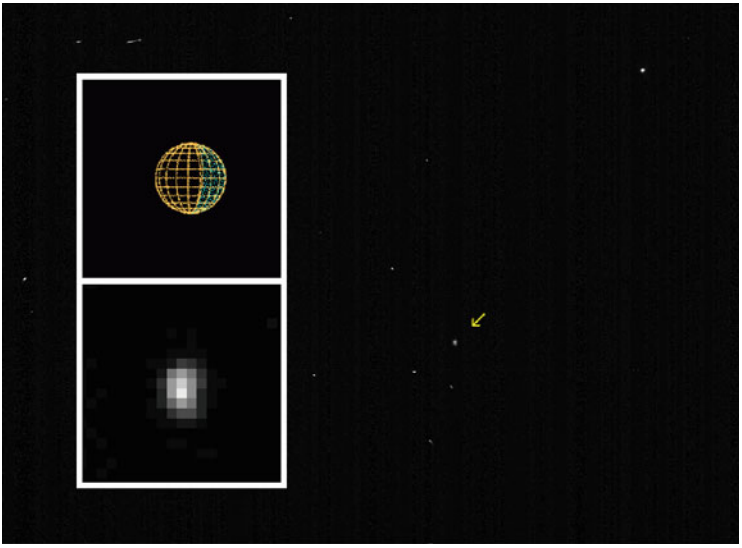

Fig. 5.12 Himalia. This is the *Cassini* image. (Credit: NASA)

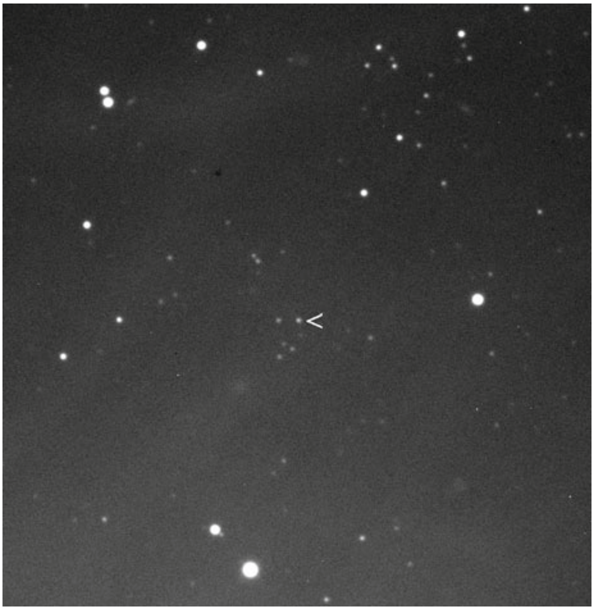

Fig. 5.13 Elara (Credit: NASA)

Dynamics: Prograde, irregular, semi-major axis 11.15–11.75 million km, inclination 26.6–28.3°, eccentricities 0.11–0.25.

Himalia: The largest irregular satellite of Jupiter with a diameter of 170 km. As such it is the easiest irregular moon to spot. Its orbit is roughly 251 Earth days, but solar and planetary perturbations make the orbit unstable. Amalthea is brighter, but much harder to see due to Jupiter's glare. The *Cassini* and *New Horizons* probes both took images of Himalia's surface.

The Himalia Ring and Dia: Dia is a small, 4 km moon discovered in 2000, which was subsequently lost. When *New Horizons* photographed Himalia the moon was not found but a ring seemed to be discovered around Himalia. Since Himalia was 170 km and the moon 4 km (the only small moon in the group) it was thought Himalia might have torn it apart. But then the moon was rediscovered in 2010. It is possible that some moon did suffer a minor collision and there may indeed be a Himalia ring, but there is no conclusive evidence at this time. Dia was officially named on 7 Mar 2015.

Carpo

Carpo is not part of any group.

Carpo is another prograde, irregular moon of Jupiter. At the risk of repeating myself, the very fact that Carpo is not part of a family makes it somewhat interesting, and unfortunately for Carpo, that is the only thing that makes this 3 km moon interesting. Its orbit is just over 453 Earth days. It was discovered in 2003 from Hawaii's Mauna Kea Observatory by a University of Hawaii group led by Scott S. Sheppard.

S/2003 J 12 and S/2011 J 1

S/2003 J 12 and S/2011 J 1 are not part of any group.

These two moons are retrograde, irregular and about 1 km in diameter.

Ananke Group

Core Members and Diameters (in km) (14+3): Ananke (28, prototype), Praxidike (7), Iocaste (5), Harpalyke (4), Helike (4), Thyone (4), Euanthe (3), Euporie (2), Mneme (2), Orthosie (2), Thelxinoe (2), S/2003 J 3 (2), S/2003 J 16 (2), S/2003 J 18 (2)

Candidate Members: Hermippe (4), S/2003 J 15 (2), S/2010 J (S/2010 J 2) 2 (1)

Dynamics: Retrograde, irregular, semi-major axis 19.3–22.7 million km, inclination 145.7–154.8°, eccentricities 0.02–0.28.

Ananke: Ananke was discovered in 1951, and was named in 1975. Between 1955 and 1975 it was sometime called Adrestea. Adrestea is now a different moon, which is prograde (as it ends in a).

Carme Group

Core Members and Diameters (in km) (15+2): Carme (46, prototype), Taygate (5), Eukelade (4), S/2003 J 5 (4), Chaldene (4), Isonoe (4), Kalyke (5), Erinome (3), Arche (3), Aitne (3), Herse (2), Kale (2), S/2003 J 19 (2), Pasithee (2), S/2003 J 9 (1), *Candidate Members*: S/2003 J 10 (2), Kallichore (2)

Dynamics: Retrograde, irregular, semi-major axis 22.9–24.1 million km, inclination 164.9–165.5°, eccentricities 0.23–0.27 (except for Taygete with 0.3678).

Carme: Carme was discovered in 1938, and was named in 1975. Between 1955 and 1975 it was sometime called Pan. Pan is now the name of a moon of Saturn (and a crater on Amalthea, and asteroid 4450 Pan, in addition to other uses).

Pasiphae Group

Core Members and Diameters (in km) (13+2): Pasiphae (60, prototype), Sinope (38), Callirrhoe (9), Megaclite (5), Aoede (5), Autonoe (4), Eurydome (3), Hegemone (3), Cyllene (2), Kore (2), S/2003 J 4 (2), S/2003 J 23 (2), and Sponde (2) (Fig. 5.14)

Candidate Members: S/2010 J 1 (2), S/2011 J 2 (1)

Dynamics: Retrograde, irregular, semi-major axis 19.3–22.7 million km (overlaps with Carme group), inclination 144.5–158.3°, eccentricities 0.25–0.43.

Pasiphae: Pasiphae was discovered in 1908, and was named in 1975. Between 1955 and 1975 it was sometime called Poseidon (of which the Roman equivalent is Neptune, there is also an asteroid 4341 Poseidon, an Apollo).

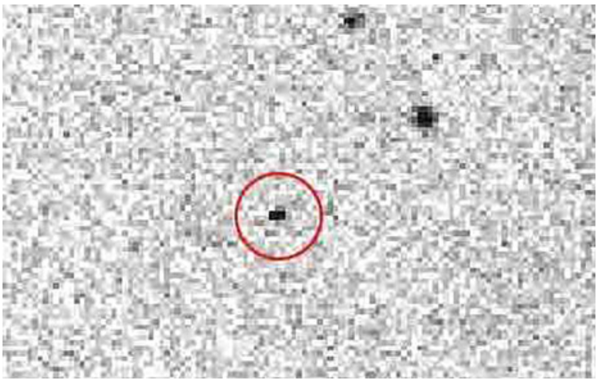

Fig. 5.14 Callirrhoe (Credit: NASA)

Sinope: Sinope was discovered in 1914, and was named in 1975. Between 1955 and 1975 it was sometime called Hades (which the Romans Latinized as Pluto, even though they considered Hades more closely similar to Dis Pater and Orcus; Pluto is also now known as 134340 Pluto, and another dwarf planet is 90482 Orcus).

Callirrhoe: Callirrhoe was discovered in 1999, has an albedo of 0.04 (not unusual for a moon), and has an apparent magnitude of 20.7 (meaning it is only about a sixth as bright as Eris) and (as a navigation exercise) was imaged by *New Horizons* in 2007.

S/2003 J 2

S/2003 J 2 is not part of any group.

This small moon is the most distant moon of Jupiter and is retrograde, irregular and about 2 km in diameter. This moon orbits at 29.5 million km. Jupiter's Hill sphere (gravitational influence) extends to 52 million km, so more distant moons may be (and likely are) waiting to be found. Furthermore retrograde moons are also stable to 2/3rds of the hill sphere (34.6 million km).

Jupiter Trojans

Jupiter's Trojan asteroids are asteroids that share Jupiter's orbit, and orbit the sun 60° 'ahead of the' or 'behind the' planet in its orbit. As they are not moons they do not fall within the scope of this book, however four deserve mention since they have moons of their own.

As there are only four such objects a full table is unwarranted.

617 Patroclus and Menoetius: (L_5 Trojan, Primary: 106 km, Secondary: 98 km, Separation: 680 km) 617 Patroclus was the second Trojan to be discovered; it was discovered in 1906, in Jupiter's L_5 area. In 2001 it was discovered to be a binary object with the primary being about 141 km in diameter and the moon being 112 km (measurements later found to be inaccurate, 106 and 98 are thought to be correct). As the barycenter is between them, and not on or in either one, this is classified as a binary system, rather than a planetoid and moon. This is still a matter of

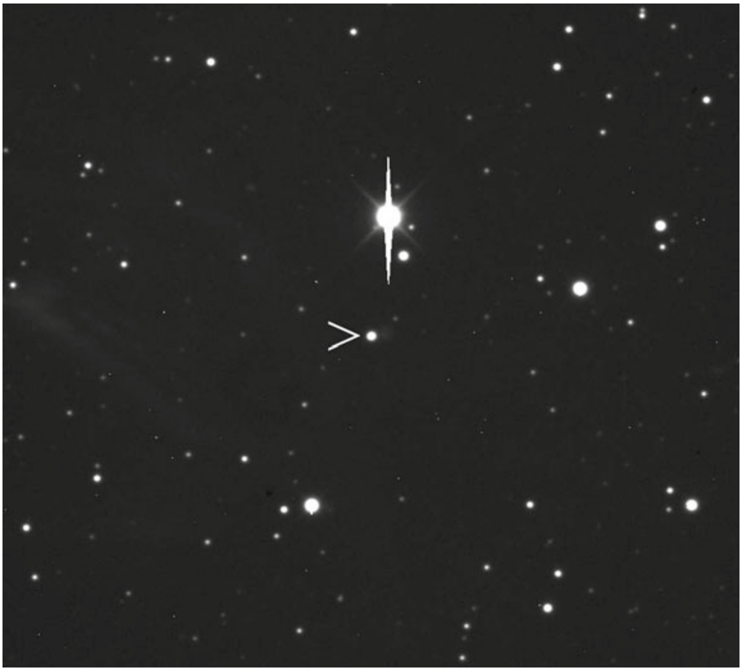

Fig. 5.15 624 Hektor (Credit: Kevin Heider, License: CC BY-SA 3.0)

debate (as to whether or not it should be classified as a "moon.") Either way, it should be included here (see the further discussion under Pluto and Charon.)

624 Hektor: (L_4 Trojan, Primary: 184 km, Secondary: 12 km, Separation: 957.5 km) (Fig. 5.15).

(*17365*) *1978 VF$_{11}$*: (L_5 Trojan, Primary: 32.6 km, Secondary: 27.5 km, Separation: 43 km)

(*29314*) *Eurydamas*: (L_5 Trojan, Primary: 32 km, Secondary: 24 km, Separation: 41 km). This Eurydamas seems to be the Trojan Elder (or Priest), the same one who interpreted dreams, and who had two sons killed by Diomedes. If so, this is named after a Trojan. There are however both Greeks and Trojans named Eurydamas; in fact, there is a Greek named Eurydamas who was in the Trojan horse.

As an interesting mythological side note Menoetius is actually Patroclus' father. Many asteroidal moons are named after offspring—Patroclus, however, had no children having been stunned, wounded, and finally killed in the Trojan War, oddly enough by the other Trojan with a moon, Hektor.

As another side note (excluding the ambivalent Eurydamas) these two asteroids are also both placed in the wrong camps. All the L_5 asteroids are named after Trojans, except for Patroclus (and its companion) who were Greeks. All the L_4 asteroids are named after Greeks except for Hektor which is named after a Trojan, a mistake which happened long before it was known that either one had a moon.

6. Saturn

Saturn is easily the most confusing of all the planetary systems to account for.

The most obvious thing that should be mentioned is its rings. The material that composes these ranges from small objects the size of dust grain to objects meters in size. It also includes larger "moonlets," first discovered in the ring system in 2002. These will be briefly discussed, but fall short of being classified as genuine moons.

As for the rest of the Saturnian system by the numbers:

- 62 Definite moons (definite meaning confirmed orbits), including:
  - 1 Major moon, Titan, at least 2400 km in diameter
  - 4 Medium moons, 1000–1599 km
  - 21 Minor moons between 10 and 999 km
  - 36 Very minor moons not exceeding 10 km
- Rings, of which few people agree on how many there are; some say thousands, some say there is only really one with a handful of gaps. In this book they are being counted as 10, 11 if the Rhea ring is included
- Ring Arcs, but again, few people agree on how many there are, though two major ones is the usual accepted figure.
- 0 Trojan asteroids are known, due to the distance of Saturn. Any found would likely be classed as a Centaur.
- 4 Trojan satellites (Trojans of other satellites)
- 1 Inner grazer, 944 Hidalgo
- 13 Numbered Saturn crossers (mostly all Centaurs)
- 0 Traditional outer grazers (again this would more likely be classed as Centaurs) (Table 6.1)

Note: This table includes about 16 of the 62 objects. The others are mostly minor unclassified moons (like Janus), very minor unclassified (like Daphnis), smaller Inuits (like Siarnaq), smaller Gallics

J.A. Hall III, *Moons of the Solar System*, Astronomers' Universe,
DOI 10.1007/978-3-319-20636-3_6

Table 6.1 Saturn satellite data

	Daphnis	Janus	Mimas	Enceladus	Tethys	Dione	Rhea
Represents	*Very minor unclassed moons* (7)	*Minor unclassed moons* (9)	(*Unique*)	(*Unique*)	(*Unique*)	(*Unique*)	(*Unique*)
Adjective	Daphnidian	Janian	Mimantean, Mimantian	Encelandean, Enceladan	Tethyan	Dionean	Rhean
Albedo	0.5	0.71	0.962	0.99	Uncertain	0.998	
Alternative names	Saturn XXXV	Satrun X	Saturn I	Saturn II	Saturn III	Saturn IV	Saturn V
Apoapsis			189,176 km				
Apparent magnitude			12.9	11.7	10.2	10.4	10.0
Axial tilt		0°	0°	0°	0°	0°	0°
Composition (Atmosphere)				91 % Water vapor			
Dimensions	9 * 8 * 6 km	203 * 185 * 153 km	416 * 393 * 381 km	513 * 503 * 497 km	1066 km	1123 km	1529 km
Discovered by	Cassini Imaging Science Team	Audouin Dollfus	William Herschel	William Herschel	G. D. Cassini	G. D. Cassini	G. D. Cassini
Discovery date	6 May 2005	15 Dec 1966	17 Sep 1789	28 Aug 1789	21 Mar 1684	21 Mar 1684	23 Dec 1672
Eccentricity	0.0000331	0.0068	0.0196	0.0047	0.0001	0.0022	0.0012583
Equatorial surface gravity	0.0001–0.0004 m/s	0.011–0.017 m/s	0.064 m/s	0.114 m/s	0.147 m/s	0.233 m/s	0.265 m/s
Escape velocity			0.159 km/s	0.239 km/s	0.394 km/s	0.51 km/s	0.635 km/s
Inclination	13″	9′ 46.8″	1° 34′ 26.4″	1′ 8.4″	7′ 12″	1′ 8.4″	20′ 42″
Mass	7.7e13 kg	1.897e18 kg	3.7493e19 kg	1.08022e20 kg	6.17449e20 kg	1.095452e21 kg	2.306518e21 kg
Mean density	0.34 g/cm	0.63 g/cm	1.1479 g/cm	1.609 g/cm	0.984 g/cm	1.478 g/cm	1.236 g/cm
Orbital period	14 h 15 m 28 s	16 h 40 m 19 s	22 h 36 m 29 s	1 d 8 h 53 m 7 s	1 d 21 h 18 m 26 s	2 d 17 h 41 m 9 s	4 d 12 h 26 m 14 s
Periapsis			181,902 km				
Rotation period	Synchronous	Synchronous	Synchronous	Synchronous	Synchronous	Synchronous	Synchronous
Satellite of	Saturn	Saturn	Saturn	Saturn	Saturn	Saturn	Saturn
Semi-major axis	136,505.5 km	151,460 km	185,539 km	239,948 km	294,619 km	377,396 km	527,108 km
Surface area			495,000 km ?			3.965e7 km	7.337e7 km
Surface pressure				Trace, variable			
Surface temperature (temp)	78 K		64 K	75 K	86 K	87 K	76 K
Volume		About 3 million km	32,600,000 km ?				
Size family	Very minor	Minor	Minor	Minor	Medium	Medium	Medium
Notes	Largest very minor unclassed	Largest minor unclassed	No family	No family	No family	No family	No family
							Some uncertainty

Titan	Hyperion	Iapetus	Phoebe	Albiorix	Siarnaq	Ymir	Skathi	Narvi
(*Unique*)	(*Unique*)	(*Unique*)	(*Unique Norse*)	*Gallic group* (*4*)	*Inuit group* (*5*)	*Norse*: *Core Subgroup* (*19/29*)	*Norse*: *Skathi Subgroup* (*8/29*)	*Norse*: *Navri Subgroup* (*2/29*)
Titanean, Titanian	**Heperionian**	**Iapetian, Japetian**	**Phoebean**			**Ymirian**		
0.22	0.3	Uncertain	0.06	0.04	0.04	0.06		
Saturn VI	Satrun VII	Saturn VIII	Saturn IX	Satrun XXVI	Saturn XXIX	S/2000 S1, Satrun XIX	S/2000 S8, Saturn XXVII	S/2003 S1, Saturn XXXI
1,257,060 km								
8.6	14.1	Varies 10–12				21.7		
0°	Varies	0°	152° 8′ 24″					
95–98.5 % nitrogen								
5149 km	360 * 266 * 205 km	1471 km	219 * 217 * 204 km	32 km	40 km	18 km	8 km	7 km
Christiaan Huygens	William Bond et al.	G. D. Cassini	W. H. Pickering	M. J. Holman et al.	Brett J. Gladman et al.	Brett J. Gladman et al.	Brett J. Gladman et al.	Scott S. Sheppard
25 Mar 1655	16 Sep 1848	25 Oct 1671	17 Mar 1899	Year 2000	Year 2000	Year 2000	Year 2000	Year 2003
0.0288	0.1230061	0.0286125	0.1562415	0.477	0.2961	0.3349	0.246	0.32
1.352 m/s	Varies 0.017–0.021 m/s	0.224 m/s	0.038–0.05 m/s					
2.639 km/s	45–99 m/s	0.573 km/s	0.1 km/s			8.7 m/s		
20′ 55.7″	25′ 48″	15° 28′ 12″	151° 46′ 48″	34° 12′ 25.2″ (to ecliptic)	46° (to ecliptic)	173° 7′ 30″	149°	137°
1.3452e23 kg	5.6199e18 kg	1.805635e21 kg	8.292e18 kg			5.1e15 kg		
1.8798 g/cm	0.544 g/cm	1.088 g/cm	1.638 g/cm					
15 d 22 h 40 m 48 s	1 d 6 h 37 m 26 s	79 d 7 h 42 m 58 s	550 d 13 h 33 m 5 s	783 d	895 d 13 h 12 m	1315 d 3 h 21 m 36 s	725 d 18 h 48 m 58 s	1006 d 12 h 59 m 2 s
1,186,680 km								
Synchronous	Chaotic	Synchronous	9 h 16 m 55 s	13 h 11 m 24 s	10 h 9 m	11 h 55 m 20 s		
Saturn	Saturn	Saturn	Saturn	Saturn	Saturn	Saturn	Saturn	Saturn
1,221,870 km	1,481,009 km	3,580,820 km	12,955,759 km	16,182,000 km	17,531,000 km	23,040,000 km	15,576,000 km	19,371,000 km
8.3e7 km		6.7e7 km						
146.7 kPa								
93.7 K	93 K	110 K						
7.16e10 km								
Major	Minor	Medium	Minor	Very minor	Very minor	Very minor	Very minor	Very minor
No family	No family	No family	Technically a Norse	Largest Gallic	Largest Inuit	Largest Norse except Phoebe	Largest Skada	Largest Norse
Due to it's elongation	Rather unique	Some uncertain	Most data missing	High uncertainty	This group include Phoebe	Very high uncertainty	High uncertainty	Very high uncertainty
Some stats vary widely			Date announced	Most data missing	I do not as it gets it own entry	Most data missing	Most data missing	Most data missing
	Photographed on 16 AUG 1898				High uncertainty			

(like Albiorix), or smaller Norses (like Ymir). The ones included indicate the largest members of such groups (the five named), and are listed in increasing semi-major orbit. Janus and other smaller unclassified moons get their own sections below depending on how much they deserve them (like all moons in this book).

Types of Moons

Saturn is so complex that in addition to families, the moons are organized into types, covered below. The types are alphabetized since they do not orbit in the same area, like dynamical families tend to.

Alkyonides

The three small moons of Anthe, Methoe, and Pallene are called the Alkyonides. They are all small (under 10 km), and have ring arcs by material blasted off them by micrometeoroids. Pallene may possess a full ring.

Co-orbital

The co-orbital moons of Epimetheus and Janus are nearly the same size and orbit close to each other. If they collided, they would both be shattered. However, due to Kepler's Laws of Planetary Motion the moons do not collide—they swap orbits. More on this later.

Dynamical Families

There are also three dynamical families, the Gallic, Inuit, and Norse groups, all described more fully, by family, later.

Inner Moons

The inner moons (within the E ring), Mimas, Enceladus, Tethys, and Dione are all too diverse and significant to not warrant a full description below.

Moonlets

Within Saturn's rings are small moonlets, some no larger than 40 meters and some up to 500 meters. In some rings such as the A ring it causes a "propeller" effect which disrupts the ring material around it. The moonlets cannot be directly imaged, but this effect can be. In the B ring where the density is higher it cannot create such an effect, but due to the greater density a shadow can be seen and this again, can be photographed. As of this writing it is believed a very small portion of these moonlets have thus far been seen. Scientists believe many more will be found. It is believed that over 700 exist over 800 meters in size and millions over 250 meters (at which point the difference between moonlet and ring particles become blurry at best). Possibly related to these is a 2014 set of observations made within the A ring, where scientists believe a new moon is forming. In the water ice-composed F ring, it has been established that they form and disintegrate within hours or days under the tidal influence of the planet's Roche limit. The occasional appearance of Prometheus near the F ring once every 17 years helps to stabilize the environment for moonlet formation, but the effect is not long-lasting.

Outer Moons

The outer moons (beyond the E ring) are Rhea, Titan, Hyperion, and Iapetus, all discussed later.

Shepherd Moons

The shepherd moons have a strong relation to the rings. They orbit within or just outside a ring, and oftentimes above or below it and are responsible for making sure that the ring particles stay in the ring where they are or keep clear of the gap where they are not supposed to be (hence the word shepherd). This classification can be applied to: Atlas (A ring); Daphnis (Keeler gap); Pan (Encke gap); Pandora (F ring), and Prometheus (also F ring).

Trojan Moons

In 1981 it was discovered that Saturn has the only two moons with known Trojan moons of their own. Tethys' Trojans are Telesto (leading), and Calypso (trailing). Dione's Trojans are Helene (leading), and Polydeuces (trailing). These are further discussed under the primaries below.

Descriptions

This list follows increasing orbital period. For families and groups, the distance of the largest member of the group is used, and then listed in descending size.

Note:
Many moons of Saturn are tidally locked, which means that as a moon goes through its orbit the same face is on the inside and the same face is on the outside. But it also means the same face is usually on the front (leading side) and the same face is usually on its back (trailing side). Since Saturn's ring system is so much more extensive than any other object (and thus debris is common), many of the moons show evidence of this on the leading side—they often get "dirty" with detritus from meteor impacts on the moon, on other moons, and ring material that has wandered out of its obit. (See sections "Tethys", "Dione", and "Rhea", and especially "Iapetus".)

Very Minor Moons Not Classed Elsewhere

Note: *This is not a true dynamical grouping* (Figs. 6.1, 6.2, 6.3, 6.4, 6.5, and 6.6)

Included "Members" and Diameters (*in km*): Daphnis (7.6, largest), Pallene (5), Methone (3.2), Polydeuces (2.6), Anthe (1), Aegaeon (0.5), S/2009 S 1 (0.3)

Seven moons, none exceeding 10 km.

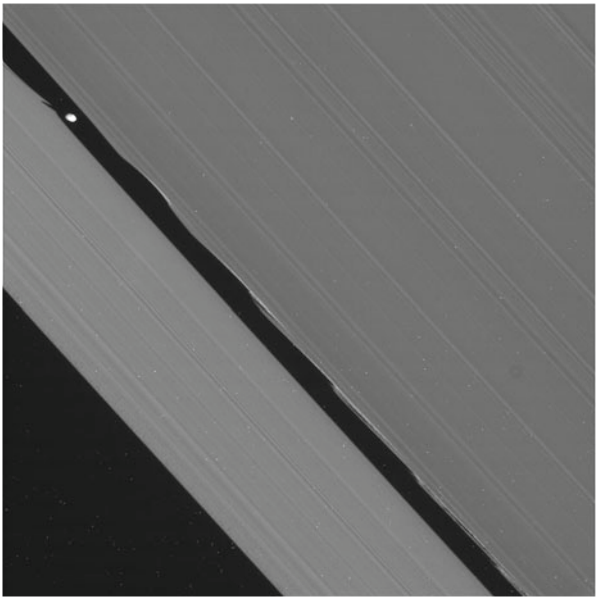

Fig. 6.1 Daphnis. Notice the wavy appearance in the A ring, which is actually caused by Daphnis, "doing its job." (Credit: NASA/JPL/Space Science Institute)

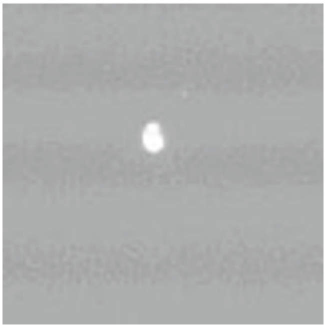

Fig. 6.2 Pallene (Credit: NASA/JPL/Space Science Institute)

Daphnis: Daphnis is under 8 km in diameter and orbits within the Keeler Gap in the A ring. It is a shepherd and keeps the Keeler gap clear of other particles. Daphnis actually induces the waves within the A ring.

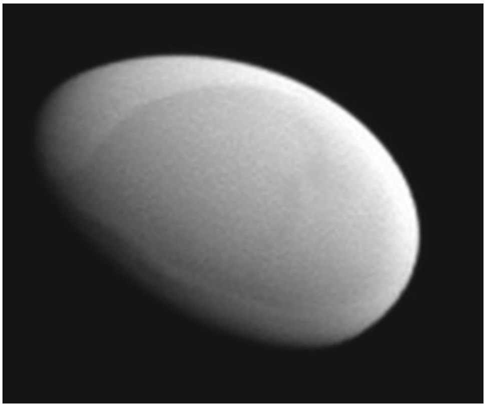

Fig. 6.3 Methone (Credit: NASA/JPL/Space Science Institute)

Fig. 6.4 Polydeuces (Credit: NASA/JPL/Space Science Institute)

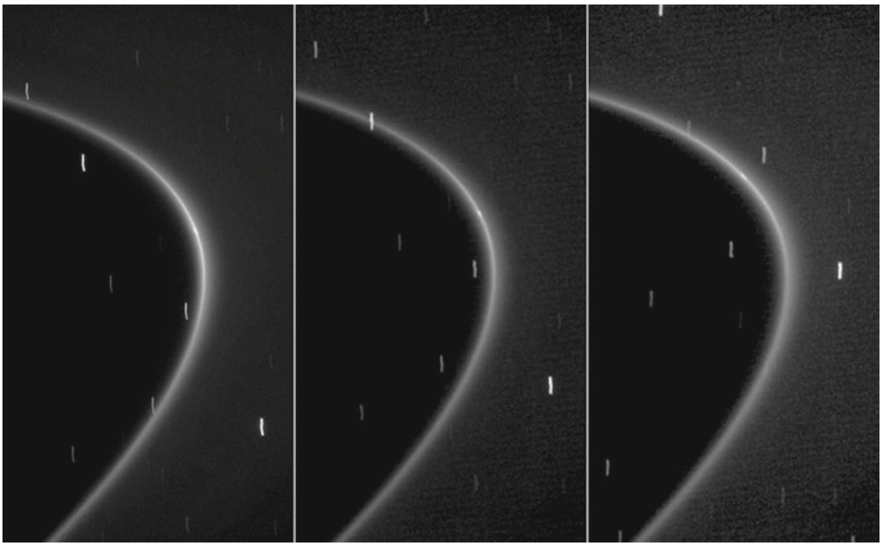

Fig. 6.5 Aegaeon (Credit: NASA/JPL/Space Science Institute)

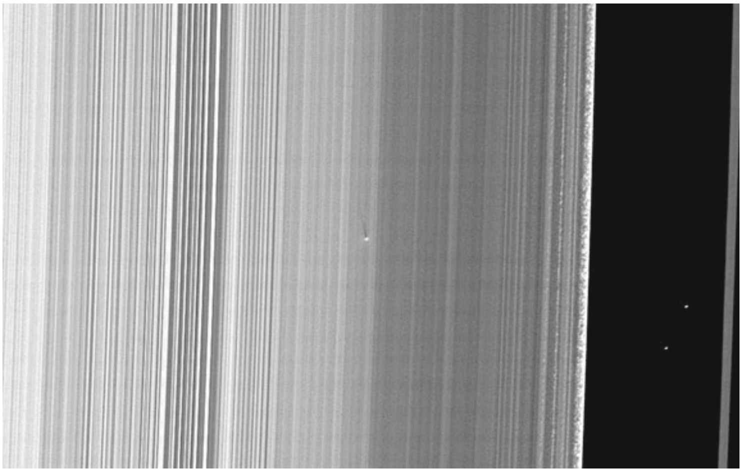

Fig. 6.6 S/2009 S1 (Credit: NASA/JPL/Space Science Institute)

Pallene: In 2006, Pallene was discovered to have a small diffuse ring.

Methone: An egg shaped moon with a remarkable smooth surface. In 2006, Methone discovered to have a small faint ring arc.

Poldeuces: See section "Dione."

Anthe: This moon has a 10:11 resonance with Mimas. In 2007 the Anthe ring Arc was discovered.

Aegaeon: This moon has a 7:6 resonance with Mimas. It orbits within the G ring, and seems to have a ring arc that replenishes this ring.

S/2009 S 1: This tiny, little moon is the closest to Saturn. The angular diameter of Saturn from this moon (not including the rings) would exceed 57°! (Including the rings is pointless since most of them are on the other side of this moon!)

Minor Moons Not Classed Elsewhere

Note: This is not a true dynamical grouping; I just put them together since there is little significant to say about any of them, except Janus and Epimetheus (Figs. 6.7, 6.8, 6.9, 6.10, 6.11, 6.12, 6.13, 6.14, 6.15, 6.16, and 6.17).

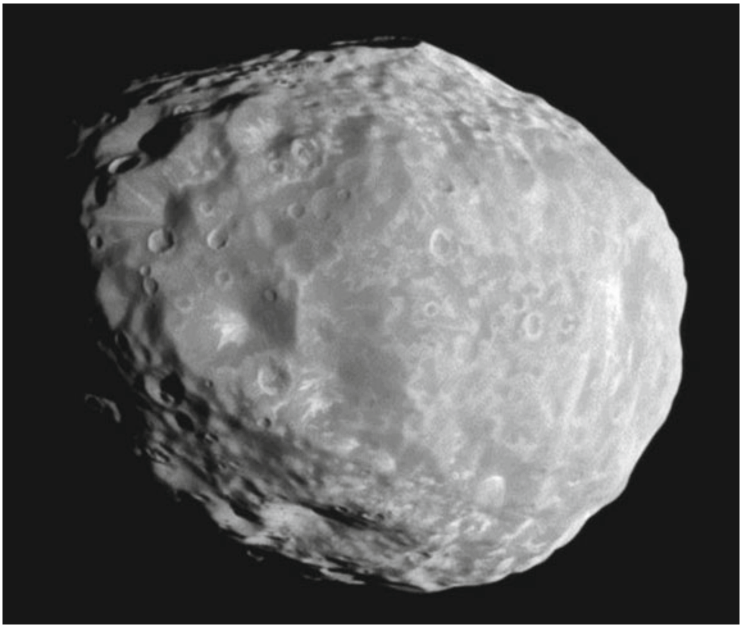

Fig. 6.7 Janus (Credit: NASA/JPL/Space Science Institute)

Fig. 6.8 Epimethus (Credit: NASA/JPL/Space Science Institute)

Fig. 6.9 Janus and Epimethus. This picture was taken right on 6 March, 2006, 2 month after the orbital swap. (Credit: NASA/JPL/Space Science Institute)

Fig. 6.10 Prometheus (Credit: NASA/JPL/Space Science Institute)

Fig. 6.11 Pandora (Credit: NASA/JPL/Space Science Institute)

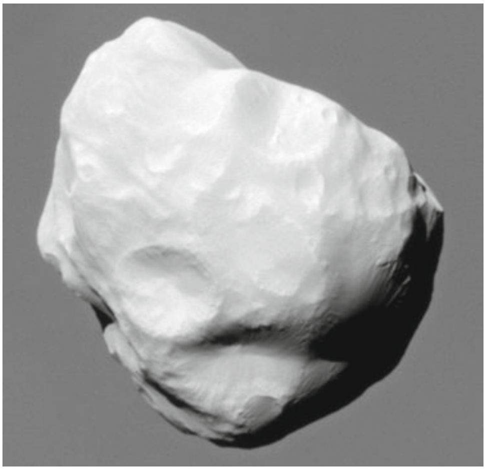

Fig. 6.12 Helene. The light-colored background of this picture is Saturn's cloud tops. (Credit: NASA/JPL/Space Science Institute)

Included "Members" and Diameters (*in km*): Janus (179, largest), Epimetheus (116.2), Prometheus (86.2), Pandora (81.4), Helene (35.2), Atlas (30.2), Pan (28.2), Telesto (24.8), Calypso (21.4)

Nine moons, all between 10 and 999 km, even though none of the ones not classed elsewhere exceed 200 km in theory (or 179 km in practice.)

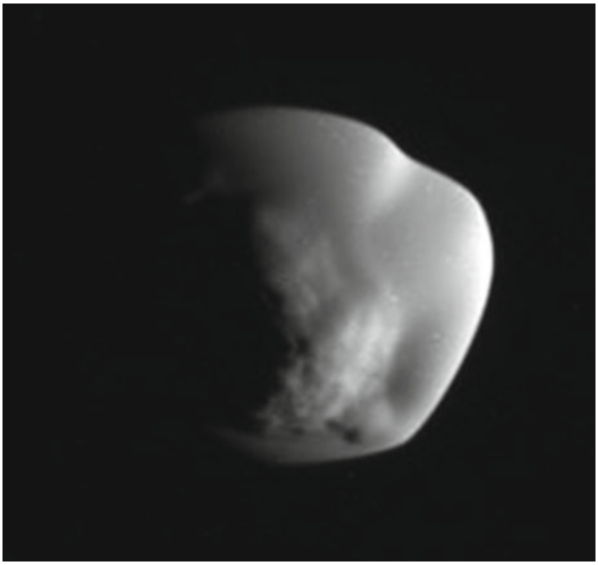

Fig. 6.13 Atlas, south polar view. From this view, the equatorial bulge is invisible, and Atlas appear round. (Credit: NASA/JPL/Space Science Institute)

Fig. 6.14 Atlas, equitorial view. This view shows the equatorial bulge of Atlas clearly. This feature is shared by many of Saturn's moons. See Iapetus. (Credit: NASA/JPL/Space Science Institute)

Janus and Epimetheus: Janus and Epimetheus occupy practically the same orbit. As an object it was first "discovered" in 1966, but the idea that it was two separate objects did not come for 12 years until 1978; *Voyager 1* confirmed this in 1980. According to Kepler's Laws of Planetary Motion, the inner moon completes

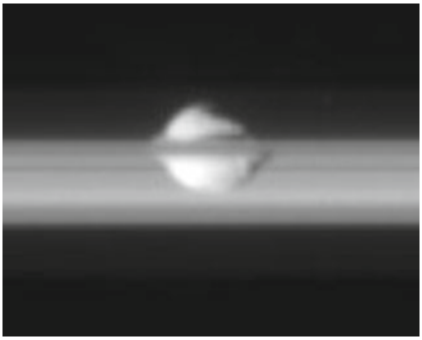

Fig. 6.15 Pan (Credit: NASA/JPL/Space Science Institute)

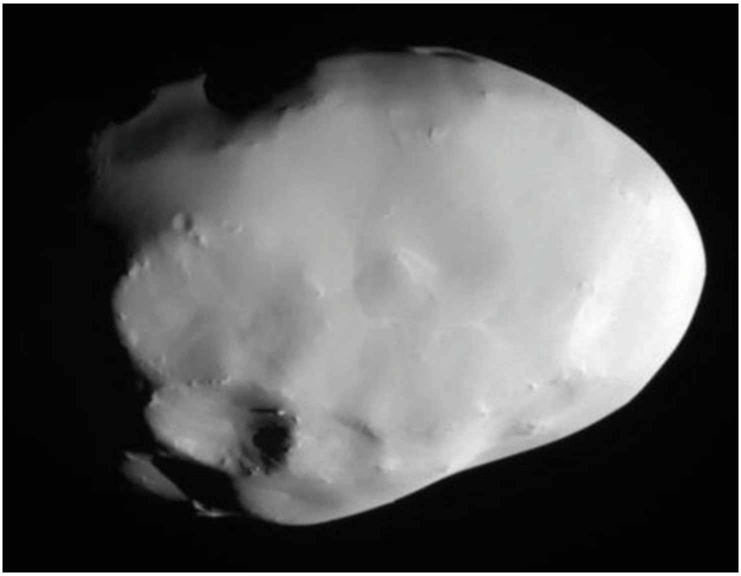

Fig. 6.16 Telesto (Credit: NASA/JPL/Space Science Institute)

its orbit faster, then the combined gravity of both moons accelerate it, then the inner moon accelerates and moves outward. At the same time the momentum is transferred from the outer moon to the inner and the outer slows down and its orbit decreases and it becomes the inner. In this manner they "swap orbits." This happens every 4 years: most recently in 2006, 2010 and 2014, and it will happen again in 2018, 2022, and 2026. It is also worthwhile to note that Epimetheus moves four times as far in this arrangement since Janus is four times as massive. In 2014–2018, Janus is closer.

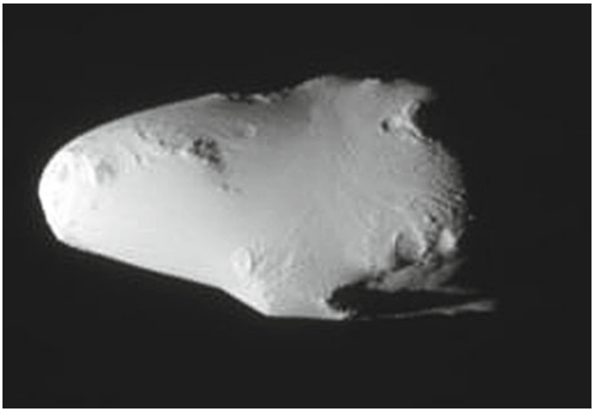

Fig. 6.17 Calypso (Credit: NASA/JPL/Space Science Institute)

Janus, Epimetheus and the A ring: Janus and Epimetheus have a faint dust ring. These two moon shepherd the A ring and keep its outer edge sharp.

Janus: Janus has several craters, some over 30 km, and few linear features. It has low density (0.63 g/cm^3) and high albedo (0.71) which means it is likely very porous (in astronomy terms, a rubble pile) and mostly icy.

Epimetheus: Epimetheus also has several craters, some over 30 km, but it also sports ridges and grooves. It also has low density (0.64 g/cm^3) and high albedo (0.73) which means it too is very porous, a rubble pile, and mostly icy. It is also largely flat near the South Pole which appears to be from a very large and ancient impact.

Prometheus: Discovered in 1980, this moon is an elongated (137 * 79 * 59) inner shepherd of the F ring. It has a 53:54 resonance with Atlas and a 121:118 resonance with Pandora.

Pandora: Discovered in 1980, outer shepherd of F ring. This moon has a 3:2 resonance with Mimas and a 118:121 resonance with Prometheus.

Helene: Discovered in 1980, see section "Dione".

Atlas: Discovered in 1980. It was at one time thought to be the outer shepherd for the A ring; however, Janus and Epimetheus are the true ones. This moon has a 54:53 resonance with larger

Prometheus which causes Atlas' orbit to be perturbed. Atlas also has an equatorial ridge. This ridge is, in fact, as high as it can possibly be. If it were any higher, it would be outside the moon's Roche lobe which means additional particles would be lost due to the centrifugal force exceeding the gravitational attraction. Because of this, this may have actually been what has happened in the past—we would have no evidence if it had.

Pan: The second closest of Saturn's moons (second only to 300 meter wide S/2009 S 1), photographed in 1981 (11 times, in fact), but not found until a 1990 analysis. This moon is responsible for the Encke gap. It has an equatorial ridge similar to the one found on Atlas. It seems to have a ringlet in its own orbit in the Encke gap. Pan is named after Pan, the Greek god of (among other things) shepherds.

Telesto: Discovered in 1980, see section "Tethys."

Calypso: Discovered in 1980, see section "Tethys."

Mimas

Overview: Mimas, at 396 km (avg.) in diameter, is the smallest solar system body to be rounded by its own gravitation. It is not a very large moon—in fact it is number 21 in the solar system, and number 7 around just Saturn. It was discovered by William Herschel in 1789, using his "Great Forty-Foot" reflecting telescope (40 feet refers to the length; the actual primary mirror was 120 cm). Mimas' most notable feature is named in honor of is discoverer, the Herschel crater (Fig. 6.18).

Herschel Crater and related features: The Herschel crater is enormous. The moon is 396 km in diameter, and the crater lies perfectly on the equator, covering a full 140 km in area, with a floor over 10 km deep floor, 5 km high walls, and a 6 km tall central peak. If Mimas were the size of Earth, the crater would be wider than Australia. This crater is about a large as it can be—any larger and there would be no Mimas, just one more ring of debris around Saturn. The kinetic force from this impact created shock waves which left scars on the far side, fracturing the crust where they met each other.

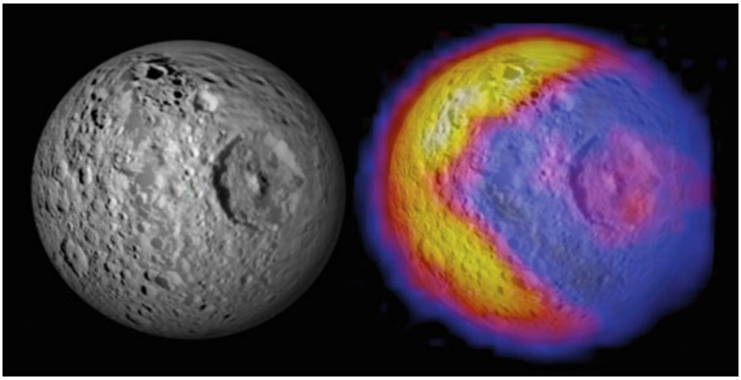

Fig. 6.18 Mimis. The image on the *left* shows the Herschel crater making Mimas resemble the fictional Death Star. The image on the *right* is the thermal map showing the cold zone around the Herschel crater and the internal heat though the rest of the moon, making Mias resemble Pac-Man. (Credit: NASA/JPL/Space Science Institute)

And the weird features do not stop there. *Cassini* analyzed Mimas' global temperature. The results were shocking. The planet is relatively "warmer" everywhere else, except near the crater. The area of the crater is decidedly colder than the rest of Mimas. Scientists believe the two must be connected—the evidence seems clear enough—but they are not sure exactly how or why.

Finally there are the comparisons that beg to be drawn. When many look at a visible light image of the rounded moon with one large crater, most people think of *Star Wars'* famous *Death Star* (which came out 3 years *before* the crater was discovered). When people look at a temperature map of Mimas, the Death Star fades and the moon now looks like the *Pac-Man* character, with the crater looking suspiciously like one of that character's power pellets which let him eat Shadow, Speedy, Bashful, and Pokey—look out Blinky, Pinky, Inky, and Clyde; Mimas is coming!

Interactions: Mimas interacts and has resonances with many of the Saturnian system features. It clears the Cassini Division. It has many resonances; it has a 2:1 with particles in the Huygens Gap; a 3:1 with the border between the B and C Ring; a 7:6 with the G Ring; a 2:1 with Tethys; and a 2:3 with Pandora.

Ocean: In 2015 it was announced that Mimas' irregular orbit may indicate that it has a subsurface ocean. This was previous thought impossible due to an apparent lack of geological activity. As research is still underway, not much else can be said with any certainty.

Enceladus

Overview: Enceladus is but the sixth largest moon of Saturn. Its most notable features are the South Pole's "Tiger Stripes." Enceladus has a trace atmosphere, most notable so at the South Pole, which is 91 % water vapor ($H_2O(g)$), with nitrogen (N_2), carbon dioxide (CO_2), and methane (CH_4) making up the rest (Figs. 6.19 and 6.20).

Orbit: Enceladus orbits within the densest part of the E ring and is the source of most of the material of this ring. It has a 2:1 resonance with Dione. The E ring is unstable and without replenishment would not last more than maybe a million years (and possible as little as 10,000).

Physical: Enceladus has a density of 1.609 gm/c^3 which sets it apart from similar moons which are mostly water and/or ice. Iapetus, Rhea, Tethys and Dione all have densities between 0.9 and 1.5. This increased density seems to support the theory of a differentiated interior, with a crust, icy mantle, and iron-silicate core.

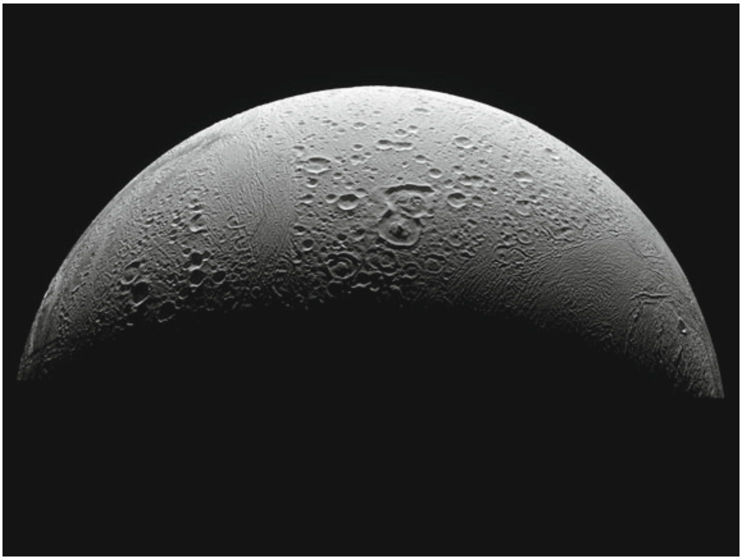

Fig. 6.19 Enceladus (Credit: NASA/JPL/Space Science Institute)

Fig. 6.20 Enceladus, tiger stripes. This is a low-resolution composite image of the south pole showing the tiger stripes. (Credit: NASA/JPL/Space Science Institute)

Tiger Stripes: The tiger stripes are four south polar surface cracks. As Enceladus has a geometric albedo of 1.375 (and a Bond Albedo of 0.99, meaning 99 % of the light that hits it is reflected), the best tiger stripe images are low resolution images—high resolution ones not in false-color return nothing but a pure white shine. They have individual names (*Alexandria Sulci*, *Baghdad Sulci*, *Cairo Sulci*, and *Damscus Sulci*), after cities in the Burton's translation of *The Book of One Thousand and One Nights*, like all Enceladan features. Each one is about 130 km long, 2 km wide and 500 meters deep. The ridges on either side are 100 meters high, and 2–4 km wide. They are 35 km apart, and each stripe is significant warmer than

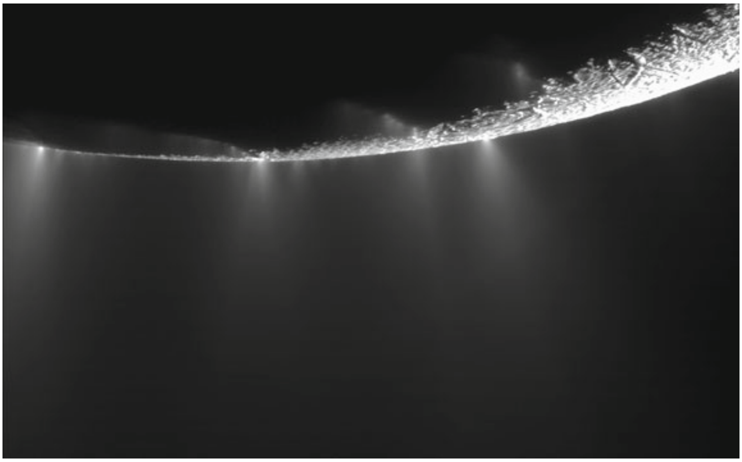

Fig. 6.21 Enceladus, geysers. This image show the geysers. Backlighting them make them show up clearly. (Credit: NASA/JPL/Space Science Institute)

the areas immediately around it and the rest of Enceladus. A 2013 study by *Cassini* Scientist Matt Hedman (University of Idaho) describes how these stripes open and close in a predictable manner, and it is now well known that there are water jets at the bottom of each stripe. This area of Enceladus is stretched and squeezed like an accordion, and when it is stretched water shoots out in plumes, three times as great as when they are closed. Some of these plumes move at over 1350 mph (2100 km/h) (Fig. 6.21).

Water: There is water inside Enceladus. Scientists believe the volume of water is about 12,000 km^3, about equal to the volume of Lake Superior. This may or may not include a subsurface liquid ocean depending on whether Enceladus is found to have enough heat at this time to support liquid water. *Cassini's* latest results indicate a warm ocean with ongoing hydrothermal activity at the southern pole. The analysis was based on the observation that Enceladus' icy geysers were able to eject material into the outermost dust ring. These dust particles have been shown to be made mostly of silica, a remnant of geyser-ejected saltwater. In May, 2015 the ice was found to 30–40 km thick, the ocean 10 km deep, and scientists are relatively certain of the presence of hydrothermal vents (black smokers). This discovery was made due to silica ending up in the E ring. The ocean should be at least 90 ºC. This make Enceladus a prime target for ongoing investigations.

Heat Output: According to *Cassini* observations, the moon has an observable heat power output of 15.8 gigawatts. This was an order of magnitude higher than what was expected to be found, as an earlier study had estimated the production of 1.1 gigawatts from tidal heating. It remains unclear how the south polar region is able to generate so much heat-generated power. Speculation includes the possibility that it depends on a cyclical interaction with Dione, and it also increases the likelihood that Enceladus has a liquid ocean. The hydrothermal activity may not be stable, however, due to being generated not by a molten core but by gravitational friction.

Life: The similarity of the hydrothermal activity on Enceladus to the Lost City hydrothermal vents in the Atlantic Ocean raises the question of whether these might also create the environment necessary for life to begin. Together with Europa, it is among the best candidates in the Solar System.

Tethys

Overview: Tethys is the smallest moon that could be called medium, just over 1000 km in diameter. It is only the 16th largest in the solar system, yet its mass is greater than all moons smaller than itself combined. With a density of 0.98 gm/cm^3, and being no more the 6 % rock, it would float on water (but barely, unlike Saturn at only 0.69). Between its density and its Bond albedo of 0.65–0.95, Tethys must be mostly ice, and evidence (such as infrared spectroscopic absorption bands) points strongly to mostly water ice (Fig. 6.22).

Orbit: Tethys orbits within Saturn's magnetosphere and has plasma falling on its trailing face. In Tethys' L_4 point is Telesto, and in the L_5 point lies Calypso. Mores on these two below (Figs. 6.16 and 6.17).

Physical Features: Tethys is thought to be mostly homogenous in its interior, and it's unlikely to have any subsurface ocean. Most of Tethys' surface is covered by small craters and chasmata (plural of chasma, or what on Earth could be called a chasm). There is a crater called Odysseus, which has a diameter of 450 km, about 45 % of Tethys' own diameter. Another notable feature is the Ithaca Chasma, 2000 km long, 100 km wide and 3 km deep. It stretches almost 75 % of the way around Tethys (being twice as long as its

Fig. 6.22 Tethys (Credit: NASA/JPL/Space Science Institute)

diameter, and with $C = \pi D$. Compare this to the Grand Canyon, 446 km long, 29 km wide and 1.8 km deep (Figs. 6.23 and 6.24)).

Note: Until the *Cassini* flybys the only exploration of Tethys was by the twin *Voyager* spacecraft. From 1980 to 2004, Tethys was best imaged moon of Saturn.

Telesto and Calypso: Telesto is a 12–13 km Trojan moon at Tethys' L_4 point. Calypso is a 30 * 23 * 14 km Trojan moon at Tethys' L_5 point. The relationship was found in 1981. Beyond this odd relationship they seem rather commonplace.

Dione

Overview: Dione is slightly larger than Tethys, medium sized at just over 1100 km in diameter. It is the 15th largest moon in the solar system, yet as the third densest moon its mass is also greater

Fig. 6.23 Tethys-Odysseus. Notice Tethys' Odysseus crater. (Credit: Wikipedia's "Ugo", License: CC BY-SA 2.5)

than all moons smaller than itself combined. However, as the third densest moon (with a density over 1.4 gm/cm^3) it would not float. In truth, Dione is actually more similar to Rhea (below) than Tethys (Figs. 6.25 and 6.26).

Orbit: Dione orbits Saturn, at nearly the same distance at which Luna orbits the Earth. (However, due to Saturn's much greater mass the orbit is much faster, being under 2.8 days.) Dione is in a 1:2 orbital resonance with Enceladus. Like Tethys, in Dione's L_4 point is Helene, and in the L_5 point resides Polydeuces. Mores on these two below.

Physical Features: At first glance Dione looks rather smooth, but when the color is enhanced lots of craters, catenae (crater chains), chasmata, dorsa (ridges), and fossae (long narrow depressions) become visible. There is also wispy terrain (below). The distribu-

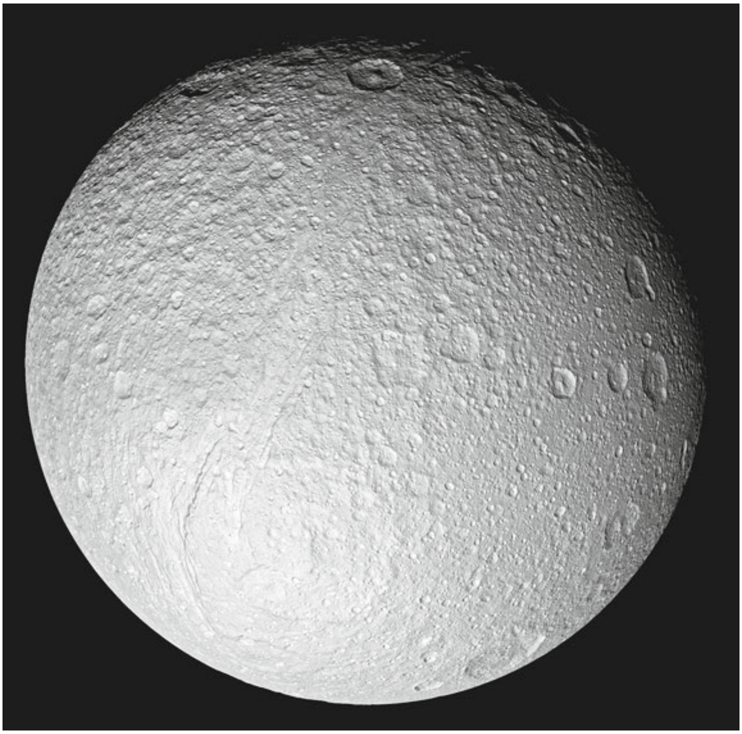

Fig. 6.24 Tethys-Ithica. Notice Tethys' Ithaca Chasmata running from *lower left* to *top center*. It is also slightly visible on 6.22 from *left* to *center-top*. (Credit: NASA/JPL/Space Science Institute)

tion of the cratering confused scientists until Shoemaker and Wolfe put forth a model that makes sense. The theory states that it would seem that during the Late Heavy Bombardment, about four billion years ago, Dione was tidally locked, but in a different orientation than the current one. An impact that could create even a 35 km crater would be able to spin the moon into a different orientation, which would also become tidally locked in time. So Dione may have been cratered, spun, cratered on a different face, spun again, and then cratered on another face (Figs. 6.27 and 6.28).

Wispy Terrain: When *Voyager* passed Dione in 1980, it found what was termed wispy terrain. It was uncertain what the wispy features were and some hypothesis were put forth, primarily ancient ice vulcanism/cyrovulcanism deposits. When *Cassini*

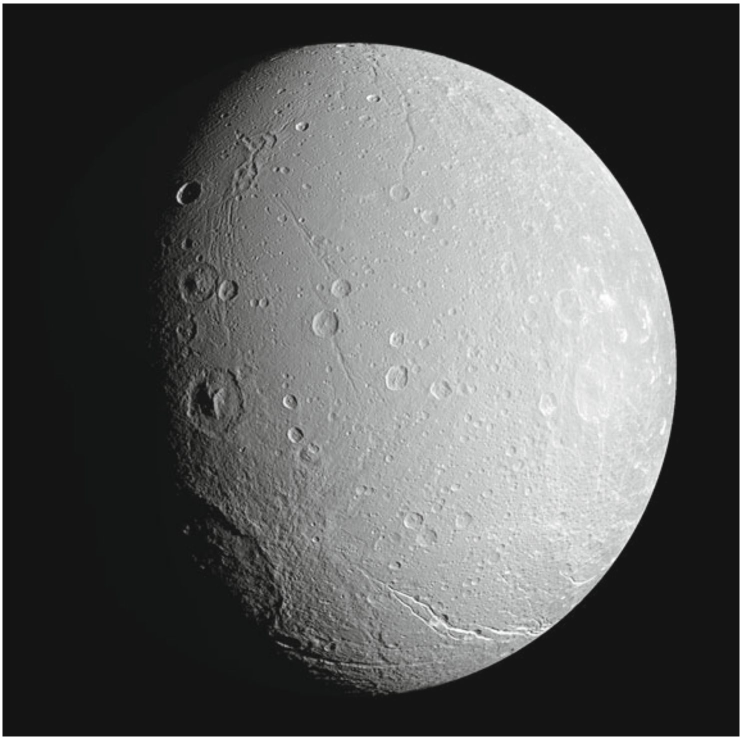

Fig. 6.25 Dione (Credit: NASA/JPL/Space Science Institute)

passed Dione it was discovered that these wispy feature were not ice deposits—they were ice *cliffs* (and chasmata). A flyby in October 2005 showed some of these are hundreds of meters high.

Exosphere: While Dione has no true atmosphere, elemental (ionic) oxygen (O_1) has been found above the moons surface (at 0.01–0.09 gm/cm^3), but no evidence of water vapor has been found yet.

Ocean?: In May 2013, *Cassini* scientists suspected that Dione may be more active like Enceladus, Titan or Europa. It may have or have previously had a subsurface liquid or a slushy ice layer under the surface. The moon has been studied since 2004, but in 2013 a faint particle stream was detected coming from the moon. Further studies have also shown inactive crack reminiscent of those seen on Enceladus. The level of activity seems too low for an extensive ocean.

FIG. 6.26 Dione-Trailing. This is the trailing hemisphere of Dione. (Credit: NASA/JPL/Space Science Institute)

Helene and Polydeuces: Helene is a 43.4 * 38.2 * 26 km Trojan moon at Dione's L_4 point. Polydeuces is a 3 * 2.5 * 2 km is another Trojan moon (Figs. 6.29 and 6.30).

Polydeuces' Orbit: Polydeusces' orbit is very unusual. It is conventionally considered to be an L_5 area Trojan (60° behind Dione), but sometimes it is as close as 33.9°, or as far as 91.4°. It also varies in its orbital distance by 7660 km in either direction. The period between one extreme and the other is about 791 days.

Rhea

Overview: Rhea is about 1500 km in diameter. It is the smallest moon confirmed to be rounded due to the force of hydrostatic equilibrium (where forces such as gravity are equivalent to the

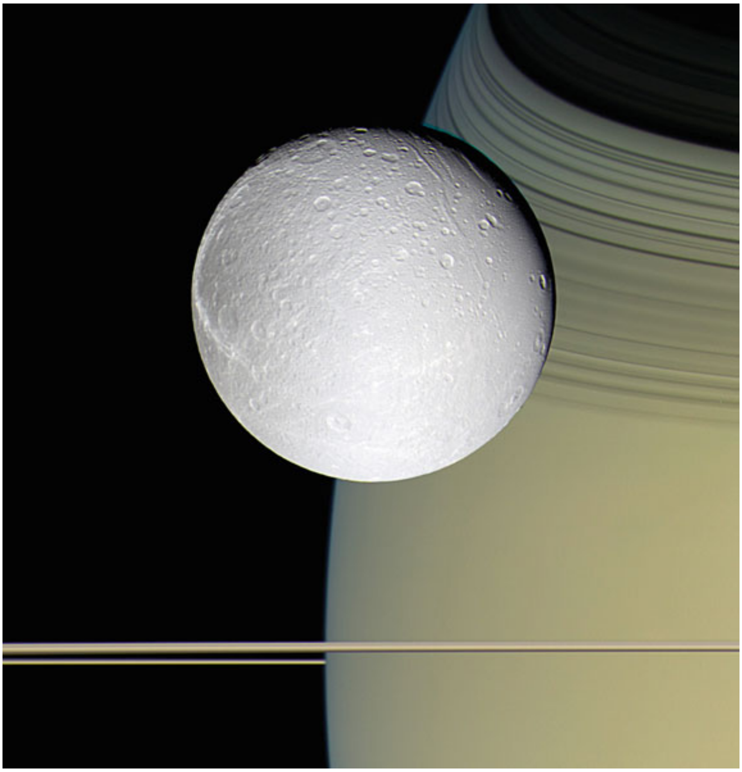

Fig. 6.27 Dione and Saturn. Dione against a backdrop of Saturn's rings. (Credit: NASA/JPL/Space Science Institute)

pressure gradient forces. This is also one of the defining characteristics of a planet according to the current IAU definition; however, Rhea does not orbit the sun, another requirement—it orbits Saturn.) (Fig. 6.31).

Physical Features: Rhea is about a 25 % rock and 75 % water ice. Measurement of Rhea's moment of inertia (a measure of torque required to affect angular rotation, and which can be used to determine mass or inertia) indicates that it has a homogeneous interior. The triaxial measurements agree with the homogenous interior model.

Rhea, like Dione, also has some "wispy terrain" on its trailing hemisphere, which was also found to be ice cliffs. It has a 500 km impact basin called Tirawa (and other basins going as large as 400 km), and a notable 48 km impact basin called Inktomi, with

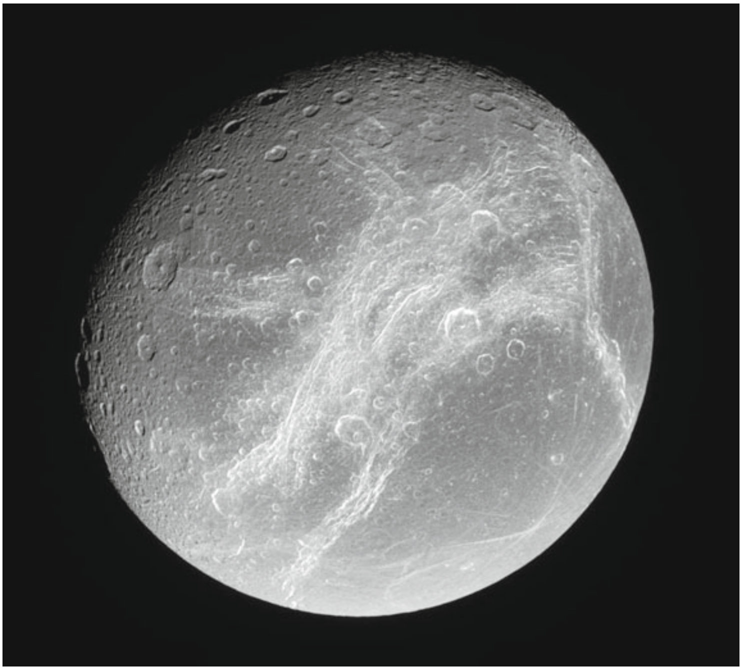

Fig. 6.28 Dione. This is a reprocessed image from *Cassini*, which highlights the so-called wispy terrain. (Credit: NASA/JPL/Space Science Institute)

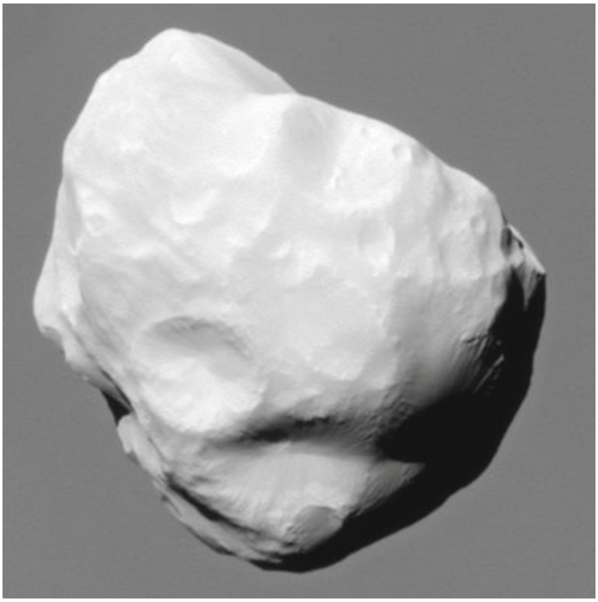

Fig. 6.29 Helene. The light-colored background of this picture is Saturn's cloud tops. (Credit: NASA/JPL/Space Science Institute)

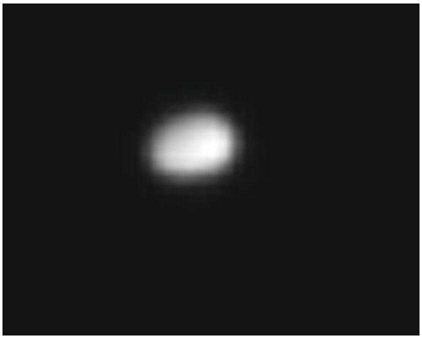

FIG. 6.30 Polydeuces (Credit: NASA/JPL/Space Science Institute)

FIG. 6.31 Rhea (Credit: NASA/JPL/Space Science Institute)

a bright ray system that may be one of the youngest craters on any of Saturn's moons. Tirawa is named after the creator god in Pawnee mythology, and Inktomi is named after Iktomi, a spider-trickster spirit in Lakota mythology.

Exosphere: There is a tenuous atmosphere, about 70 % oxygen, and the remaining amount is carbon dioxide. There are 1,000,000–10,000,000 molecules per cubic centimeter (depending on local temperature. That is 10e5 to 10e6. Compare to Earth's atmosphere of 1e20/cm^3 near sea level.)

Rings?: In 2008 it was announced by NASA that Rhea has its own ring system. It was not directly discovered, but its existence was inferred by a change in the flow of electrons moving around in Saturn's magnetic field. There is also a small ridge along the equatorial ranges (but not nearly as large or preeminent as that on Iapetus, see below) which supported the argument for the ring. *Cassini* made several attempts to detect ring(s) from various angles, but nothing was found. The search was abandoned, and now the *Cassini* and NASA teams are seeking new explanations for the observed changes. Some people believe the ring(s) only exist part-time, which would explain why sometime it is visible, and sometime nothing can be observed and it would explain the material which lies along the equators of a number of Saturnian moons.

Titan

Overview: Titan is the largest moon of Saturn, larger than either Earth's moon Luna or Mercury, and for a long time (until 1980) was thought to be the largest moon of the solar system. However, it was found that the atmosphere made up for some of that apparent bulk, and it is now known to be the second largest moon of the solar system at less than 87.8 % the diameter of Ganymede and less than 91.8 % of its volume. (The mass is also 90.8 % of Ganymede, since the density is only 0.0562 gm/cm^3 (<3 %) greater on Ganymede.) It is also one of the few places in the solar system where liquid exists at the surface, even if it is liquid methane. On Earth methane is usually a gas and flammable (Figs. 6.32, 6.33, and 6.34).

Names: Titan is named for the race of the Titans, a primeval race of powerful deities, and the offspring of the Earth (as Gaia), and Sky (as Uranus.) Many of the names of Titans were later given to the other Saturnian moons; this is the source of Atlas, Epimetheus, Hyperion, Iapetus, Phoebe, Prometheus, Rhea, and Tethys. Other notable titans include Cronus (the Greek equivalent of Saturn),

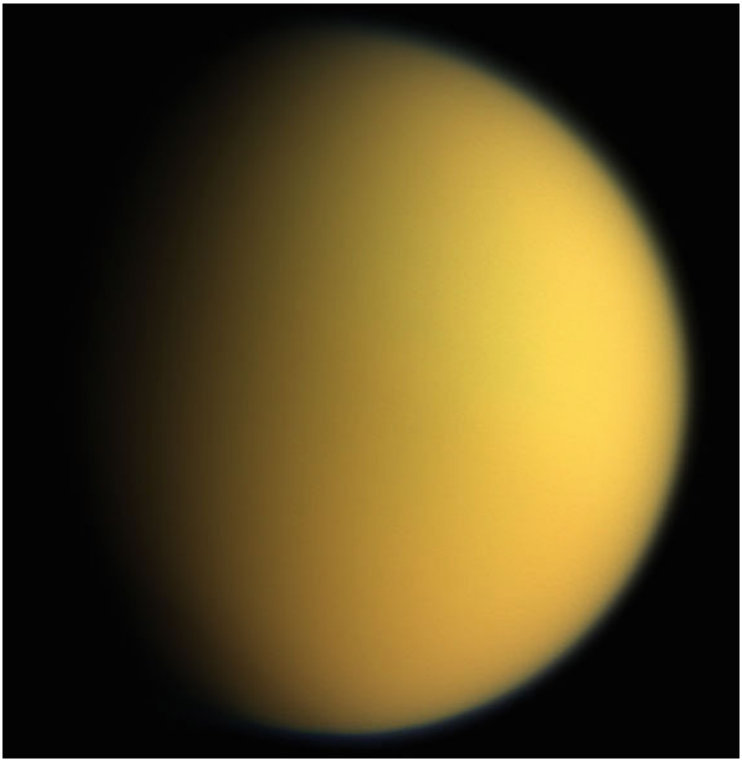

Fig. 6.32 Titan-True. This is a true color image of Titan. (Credit: NASA/JPL/Space Science Institute)

Helios (the Sun), Selene (the Moon, Luna), Theia (the hypothetical planetoid that hit the Earth creating Selene) and Themis (mentioned at the end of this chapter.) Titan was named such in 1837. From 1789 to 1837 it was called Saturn VI. It was also Saturn II and IV at times. Before that Christiaan Huygens called it *Saturni Luna*. Apparently he could come up with no better name for Saturn's moon than "Saturn's Moon."

Orbit: Much smaller moon Hyperion is in a 3:4 orbital resonance to Titan.

Interior: Titan is believed to be more planet-like than most small moons, with a solid core. There is also believed to be a liquid layer since radar reflectivity, spontaneous shifting of surface features, and a variable gravity field support this. The eutectic

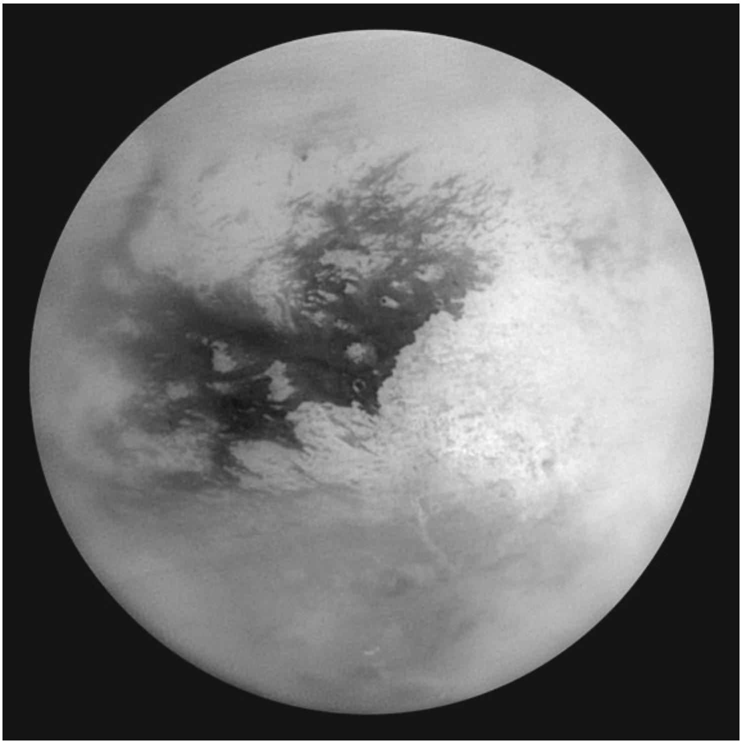

Fig. 6.33 Titan-Clear. This is a *Cassini* infrared image (to which the haze is transparent). The large dark region is called Shangri-la. (Credit: NASA/JPL/Space Science Institute)

mixture of ammonia and water (that is, the ideal mixture of the two compounds which solidify (freeze) at a lower temperature than any other mixture) can remain liquid even as cold as 176 K. There could also be (a) layer (s) of water under such compression that it crystallizes in the most efficient shape possible (four-sided tetragonal crystals). It is therefore believed that both solid and liquid layers lie beneath a rigid icy crust.

Atmosphere: Titan has an atmosphere the envy of any other moon. It is 98.4 % nitrogen as diatomic N_2, 1.4 % Methane (CH_4), and becomes more methane-enriched at lower altitudes (nearing 5 % close to the surface). The pressure at the surface is 146.7 kPa, 21.3 psi, 1100 torr, or 43.33 inches of mercury—it is about 1.45 atm (the air pressure at Earth's surface), so the atmosphere is signifi-

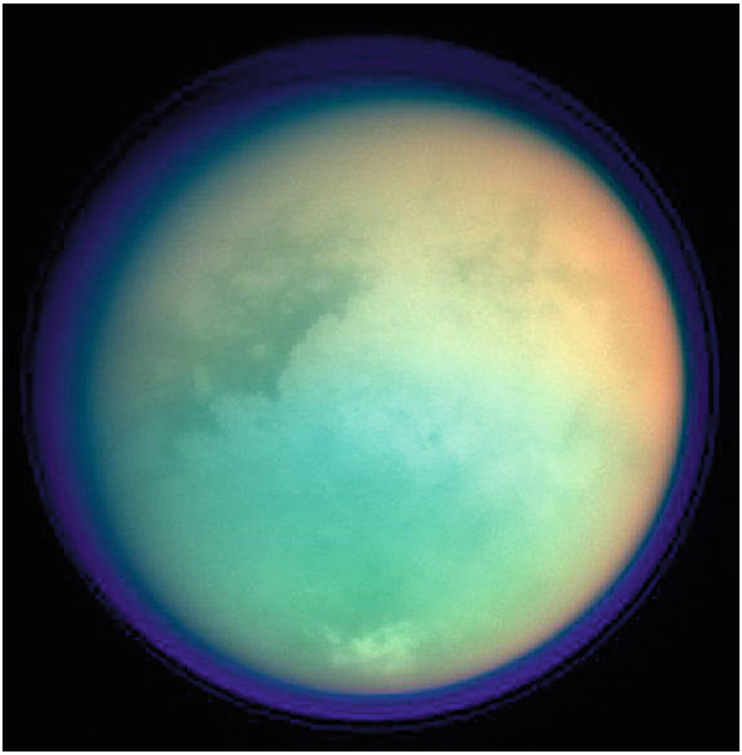

Fig. 6.34 Titan-Spectral. This is the spectroscopic image of Titan. Notice Xanadu (light) at *center-right*. (Credit: NASA/JPL/Space Science Institute)

cant, but does not *vastly* exceed our own. Titan is about 94 K on the surface—hot by interstellar standards. This is due to the greenhouse effect of the methane. The sunlight that reaches Titan's surface is about 1 % of the sunlight hitting the upper atmosphere. Titan also experiences light rain, mostly methane, ethane, and other simple organics. Cloud cover is often 1–8 % though methane haze is omnipresent.

Features: The surface of Titan is young. It has features that are about 100 million years old, ranging up to 1 billion years old. The youth of the features is due to the fact that the liquid methane lakes and rivers still process the surface of the moon. It is believed there are also cryovolcanoes (which shoot up ammonia and water onto the surface). *Cassini* uses infrared instruments (to which the haze is transparent) to image Titan. There are many features of about one and half dozen different classes, some with names of fantastical places such as Shangri-la (the large dark feature in Fig. 6.33) or Xanadu (the bright region in the center right of Fig. 6.34). Lakes, possible cryovolcanoes, and various dark features are all areas of ongoing research.

Observation and Exploration: Titan is not a naked eye target, but at magnitude 8.2+ it is a target for telescopes and the more powerful binoculars (power meaning light-gathering power). The glare from Saturn (and possibly the rings) can, however, make it a challenging target. In 1907 evidence of an atmosphere was detected, and in 1944 spectroscopy revealed the (relatively) large amount of methane. *Pioneer 11* (1979) found that Titan was too cold for life. *Voyager 1* passed Saturn in 1980. The mission controllers at JPL had to make a decision. They could fly by Titan and take a close look, or they could fly by Uranus and Neptune or they could swing around Saturn and fly out to Pluto (still considered a bona fide planet at that time). They chose the Titan option since it was thought to have value. Unfortunately, none of the instruments on *Voyager 1* could pierce the thick clouds, but the damage was done; that decision meant *Voyager 1* had to fly out of the ecliptic—and marked the end *Voyager 1*'s planetary mission (although *Voyager 1*, even to this date, is still sending us some valuable information about the extreme outer solar system, as it is now the furthest man-made object and will remain such, for the foreseeable future, as it is also the fastest departing space probe at this time.) *Voyager 2* was able to complete the mission to Uranus and Neptune, and is so far the best source of information we have on these planets and their respective moons.

In 2005 *Cassini* arrived near Saturn, and it carried the docked *Huygens* probe, itself bound for Titan. *Huygens* was released on December 25, 2004, after a final health check. It was completely powered down save for a 22 day timer set to wake up the probe 15 minutes before it would reach Titan's atmosphere. It woke up on schedule on January 14, 2005. It transmitted data for 150 minutes during descent and then for about 90 minutes on the surface. It carried six instruments, which were transmitted on two redundant radio bands, except in two cases: a wind speed experiment would only be transmitted on Channel A, and there were 700 pictures taken half-transmitted by each channel. However, due to a programming error, the Channel A recorder aboard *Cassini* was never turned on, so that data was lost. (Wind speed was later determined by looking at Doppler shifts in the transmission stream from *Huygens*. Note that there was a fatal error in the original design of the mission—*Cassini* was designed to understand *Huygens* through its (relatively) accelerated Doppler shift, but the data was not collected at the proper rate, which would lead to hopelessly corrupted information, but this was discovered and corrected *en route* by software patches, and a change in *Huygens'* trajectory which reduced the Doppler shift.) The data collected has value for itself, and may have additional value which can be used as a starting point for proposed future missions.

Life?: It has been hypothesized that life may exist on Titan. We have found liquid methane lakes and have been able to observe changes in them over time as they move. Such life would inhale diatomic hydrogen rather than oxygen (H_2 in place of O_2), and rather than process it with glucose ($C_6H_{12}O_6$) it would use acetylene (C_2H_2), and it would thus exhale methane (CH_4) instead of carbon dioxide (CO_2). The half-reactions would change from:

$$C_6H_{12}O_6(s) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l) \ldots \text{to}$$

$$3H_2(g) + C_2H_2(g) \rightarrow 2CH_4(g).$$

The Future: At some point in the distant future, Titan could become habitable. In about 5 billion years, the sun should expand into a red giant star. Depending on the exact conditions, Titan may become able to support liquid water on its surface. Some of the haze could be depleted, reducing the greenhouse effect. Together there could be an Earth-like environment able to support life, possibly for several hundred million years. Humans could live there or in time, its own intelligent life could develop.

Hyperion

Overview: Hyperion is not the largest moon of Saturn but it does take the award for most bizarrely shaped moon of Saturn. It is a minor moon with dimensions of 360.2 * 266 * 205.4 km.

Fig. 6.35 Hyperion (Credit: NASA/JPL/Space Science Institute)

It was discovered in 1848, and also takes the award for being the first moon to be found that was certainly <u>not</u> rounded. It is also the runner up for largest irregular moon, trumped only by Proteus (Neptune) (Fig. 6.35).

Characteristics: The largest crater is not necessarily the most obvious to the untrained eye. It is 121.57 km in diameter, and 10.2 km deep. It is clearly visible on the front face, and the stretched lines indicate the edges of the depression. (And although information on this is sketchy it appears to either be the crater Meri and/or the Bond-Lassell Dorsum. All sources of information are pretty unclear on this fact.) Hyperion has a density below 0.6, would easily float on water (better than even gaseous Saturn), and is largely made of water ice. It has a porosity of 46 % (meaning that 46 % of it is "voids" or "hollows.")

Orbit: Hyperion's orbit is chaotic. The moon wobbles so wildly that every time it is observed the orientation is different. It is the only moon that orbits chaotically. Furthermore, it's the largest "regular moon" that is not tidally locked to its primary. (Regular in this sense meaning close, prograde, has little inclination to the orbital plane, and is not a captured object.) There is a 3:4 orbital resonance between Titan and Hyperion.

Electromagnetism: According to a 2015 analysis of the first targeted flyby of Hyperion in 2005, *Cassini* was hit by a beam of electrons from the surface, indicating that this moon has an electromagnetic field. Until this discovery, our moon was unique in having such a field.

Iapetus

Overview: Iapetus is the largest body in the solar system which is known to not be in hydrostatic equilibrium, and is the third largest moon of Saturn (after Titan and Rhea). The density of Iapetus points to it being only about 20 % rock (Figs. 6.36 and 6.37).

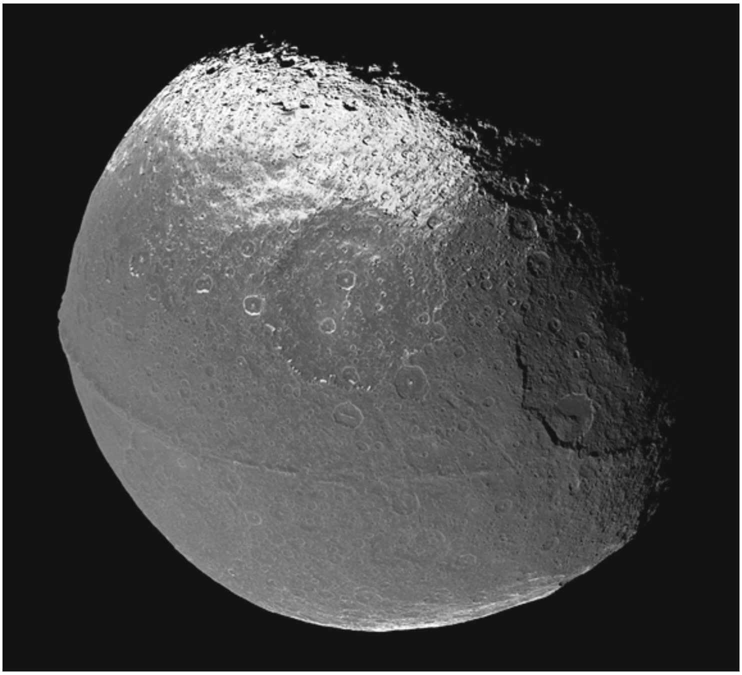

Fig. 6.36 Iapetus. This is the dark leading side of Iapetus. (Credit: NASA/JPL/Space Science Institute)

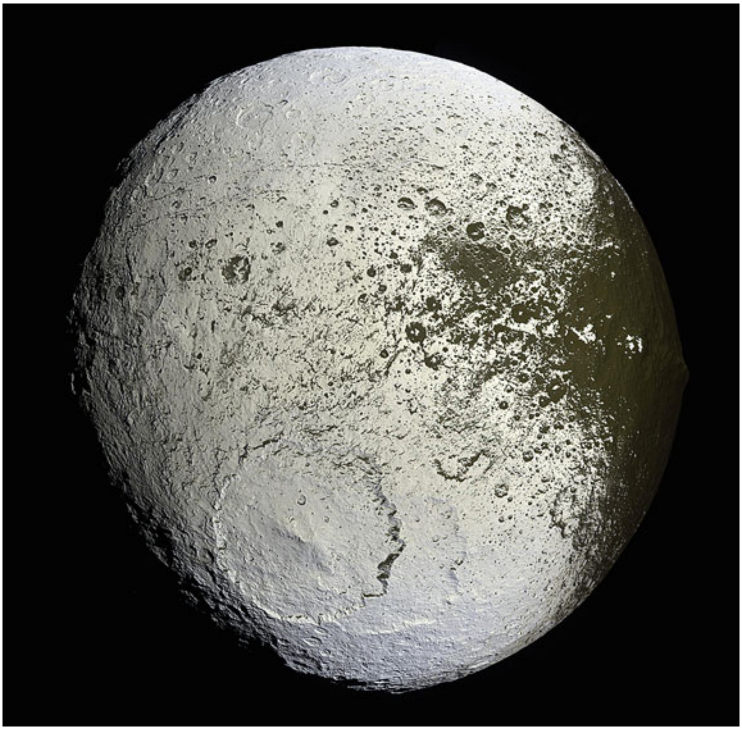

Fig. 6.37 Iapetus. This is the trailing side of Iapetus. Notice the striking color difference, and the ridge just peeking around the *right side*. (Credit: NASA/JPL/Space Science Institute)

Discovery: The moon was discovered in 1671, when it was seen on the west side of Saturn. When it traveled to the eastern side of Saturn it went unobserved. This continued every orbit for 34 years until it was finally detected on the eastern side of Saturn in 1705. Today any amateur astronomer wishing to view Iapetus should be made aware that while on the west side of the moon, we see the magnitude 10.2 trailing hemisphere; When it is on the east we side we see (or don't see) the magnitude 11.9 leading hemisphere—1.7 magnitudes is about a fifth as bright. The two pictures show two hemispheres, as different as day and night. The dust is about 1 foot thick (30 cm) in some areas observed by *Cassini*.

Orbit: As far as orbit goes, Iapetus is the Pluto of Saturn's system. Its inclination is larger than all other non-dynamical family related moons at 17.28° to the ecliptic, its orbit is also much further the Titan.

By comparison, the moons here are listed in order of closest to furthest, and Hyperion's orbit (semi-major axis) is 1,481,009 km compared to Iapetus' 3,560,820 km, at almost 2.4 times the orbit of Hyperion. (As a side note, Iapetus would offer an fair view of the rings (and incredible through any optical aid); from the other moons they are just thin sky scratches, all but invisible, and out-glared by Saturn with ease). Saturn has almost 2° of angular diameter from Iapetus.

Physical Features: Iapetus has some sizable craters, some over 350 km. The largest, Turgis, is 580 km, and is clearly visible on the trailing edge.

Equatorial Ridge: Iapetus may be most well-known for its two-tone appearance (see photos), yet more would likely say that is most well known for its equatorial ridge. At 20 km wide, 1300 km long, and 13 km high, it is a clearly visible feature even from a distance. It runs perfectly along the equator, but only on the front. There are four leading hypothesis to why there is such a ridge (remnant of an oblate shape, subsurface ice welling, former ring system, and ancient convective processes) but not one of the theories explain why it is limited to the equator AND only on Cassini Regio (the dark, leading hemisphere.) See Phoebe's ring, below.

Exploration: Iapetus's great distance from Saturn mean that *Cassini* does not get very good views of it. In 2007 *Cassini* closed to within 1300 km. It gets another opportunity in March 2015. Unfortunately such current data cannot be compiled into this edition. July 2015 update: It flew by Rhea in February 2015 and flew by Hyperion in May, 2015. It appears the 2015 opportunity was not utilized, possibly due to being out of position for it. There is only one *Cassini* spacecraft after all.

Phoebe

Phoebe is part of the Norse group but needs separate treatment (Fig. 6.38).

Overview: Phoebe (fē-bē) is 219 * 217 * 204 km. It is one of the Norse moons by dynamical family grouping, but is almost 12 times the diameter of Ymir (the next largest Norse). Phoebe is the largest body in <u>any</u> of the families, still over five times the diameter

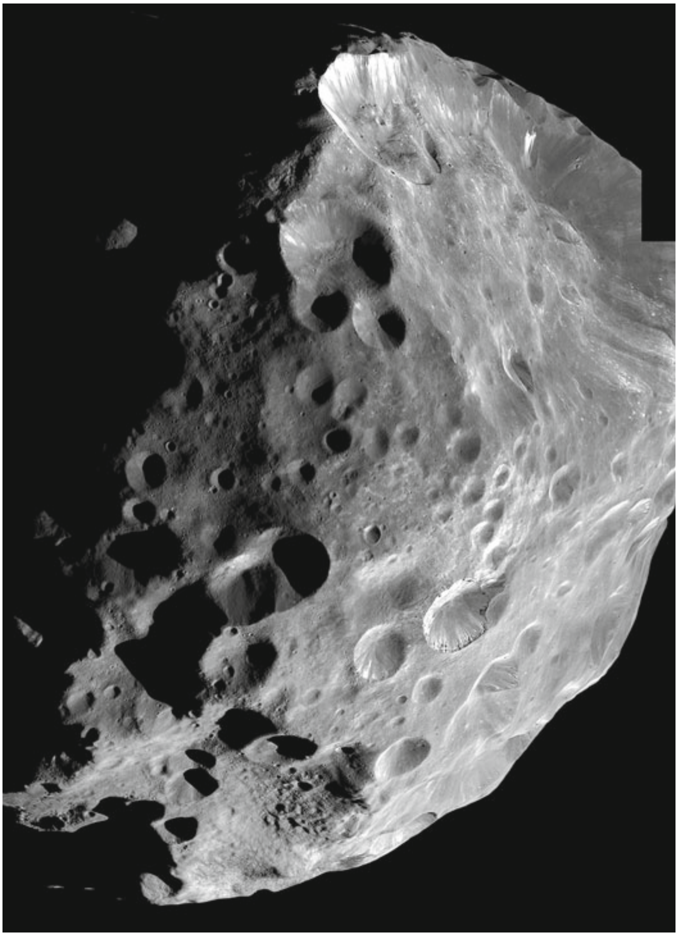

Fig. 6.38 Phoebe (Credit: NASA/JPL/Space Science Institute)

of Siarnaq. It is even larger than Himalia (Jupiter's largest moon in a dynamic family at 170 km). It was the most distant moon until many smaller ones were discovered in and since 2000 by the *Cassini* probe. It is irregular and retrograde.

Orbit and Exploration: The orbit of Phoebe is 3.6 times the orbit of even Iapetus. However, where such distances made study of Iapteus difficult, Phoebe was seen by *Cassini* on "the way in." So it has had some study done. But further close-up observations from this point would be impossible.

Physical Features: Phoebe is about 50 % rock. It is believed that this body, far smaller than some completely icy bodies, may also be more planet-like having a differentiated interior.

Origin: A number of theories have been put forth to explain Phoebe oddities. It is now thought by some that Phoebe may be a captured Centaur. If this is true, it is the first Centaur to be imaged as something other than a pinprick of light.

Phoebe Ring: In October 2009, Phoebe was found to have its own ring. The ring is rather amazing in and of itself. The phoebe ring is tilted 27 degree to the equator of Saturn (compare to Phoebe which, since it is retrograde, is tilted 173 degrees) and is about 20 times as wide as the planet itself is! This makes it far wider than the other rings. The main rings (D, C, B, A, G, and F) cover from 66,900 to 180,000 km, the E ring alone covers twice that from 180,000 to 480,000 km and a total combined width of 413,100 km. The Phoebe ring is believed to be present from 4,000,000 km to over 13,000,000 km in diameter—over 9,000,000 km, 20 times wider than all the rest put together. It is very thin, and invisible in visible wavelengths, but can be imaged in infrared. When the Phoebe ring was discovered it was suspected that it may be the source for the darkening of Iapetus. Judging from the semi-major axis it orbits at 7,121,640 km from Saturn, well inside the ring. But since Phoebe is about 3.6 times farther (25,911,518 km) it is well outside the ring. The name "Phoebe ring" refers to the source of the material not the location.

Notes: Saturn's three dynamical groups, unlike those of Jupiter, are not named after the largest moon therein. Therefore I do not usually list a prototype, but if there were a prototype it would be the first listed in the group, and the one listed in the table is also the first (since I list them in size, descending order.) The Norse subgroup is a bit different and is named after the largest. Since I describe Phoebe separately due to its size, I also listed Ymir.

Gallic Group

Core Members and Diameters (*in km*) (*4*): Albiorix (32), Tarvos (15), Erriapus (10), Bebhionn (6)

Four prograde, irregular moons.

Dynamics: Prograde, irregular, semi-major axis 16–19 million km, inclination 35–40°, eccentricities are all about 0.53.

Names: The names of the Gallic moons are taken from creatures and entities in Gallic (Celtic) mythology.

Inuit Group

Core Members and Diameters (in km) (5): Siarnaq (40), Paaliaq (22), Kiviuq (16), Ijiraq (12), Tarqeq (7)

Five prograde, irregular moons.

Dynamics: Prograde, irregular, semi-major axis 11–18 million km, inclination 40–50°, eccentricities 0.15–0.48.

Names: The names of the Inuit moons are taken from creatures and entities in Inuit mythology. The Inuit are a group of native people who live in extreme northern Canada.

Norse Group

The Norse group is not as homogeneous and consists of a number of subgroups. I have grouped the following members (of which there are 29 total) by subgroup.

Core Norse (Core) Members and Diameters (in km) (19): Phoebe (213), Ymir (18), Mundilfari (7), Suttungr (7), Thymr (7), S/2007 S2 (6), Greip (6), S/2004 S13 (6), Jarnsaxa (6), S/2004 S7 (6), Hati (6), Aegir (6), Surtur (6), Loge (6), Fornjot (6), S/2004 S12 (5), S/2007 S3 (5), S/2004 S17 (4), Fenrir (4),

Core Norse: *Skathi Members and Diameters (in km) (8)*: Skathi (8, prototype), Hyrrokkin (8), Kari (7), Skoll (6), S/2006 S1 (6), Bergelmir (6), S/2006 S3 (6), Farbauti (5)

Core Norse: *Narvi Members and Diameters (in km) (2)*: Narvi (7, subgroup prototype), Bestla (7)

Twenty nine retrograde, irregular moons.

Dynamics: Retrograde, irregular, semi-major axis 12–24 million km, inclination 136–175°, eccentricities 0.13–0.77. The Skathi orbit from 15 to 20 million km, inclined 147–158°. Navri is about 19.37 million km, with an inclination of 137°, and an eccentricity of 0.32; Bestla is 20.192 million km, with an inclination of 147°, and an eccentricity of 0.77.

Hati: In March 2013, *Cassini* measured Hati's synodic rotational period as about 5.5 hours, the shortest of any known moon. (Synodic period is the period of time between when an object reappears in a specific configuration from a given frame of reference; an example would be between one Martian opposition to another Martian opposition (from Earth) or one Venusian greatest western elongation to another Venus greatest western elongation (from Ganymede).)

Suttungr and Thymr: These two moons were named in IAU circular 8177, but without the "-r" ending. Later the ending was added to make the word the nominative case.

Fenrir: Fenrir has an apparent magnitude of 25, and an assumed albedo of 0.04. It is the dimmest known moon, and in fact is too dim to be seen even by *Cassini*. It was discovered with work done by the Subaru, and Gemini 8 m and the Keck 10 m telescopes.

Ymir: Ymir is one of the moons that takes more than 3 years to orbit Saturn (Ymir takes over 1315 days to orbit Saturn, 3.6 Earth years), Ymir is the largest one at 18 km. Since the rotation is under 12 hours, Ymir experiences over 2630 "days" in one orbit of Saturn.

Chiron

Chiron is hypothetical.
Chiron was announced by Hermann Goldschmidt in April 1861. It was never confirmed and was never seen again. An unrelated centaur (Uranian inner-grazer) discovered in 1977 now bears the designation 2060 Chiron.

Themis

Themis is hypothetical.

Themis was announced by William H. Pickering (discoverer of Phoebe). He claimed to have discovered the moon on plates taken in April 1904. Pickering tried to calculate an orbit, but the moon was never seen again. An unrelated main-belt asteroid discovered in 1853 now bears the designation 24 Themis. It is a large asteroid at about 198 km, and is the prototype of the Themistian asteroid family.

Others

S/2004 S 6: This intermittent spot may be a moon between 3 and 5 km. It is located in the F ring.

S/2004 S 3 and S/2004 S 4: These spots, later thought to be the same spot, but lost and rediscovered, may also be a moon between 3 and 5 km. It is also located in the F ring.

"*Peggy*": *Cassini* has captured images which suggest a moon may be in the process of forming from ring material and that this moon may be migrating outward. The discovery was announced 28 March 2014 in *Icarus*, and republished in other publications.

7. Uranus

The Uranus (YUR-uh-nus, no "a" sound, and stress on the first syllable) system is the smallest system, by mass. Neptune has fewer objects, but also has Triton (2.14e22 kg), of which the entire Uranian system masses less than 43 % (9.14e21 kg).

The Uranian system—by the numbers:

- 27 Definite moons (definite meaning confirmed orbits),
  - 0 Major moons, 2400 km in diameter
  - 4 Medium moons, 1000–1599 km,
  - 23 Minor moons between 10 and 999 km,
  - 0 Very minor moons not exceeding 10 km, and
- 13 Rings currently known
- 1 Trojan asteroid is known, 2011 QF_{99}
- 3 Inner grazers, including 2060 Chiron
- 2 Outer grazers
- 17 Numbered Uranus crossers (all Centaurs) (Table 7.1)

Note: This table includes 8 of the 27 objects. A representative of the 13 inner moons, the 4 medium moons (plus tiny Miranda), and then a representative each of the prograde and retrograde irregular moons (in theory; in practice there is only one prograde irregular moon, Margaret.)

Descriptions

This list follows increasing orbital distance. For families and groups the distance of the largest member of the group is used, and then listed in descending size.

Notes:

Very little is known abut any of these save for their magnitude and diameter. No probe has been out to Uranus since *Voyager 2* in 1986, and none is planned. Although some have been

J.A. Hall III, *Moons of the Solar System*, Astronomers' Universe,
DOI 10.1007/978-3-319-20636-3_7

TABLE 7.1 Uranus satellite data

	Puck	Miranda	Ariel	Umbriel	Titania	Oberon	Sycorax	Margaret
Represents	*Inner moons* (13)	(*Unique*)	(*Unique*)	(*Unique*)	(*Unique*)	(*Unique*)	*Retrograde irregular moons*	(*Unique*)
Adjective	Puckian	Mirandan	Arielian	Umbrielian	Titanian	Oberonian		
Albedo	0.035	0.32	0.23	0.1	0.17	0.14	0.04?	0.04?
Alternative names		Uranus V	Uranus I	Uranus II	Uranus III	Uranus IV		
Apparent magnitude	20.5	15.8	14.4	14.5	13.9	14.1	20.8	
Axial tilt	0°	0°		0°				
Composition (Atmosphere)					Carbon Dioxide mainly			
Dimensions	162 km	472 km	1158 km	1169 km	1578 km	1523 km	150 km?	20 km
Discovered by	Synnott, *Voyager 2*	Kuiper	Lassell	Lassell	Herschel	Herschel	Nicholson et al.	Sheppard, Jewitt
Discovery date	30 Dec 1985	16 Feb 1948	24 Oct 1851	24 Oct 1851	11 Jan 1787	11 Jan 1787	6 Sep 1997	29 Aug 2003
Eccentricity	0.00012	0.0013	0.0012	0.0039	0.0011	0.0014	0.5224	0.6608
Equatorial surface gravity	0.028 m/s	0.079 m/s	0.27 m/s	0.2 m/s	0.38 m/s	0.348 m/s		
Escape velocity	0.069 km/s	0.193 km/s	0.558 km/s	0.52 km/s	0.773 km/s	0.726 km/s		
Inclination	19′ 9.2″	4° 13′ 55.2″	15′ 36″	7′ 40.8″	20′ 24″	3′ 28.8″	159° (ecliptic)	57° (ecliptic)
Mass	2.9e18 kg	6.59e19 kg	1.353e21 kg	1.172e21 kg	3.527e21 kg	3.014e21 kg	2.3e18 kg?	5.5e15 kg?
Mean density	1.3 g/cm	1.2 g/cm	1.66 g/cm	1.39 g/cm	1.711 g/cm	1.63 g/cm	1.3 g/cm?	1.3 g/cm?

Orbital period	18 h 17 m 2 s	1 d 9 h 55 m 25 s	2 d 5 h 28 m 48 s	4 d 3 h 27 m 22 s	8 d 16 h 56 m 59 s	13 d 11 h 7 m 3 s	1288 d 6 h 53 m 12 s	1687 d 14 m 24 s
Rotation period	Synchronous	Synchronous	Synchronous	Synchronous?	Synchronous?	Synchronous?	3 h 36 m	
Satellite of	Uranus	Uranus	Uranus	Uranus	Uranus	Uranus	Uranus	Uranus
Semi-major axis	86,000 km	129,390 km	191,020 km	266,000 km	435,910 km	583,520 km	12,179,000 km	14,345,000 km
Surface area	82,400 km	700,000 km	4,211,300 km	4,296,000 km	7,820,000 km	7,285,000 km	70,000 km?	1300 km?
Surface pressure				None	<20 nbar	None		
Surface temperature (temp)	64 K	60 K	60 K	75 K	70 K	75 K	65 K?	65 K?
Volume	2,225,000 km	54,835,000 km	812,600,000 km	837,300,000 km	2,065,000,000 km	1,849,000,000 km	1,800,000 km?	4200 km?
Size family	Minor	Minor	Medium	Medium	Medium	Medium	Minor	Minor
Notes	No family High uncertainty	No family	No family	No family	No family	No family	No family High uncertainty	No family High uncertainty

? Less certain values

proposed, the soonest arrival for any proposed mission would be in the 2030s. Most of these moons were discovered by *Voyager 2*.

The images included are the finest that could be found, which says very little.

Moon Discoveries?

Herschel discovered Titania and Oberon on 11 Jan 1787. He then claimed to find four more on: 18 Jan 1790, 9 Feb 1790, 28 Feb 1794, and 26 Mar 1794. They were discovered and placed into orbits (one inferior to Titania, two between Titania and Oberon, and one superior to Oberon). These moons were then unable to be found again. When Lassell made his two discoveries in 1851, he found his moons did not match any of Herschel's "discoveries." His discoveries are now though to have been misidentified stars.

Inner Moons

Note: *This is not a true dynamical grouping; I just put them together since there is little significant to say about any of them* (Figs. 7.1, 7.2, 7.3, 7.4, 7.5, 7.6, 7.7, 7.8, 7.9, 7.10, and 7.11).

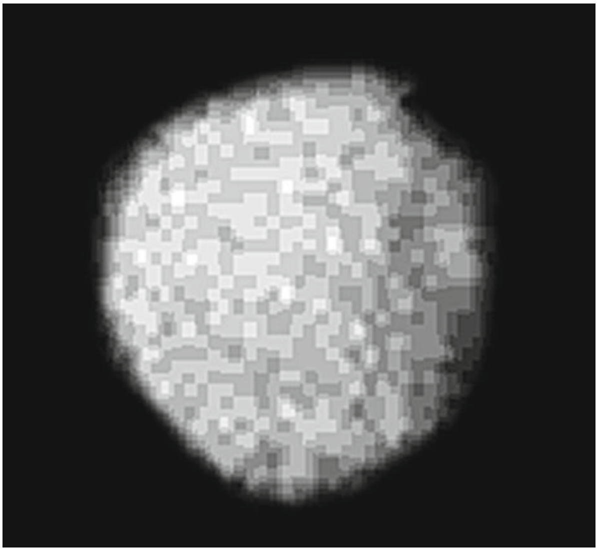

Fig. 7.1 Puck (Credit: NASA)

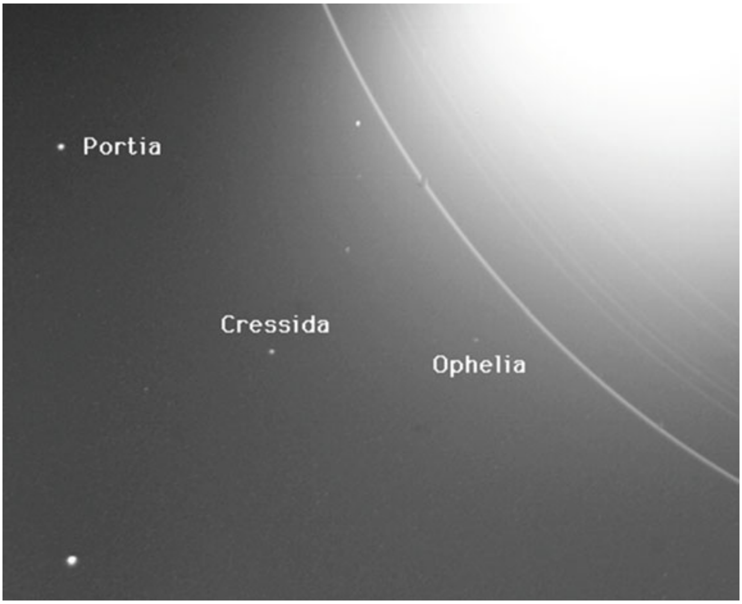

Fig. 7.2 Moon Trio. This image shows Portia, Cressida, and Ophelia (the moon Ophelia is hard to see in this image but it is there above the space between the "h" and "e" in its name.) (Credit: NASA)

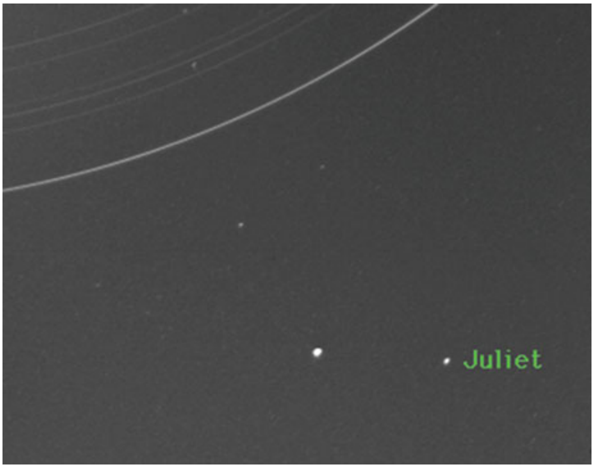

Fig. 7.3 Juliet (Credit: NASA)

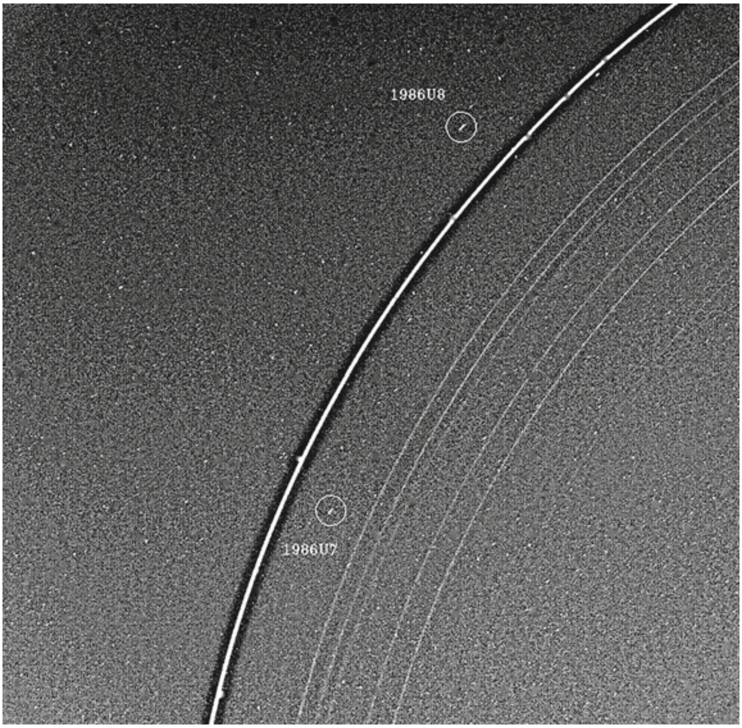

Fig. 7.4 Moon Duet. The moon at the *top* (1986 U 8) is Ophelia, the moon *below* (1986 U 7) is Cordelia. (Credit: NASA)

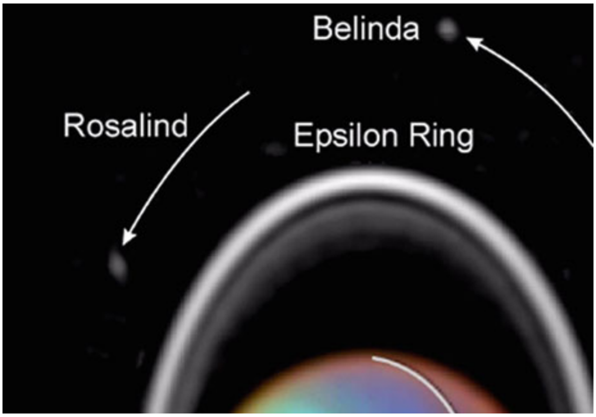

Fig. 7.5 Moon Duet. Belinda and the only image known of Rosalind (Credit: NASA)

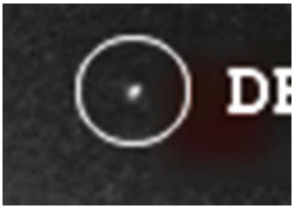

Fig. 7.6 Desdamona. The best image of Desdemona is this tiny fuzzy image. (Credit: NASA)

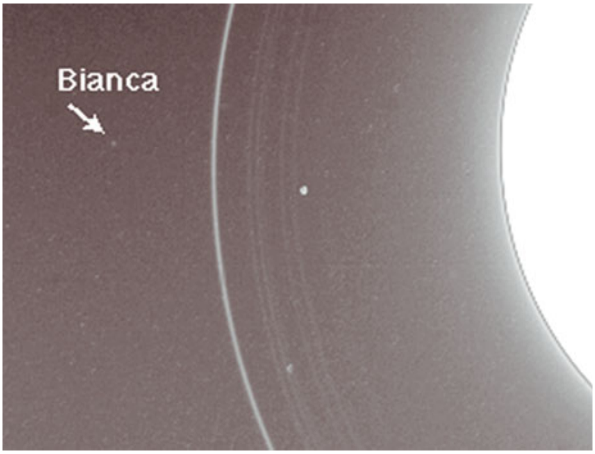

Fig. 7.7 Bianca (Credit: NASA)

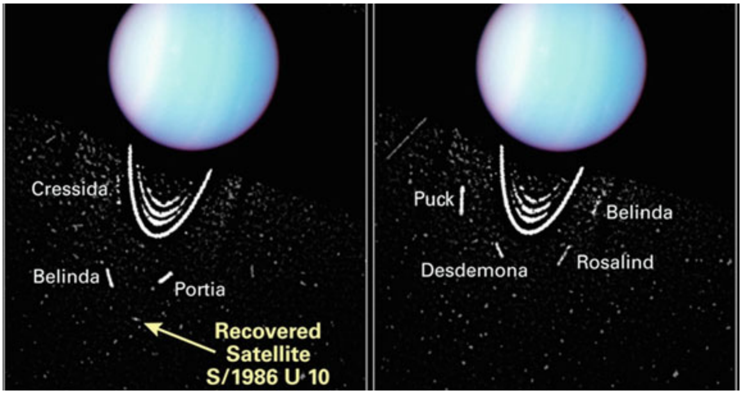

Fig. 7.8 Perdita. One image includes Puck, Desdemona (which is better than its own image) Belinda, and Rosalind. The *left image* which includes Cressida, Belinda, and Portia is one of the few images where Perdita is visible. It is a very shy moon and tends to hide. (Credit: NASA)

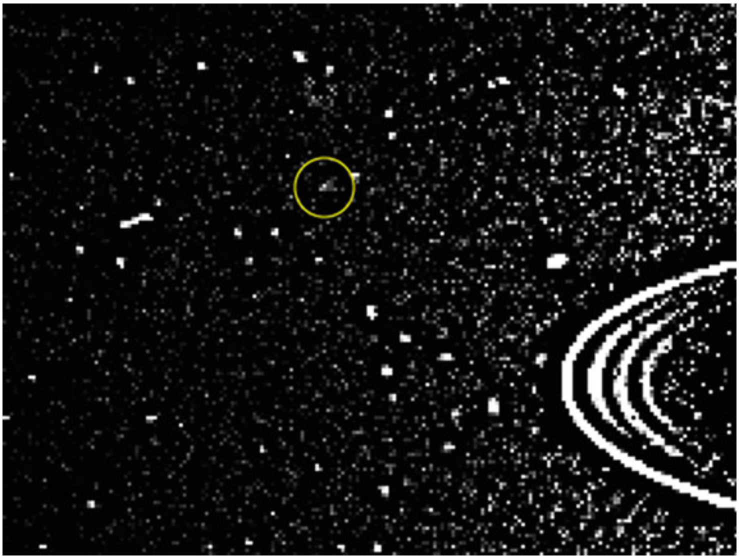

Fig. 7.9 Mab (Credit: NASA)

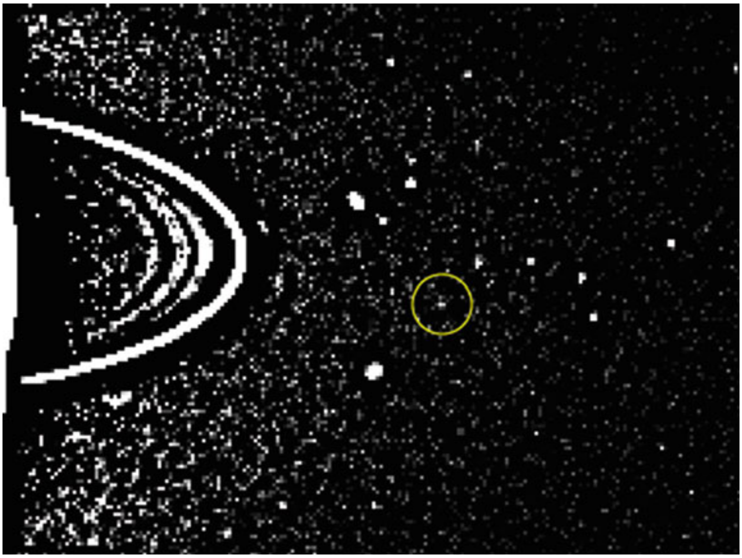

Fig. 7.10 Cupid (Credit: NASA)

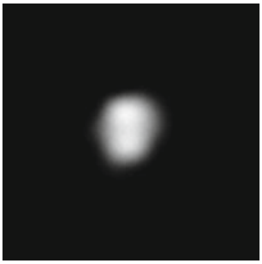

Fig. 7.11 Belinda (Credit: NASA)

Core Members and Diameters (in km) (13): Puck (162), Portia (135), Juliet (94), Belinda (90), Cressida (80), Rosalind (72), Desdemona (64), Bianca (51), Ophelia (43), Cordelia (40), Perdita (30), Mab (25), and Cupid (18)

Thirteen prograde, regular moons.

Cordelia and Rosalind: Little information is known, shepherd moons of the Epsilon (ε) ring, Cordelia close to a 5:3 resonance with Rosalind.

Ophelia: Little information is known, shepherd moon of the ε ring

Cressida and Desdemona and Juliet: One of these satellites may collide with Desdemona within the next 100 million years or so. (Cressida and Juliet cannot collide as they are separated by Desdemona.)

Portia Group: The Portia group is a dynamic family consisting of Bianca, Cressida, Desdemona, Juliet, Rosalind, Cupid, Belinda and Perdita.

Cupid: Cupid at magnitude 14.21 and with an albedo of only 0.07 was too dim to be seen by *Voyager 2*. The moon was discovered in 2003.

Perdita: This moon was photographed in 1986 by *Voyager 2*. However, it was not discovered on photographic plates until 1999. It was later lost until 2003 when Hubble spotted it. Perdita is in a 43:44 resonance with Belinda, and close to an 8:7 resonance with Rosalind.

Mab: Like Perdita, Mab was photographed by *Voyager 2*, but not detected. After Perdita was discovered, the rest of the images were reexamined, and Mab was found. Mab is believed to be the source for replenishing the outermost ring, the Mυ (μ) ring. Larger moons collect their own dust, and smaller moons have insufficient surface area (in general) to replenish rings—Mab is in a sweet spot in this respect, not too big, not too small.

Miranda

Overview: Miranda is largest of all the minor moons of Uranus, and while Hyperion is the most bizarre moon of the Saturnian system, Miranda puts it to shame (Fig. 7.12).

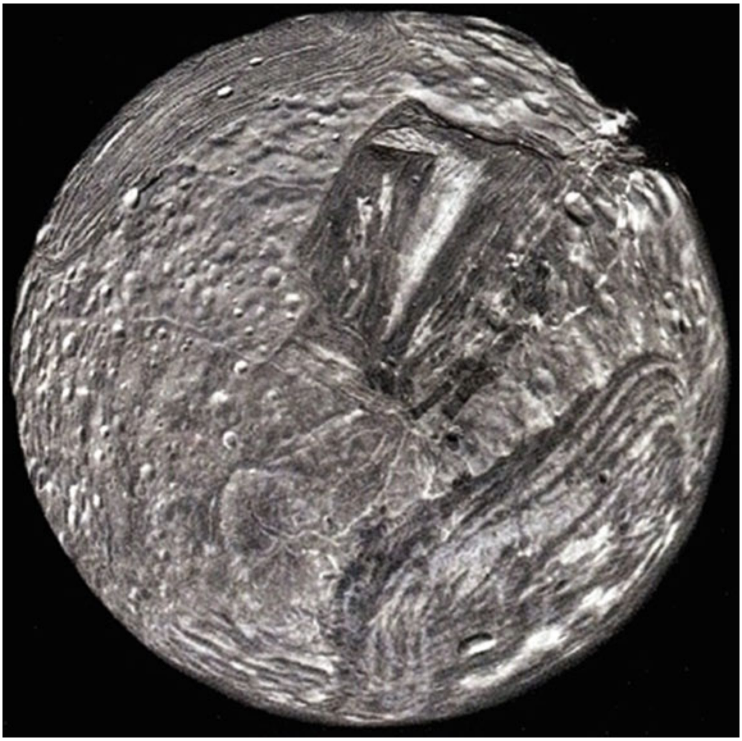

Fig. 7.12 Miranda. After taking note of the chevron ice cliff, note the flatter terrain at the *top* of this image and the unusual terrain at the *bottom*, which reflect the *top* in megalithic proportions. This image has been reduced in brightness to bring these features into sharper focus. (Credit: NASA)

Physical Features: The various features of Miranda include the coronae, which are the raised grooved features north and south, and the graben that would naturally fall between such features. It is thought that the chevrons (V-shapes) prominent in the center of the image are cryovolcanic features, ice cliffs thrust up from beneath the surface. Unfortunately, when *Voyager 2* passed the planet, due to Uranus' orbital inclination of around 90°, and the moon's proximity to the equator (inclination of about 4°, which is still about ten times that of any other moon so close), *Voyager 2* could capture nothing other than the moon's south side. We have no clue abut what the north face might hold or hide, and with the soonest possible mission still over a decade away, it is likely to stay that way.

Inclination: The question has been raised as to why Miranda has such a high inclination. It is thought that at one time Miranda had a 3:1 orbital resonance with Umbriel. At another point in its past it is thought it had a 5:3 resonance with Arial. The mechanism of escape from this is thought to be from a secondary resonance, and this may have pulled it out of a very nearly equatorial orbit into one with a higher inclination.

Ariel

Overview: Ariel is the fourth largest moon of Uranus. The *Voyager 2* flyby was able to image only 35 % of its surface. This moon is thought to be equal parts rock and ice due to its density of 1.66 g/cm^3 (Fig. 7.13).

Orbit: In the past, Ariel was in a 5:3 resonance with Miranda. It was also previously in a 4:1 resonance to Titania. These were both about 3.8 billion years ago, and likely caused heat resulting in no more the about 20 K.

Interior: It is not known whether or not Ariel has a rocky core. If it does, we can determine that is must take up 64 % of the radius. A subsurface ocean seems unlikely either way.

Observation and Exploration: Ariel has a bond albedo of 0.23, the highest or any Uranian satellite. The apparent magnitude is 14.4. Whereas Pluto (magnitude 13.65—less than 16) is visible through

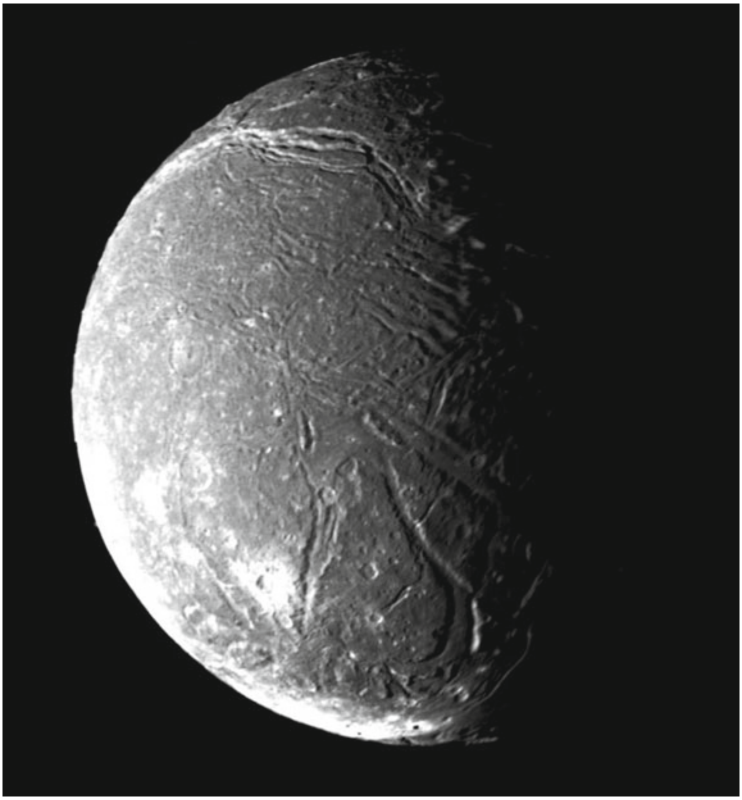

Fig. 7.13 Ariel (Credit: NASA)

large scopes (greater than 12 in, or 300 mm), Ariel is not visible to telescopes even larger, due to the glare of Uranus. Once again we must rely on *Voyager 2*'s grayscale photographs. As with Miranda, only the south could be imaged.

Physical Features: Features include crater fields, plains, and troughs. The largest trough is the Kathina Chasma, which is 15–50 km wide and with a convex floor which rises up 1 or 2 km in the center. This Chasma is 620 km long that we can see. It passes into the hemisphere that *Voyager 2* could not see, so must be longer. The ridged terrain contains individual ridges 25–70 km wide, up to 200 km long and from 10 to 35 km apart.

Umbriel

Overview: Umbriel is the third largest moon of Uranus by radius, and fourth by mass. (Ariel is 19.4 % more dense, 840 meters wider, and is thus 51.4 % more massive.) The *Voyager 2* flyby was able to image 40 % of its surface. This moon is thought to be about 60 % ice, and has a 1.39 g/cm^3 (Fig. 7.14).

Orbit: In the past, Umbriel was in a 1:3 resonance with Miranda, although now it is not in any resonances.

Interior: Umbriel is not likely to have a rocky core. If it does, we can determine that is must take up 54 % of the radius. A subsurface ocean seems unlikely either way.

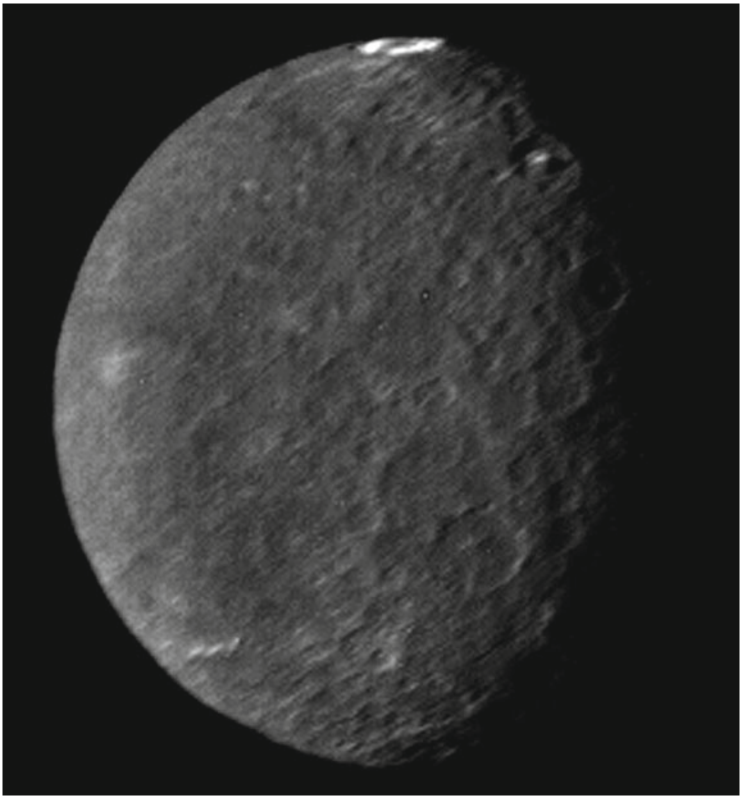

Fig. 7.14 Umbriel. This poor fuzzy image is among the best we have of Umbriel. (Credit: NASA)

Observation and Exploration: Ariel has a bond albedo of 0.1, the lowest of any regular Uranian satellite (that is a satellite in a close, prograde orbit with low inclination, which is not captured). The apparent magnitude is 14.5, making it the dimmest as well. We must rely on *Voyager 2*'s grayscale photographs; only 40 % (all in the south) could be imaged.

Physical Features: Whereas Ariel's features are crater fields, plains and troughs, Umbriel has only craters. It is the second most heavily cratered surface in the Uranian system (only Oberon has more craters). The largest crater on the surface seen is 210 km Wokolo (named after a West African devil-type spirit). Wunda (named from Australian Aboriginal mythology) is a 131 km crater, with a floor covered with bright material; it is right on the edge of the available images. All craters have peaks; none that we know of have rays.

Titania

Overview: Titania is the largest moon of Uranus by radius, and eighth largest in the solar system (by mass). *Voyager 2*'s flyby was able to image 40 % of its surface, but only 24 % with enough precision for mapping. This moon has about a 1.71 g/cm^3 density, making it the densest Uranian satellite; hence it cannot be more than 50 % ice. (As a side note, many of the smaller moons density cannot be known for certain, but they that can are close to 1.3. So any unknown is assumed to be 1.3.) (Figs. 7.15 and 7.16).

Orbit: Water ice signatures are (slightly) stronger on Titania's leading side. It is also the last major moon in Uranus' magnetosphere, and thus its trailing side lies within the plasma torus which runs throughout Uranus' magnetosphere. Oberon, which lies outside this zone, does not display the same characteristic asymmetry.

Interior: Titania may have a rocky core. If it does, we can determine that it can be up to 520 km, 66 % of the radius, and 58 % of the mass. A subsurface ocean may be possible, but not enough is known about the geologic history of Titania to hypothesize further.

Observation and Exploration: Ariel has a bond albedo of 0.17. The apparent magnitude is 13.9, making it a bit brighter which is why

Fig. 7.15 Titania (Credit: NASA)

it was discovered sooner (1787). We must rely on *Voyager 2*'s grayscale photographs once more; only the south side could be imaged.

Physical Features: Titania's features are craters, chasmata (or canyons), and rupes (or scarps; cliff escarpments). It has fewer craters than some moons meaning the surface is younger. The largest crater on the surface seen is 326 km Gertrude (named after a charter in Shakespeare's *Hamlet*). There is a basin which is 4 km larger which may be a degraded crater, but it is unsure whether or not it is a genuine crater. Many of the craters have flat floors and central peaks. A few have rays. Messina Chasma is named after an Italian town in Shakespeare's *Much Ado about Nothing*, and is 1500 km from the equator to the South Pole, up to 20–50 km wide ad up to 5 km high.

Atmosphere: The atmosphere is similar to some other moon's atmospheres, but nitrogen and methane would easily escape to space. The carbon dioxide level is hard to measure. It is thought it may exist as dry ice, and may sublimate in the sun, and move to the darker region of Titania, since (like Uranus) light will shine on

Fig. 7.16 Titania, high resolution. This picture shows Messina Chasma, center stage, on the terminator. (Credit: NASA)

one pole for 42 years before a weird day and night cycle takes over and then it shines on the other for 42 years. Uranus' and Titania's ecliptic is unusual: the sun touches every point on the sky at some time and can reach zenith over the equator and both poles over an entire Uranian year cycle!

Oberon

Overview: Titania's twin moon is Oberon. It is the second largest moon of Uranus, 4 % smaller than Titania by radius, and (due to reduced radius and density) massing about 15 % less than Titania. In Shakespeare's *A Midsummer Night's Dream*, these characters are

Fig. 7.17 Oberon (Credit: NASA)

married, which is likely how they appeared to William Herschel. It is also ninth largest in the solar system (by mass). *Voyager 2*'s flyby was able to image 40 % of its surface. This moon has a 1.63 g/cm^3 density, making it the second densest Uranian satellite. It is about half ice (Fig. 7.17).

Orbit: Oberon is the closet moon not traveling inside Uranus' magnetosphere. While the closer moons may show darkening in the trailing hemisphere due to the effect of the plasma torus, Oberon should not show the trait. If it does show this trait (whenever it may be discovered what the north hemisphere looks like) it would have to be explained by a different mechanism. We would also need to reexamine the other moon to find out which mechanism(s) explained the effect on them.

Interior: Oberon may have a rocky core. If it does, we can determine that it can be up to 480 km, 63 % of the radius, and 54 % of the mass. A subsurface ocean may be possible, but again not enough is known about the geologic history of Oberon for anything more to be said.

Observation and Exploration: Oberon has a bond albedo of 0.14. The apparent magnitude is 14.1. Again, we must rely on *Voyager 2*'s grayscale photographs. Only the south could be imaged.

Physical Features: Oberon's features are similar to Titania's once again (craters, chasmata, and rupes). It has more craters than any other Uranian moon and in fact cannot have more craters—at this point if any crater was created an old one would be erased. There is no part of Oberon which is crater free. Therefore, the surface must be far older than Titania (or any other Uranian moon's surfaces. This is supported by the lack of orbiting within of the plasma torus, since that would naturally generate heat.) The largest crater on the surface seen is 206 km and named Hamlet (named after Shakespeare's eponymous *Hamlet*). Some *Voyager* images show an 11 km peak near the southeastern limb of the moon. If this is a central peak of an impact basin, then by using the size of other basins the impacts would be 375 km in diameter! There are chasmata, but none are long, wide, or deep enough to warrant a long description in this work.

Irregular Moons

Note: *Uranus may or may not have dynamic groups. Some of these do show similar inclinations and distances, therefore there may be dynamic groups. See below for possible groupings* (Figs. 7.18, 7.19, 7.20, 7.21, and 7.22).

Included "Members" and Diameters (*in km*) (*8*): Sycorax (150, largest), Caliban (72), Prospero (50), Setebos (48), Stephano (32), Franscisco (22), Ferdinand (20), Trinculo (18).

Eight retrograde moons, from 18 to 150 km. Many of these were not found (or even seen) by *Voyager 2*, but instead discovered by large earth based telescopes. The images which are available reveal no details. For example Sycorax was discovered by the 200 inch hale telescope in 1997. Also, all of these moons seem to be captures.

Sycorax: Sycorax is the closest irregular moon, but it is over 20 times more distant than Oberon.

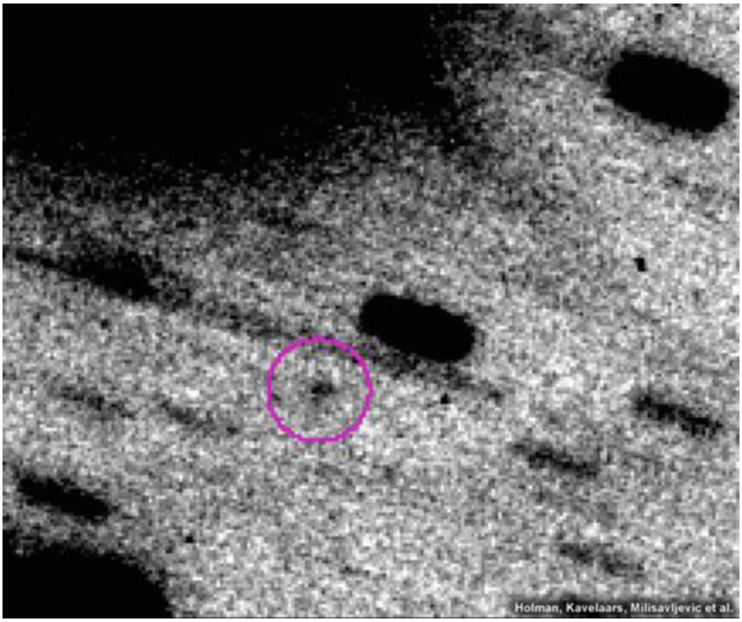

Fig. 7.18 Francisco (Credit: NASA)

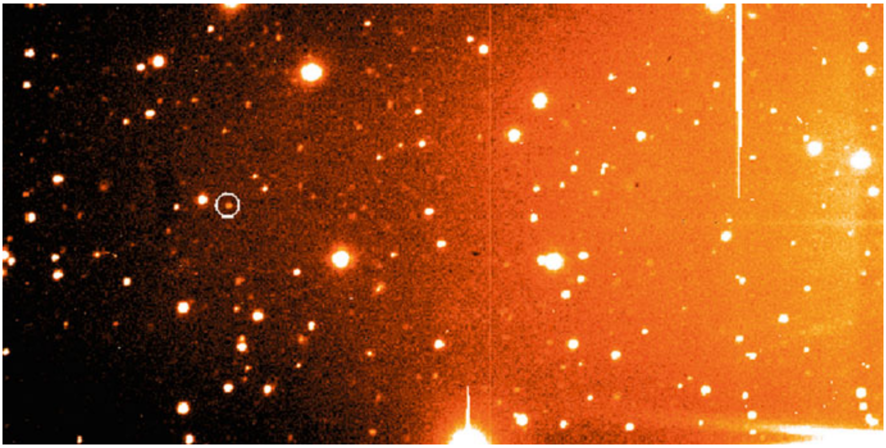

Fig. 7.19 Caliban (Credit: NASA)

Fig. 7.20 Stephano (Credit: NASA)

Sycorax, Setebos, and Prospero: These three may be a group, which would be called the Sycorax group. However the largest member is light red while the smaller two are greyer. This hurts the argument but a group is still possible.

Caliban, Stephano, and Francisco: These three may be a separate group, which would be called the Caliban group. However the largest member is light red while the smaller two are greyer (again). This hurts the argument but a group is still possible (again).

Ferdinand: This moon is in the most distant orbit from Uranus.

Margaret

Margaret is not part of any group.

Margaret is a prograde, irregular moon of Uranus. In fact, it is *the* prograde irregular moon of Uranus. It is only 20 km in diameter and its orbital eccentricity is 0.7979 (as of 2008). In 2008 it was the most eccentric orbit of any known moon. Nereid's (Neptune) mean orbital eccentricity is greater the Margaret's (0.7507 compared to

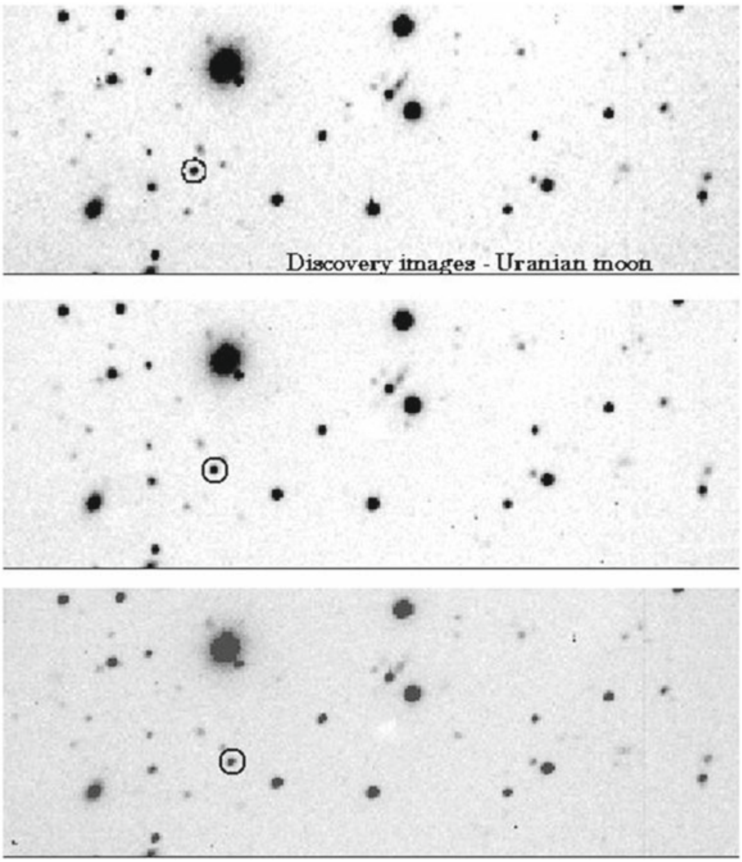

Fig. 7.21 Sycorax (Credit: NASA)

Margaret's 0.6608) but in 2008 Margaret's was unusually high. Its inclination is 57°, and if it were even 3° higher it would enter into a Kozai instability. That is to say, the orbit would be perturbed by the sun so the moon would experience a libration of it argument of pericenter; that being the angle between the ascending node and the apoapsis. It also has effects on the inclination and the eccentricity. If the moon were in a Kozai instability it would either spiral inward to be torn apart, collide into another moon or the planet itself, or exceed the Hill sphere and escape, becoming just one more Centaur. Its current periapsis procession takes 1.6 million years.

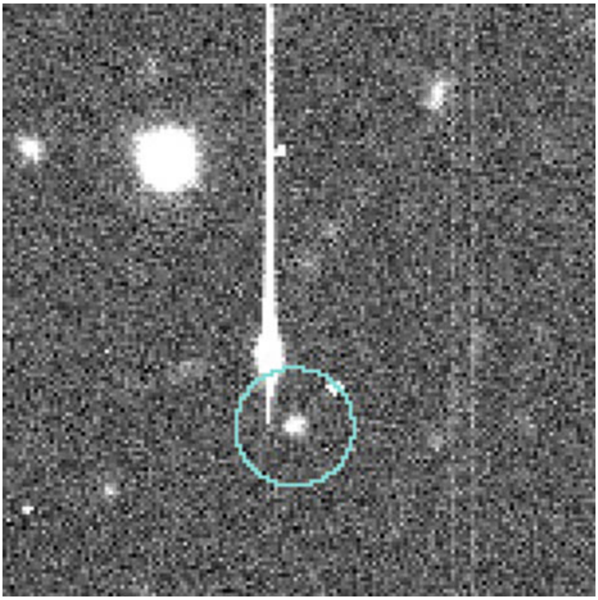

Fig. 7.22 Setebos (Credit: NASA)

8. Neptune

The Neptune system is the smallest system, by quantity (at least among the giant planets). The Neptunian system—by the numbers:

- 14 Definite moons (definite meaning confirmed orbits)
  - 1 Major moon, 2400 km in diameter or greater (Triton at over 2700 km)
  - 0 Medium moons, 1000–1599 km
  - 13 Minor moons between 10 and 999 km
  - 0 Known very minor moons not exceeding 10 km
- 5 Known rings
- 9 Trojan asteroids
- 0 Inner grazers
- 2 Outer grazers, (26308) 1998 SM_{165}, 28978 Ixion
- 31 Numbered Neptune crossers (including 134340 Pluto) (Table 8.1)

  Note: This table includes 5 of the 14 known objects.

Descriptions

This list follows increasing orbital period. For families and groups the distance of the largest member of the group was used, and listed then in descending size.

Inner Moons

(Figs. 8.1, 8.2, 8.3, 8.4, 8.5, 8.6, and 8.7).

Note: *This is not a true dynamical grouping*.

J.A. Hall III, *Moons of the Solar System*, Astronomers' Universe,
DOI 10.1007/978-3-319-20636-3_8

Table 8.1 Neptune satellite data

	Proteus	Triton	Nereid	Halimede	Sao
Represents	*Inner moons* (7)	(*Unique*)	(*Unique*)	*Retrograde irregular moons* (4) *3 excluding Triton*	*Prograde irregular moons* (3) *2 excluding Nereid*
Adjective	Protean	Tritonian	Nereidian		
Albedo	0.096	0.76	0.155	0.006	0.006
Alternative names		Neptune I			
Apoapsis	117,709 km		9,655,000		
Apparent magnitude	19.7	13.47			
Average orbital speed	7.623 km/s		934 m/s		
Axial tilt	0°	0°			
Composition (Atmosphere)		Nitrogen			
Dimensions	424 * 390 * 396	2707 km	340 km	62 km	44 km
Discovered by	Synnott	William Lassell	Gerard P. Kuiper	Holman et al.	Holman et al.
Discovery date	16 Jun 1989	10 Oct 1846	1 May 1949	14 Aug 2002	14 Aug 2002
Eccentricity	0.00053	0.000016		0.2646	0.1365
Equatorial surface gravity	0.07 m/s	0.779 m/s	0.072 m/s?		
Escape velocity	0.17 km/s	1.455 km/s	0.156 km/s?		

Inclination	31′ 26.4″	156° 53′ 6″	32° 33′	112° 42′ 43.2″ (to ecliptic)	53° 28′ 58.8″ (to ecliptic)
Mass	4.4e19 kg	2.14e22 kg	3.1e19 kg		
Mean density	1.3 g/cm?	2.061 g/cm	1.5 g/cm?		
Orbital period	1 d 2 h 56 m 8 s	5 d 21 h 2 m 40 s*	360 d 3 h 16 m 8 s	1879 d 1 h 55 m 12 s	2912 d 17 h 16 m 48 s
Periapsis	117,584 km		1,372,000 km		
Rotation period	Synchronous	Synchronous	11 h 31 m 12 s		
Satellite of	Neptune	Neptune	Neptune		
Semi-major axis	117,647 km	354,759 km	5,513,787 km	16,611,000 km	22,228,000 km
Surface area		23,018,000 km			
Surface pressure		<1.9 Pa			
Surface temperature (temp)	51 K?	38 K	50 K		
Volume	34,000,000 km	10,384,000,000 km			
Size family	Minor	Major	Minor	Minor	Minor
Notes	Inner moons	Retrograde irregular moon *This is retrograde	Prograde irregular moon High uncertainty	Retrograde irregular moons Very high uncertainty	Prograde irregular moon Very high uncertainty

? A guess

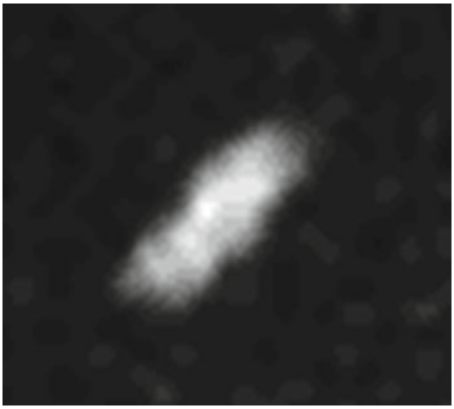

Fig. 8.1 Naiad (Credit: NASA)

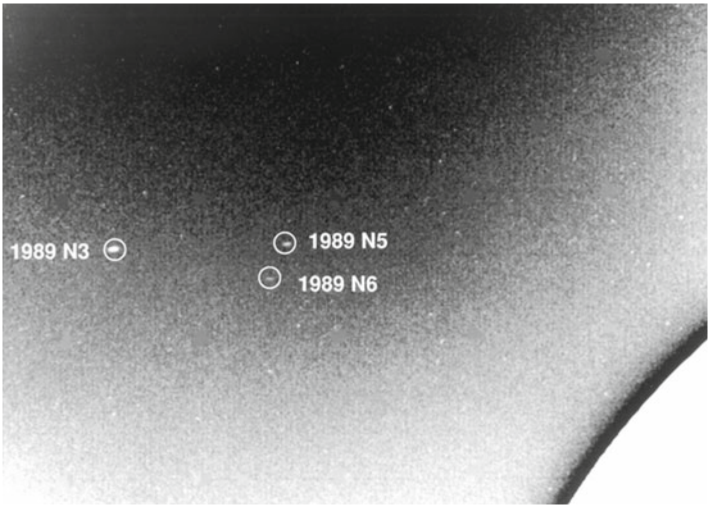

Fig. 8.2 Neptunian Moon Trio. This shot shows *Despina* (*S/1989 N 3*), *Thalassa* (*S/1989 N 5*) and *Naiad* (*S/1989 N 6*). (Credit: NASA. The author also wishes to thank Stephen Edberg for clarifying the incorrect caption.)

Core Members and Diameters (*in km*) (7): Proteus (420), Larrisa (194), Galatea (176), Despina (150), Thalassa (82), Naiad (66), S/2004 N 1 (<20)

Naiad: Naiad is orbiting closer to Neptune than its fluid Roche limit, and is expected to break up long before it reaches the rigid Roche limit due to its density which is assumed to be 1.3 g/cm^3 (see the Chap. 3 for a full treatment of this subject.)

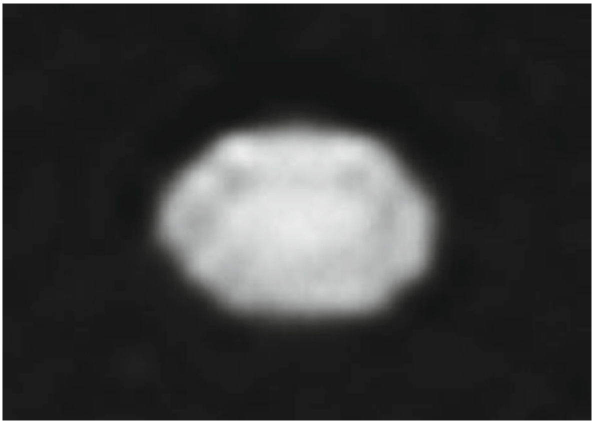

Fig. 8.3 Despina (Credit: NASA)

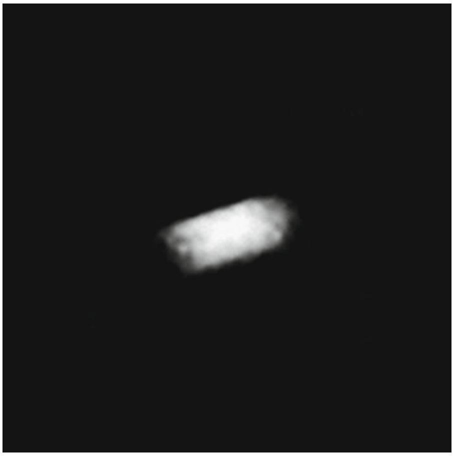

Fig. 8.4 Galatea (Credit: NASA)

Naiad, Thalassa, Despina, Galtea, and Larissa: These moons were perturbed when Triton was captured by Neptune. They are now all within the synchronous orbit limit. They will either fall within the fluid Roche limit and break apart (if weak enough), fall below the rigid Roche limit and break up certainly (if made of rigid material), or crash into Neptune whole (regardless of whether or not they break up at all). No matter how you slice it, these five moons are doomed.

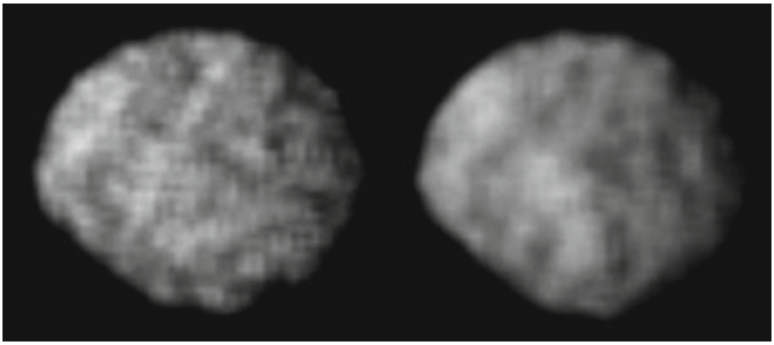

Fig. 8.5 Larissa (Credit: NASA)

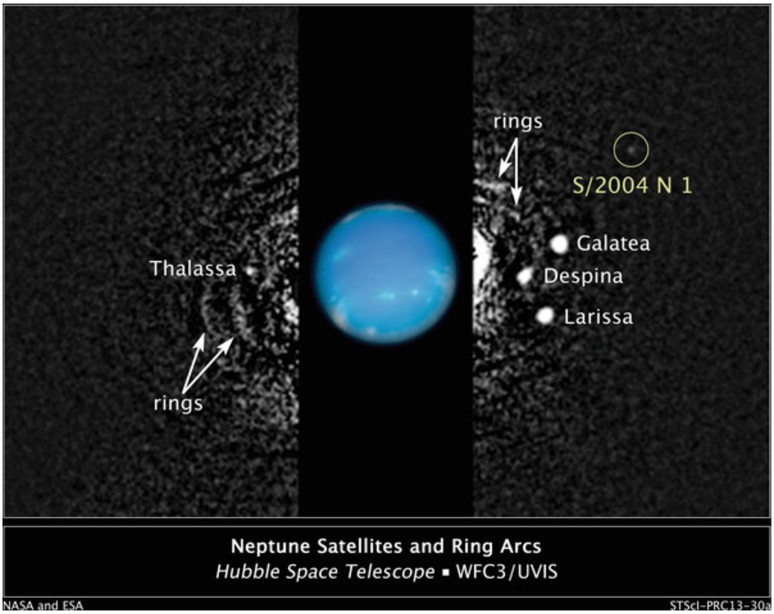

Fig. 8.6 S/2004 N 1 (Credit: NASA)

S/2004 N1, *Proteus*: These moons are being accelerated and will eventually end up in higher orbits.

Proteus: Actually quite a bit is known about Proteus. Proteus is about 210 km, and mostly spherical. It has variation of 20 km. Scientists believe it is close to as large as it can be without being

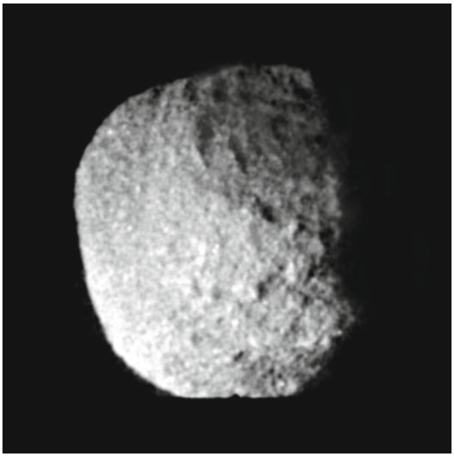

Fig. 8.7 Proteus (Credit: NASA)

truly spherical. Mimas (Saturn) is less massive and is more of an ellipsoidal shape. Proteus is heavily cratered. The largest crater on the surface seen is the 230–260 km Pharos (named after the island where the shape-changing sea god Proteus reigned). It is 10–15 km deep with a central dome feature. Other features include shock features and tidal features.

Triton

Overview: Triton is by far the largest moon of Neptune. Hyperion and Miranda look quite unusual, but Triton looks unusual and is in many ways more bizarre than the others. Trion is the seventh largest moon in the solar system and (on its own) comprises almost 99.6 % of all the mass of Neptune's moons! (Figs. 8.8 and 8.9)

Capture: Triton did not form in its current position. It is believed that Triton was one of two large objects living out in the Kuiper belt. Triton is a bit larger than Pluto and is of similar composition. The two may well share a common origin and could even be the objects that were traveling together, though so could any other object in a resonance with Neptune. When the two objects traveled by Neptune, one was captured and decelerated, falling into a circular orbit and losing energy. Due to the law of conservation of energy when one object loses energy, another object must gain it,

Fig. 8.8 Triton (Credit: NASA)

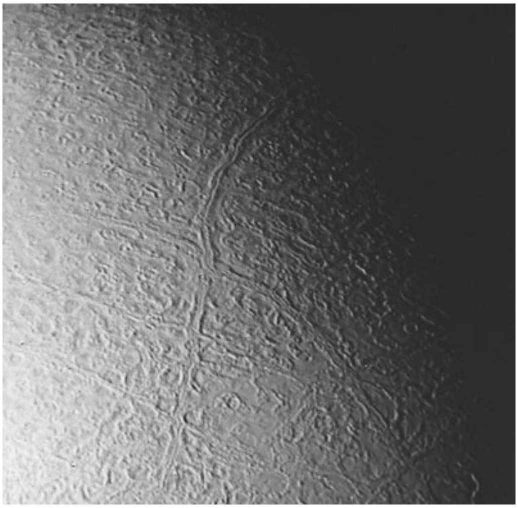

Fig. 8.9 Triton, close-up. Notice the famous "Cantaloupe Terrain." (Credit: NASA)

so its traveling companion gained the energy and was subsequently ejected into the Kuiper belt, scattered disc, detached disc, Oort cloud or out of the solar system altogether. Without a companion, no theory can explain Triton's nearly circular orbit. The capture changed many conditions near Neptune. First off, when it arrived it ripped any moons that were nearby (all of them really) to shreds. Then the rubble surrounding Neptune eventually accreted to form the moons we see today; now, Naiad, Thalassa, Despina, Galtea, and Larissa are within the liquid Roche limit, and are inside the synchronous orbit limit, so they all spiral inward. When they cross the rigid Roche limit they will either be ripped to pieces (again), or they will fall into Neptune, or more likely both. Triton's arrival doomed all these moons, as well as itself (see below).

Rotation: Euporie (Jupiter) and Phoebe (Saturn) have retrograde rotations, and rotate in over 540+ days, Francisco (Uranus) has a 250+ day rotation and Triton has a retrograde orbit that takes only 99 <u>hours</u>! In the time it takes for Francisco to complete one retrograde orbit, Triton completes 84.8!

Orbit: Two of the best arguments for capture are Triton's composition and its orbit. Its orbit is retrograde, and it is easily the largest moon and the only major moon to orbit in a retrograde direction. Many of the captured irregular moons of Jupiter, Saturn, and Uranus orbit in retrograde motion, but none are anywhere near as large—the largest one is Saturn's Phoebe, which is less than 8 % of the diameter and less than 0.04 % of the mass of Triton. Neptune has an axial tilt of 30° so its equator is similarly tilted. Triton's orbital inclination is 130°. Now, since $130-30=100$, then relative to Neptune's orbital plane, Triton's orbit *appears* to be a polar orbit, which perturbs the other moons even more. Its orbit is nearly circular (99.9984 % circular.) It is also 7.7 % closer to its primary than Luna is to the Earth, and Neptune weighs much more than the Earth, 17 times more. And Triton weighs more than Luna. Triton destroyed and further doomed other moons, and Neptune has in turn doomed Triton. The planet is expected to pass by the Roche limit or crash into Neptune's atmosphere in about 3.6 billion years, and then Neptune's thin and tenuous ring system will look more like Saturn's ring system. As with some other moons, it's more massive than all moons smaller than itself combined.

Composition: Triton is similar to Pluto in composition, thought larger than Pluto or Eris. The surface of Triton is 55 % frozen nitrogen ($N(s)$), 15–35 % water ice ($H_2O(s)$), and 10–20 % dry ice (frozen carbon dioxide, $CO_2(s)$). There are also traces of methane ($CH_4(s)$) and carbon monoxide ($CO(s)$) ices. After Triton was captured it would have stayed molten for a billion years due to tidal heating, which is more than enough time for Triton to have developed a fully differentiated interior. After the orbit became circular this source of heat would eventually disappear. Triton may well have a subsurface ocean and if so then life is a possibility, but there are full discussions of this in multiple other places in this book.

Atmosphere: Triton has a very thin atmosphere; the surface pressure is about 1.5–1.75 Pa (compare to Earth's surface pressure of over 101 kPa). The atmosphere is primarily diatomic nitrogen (N_2). This is natural since nitrogen is the most common ice on the surface. The nitrogen ice forms crystalline hexagons, and not cubic blocks from which scientists can infer the temperature must be at 36.5 K (where such a change occurs). Vapor pressure equilibrium may allow the temperature to be as high as 40 K, but either way it is actually colder the Pluto's (average) temperature which is 44 K. Triton does have a layered atmosphere much like earth with a troposphere, thermosphere and exosphere, but it also lacks a stratosphere (and mesosphere). In the 1990s an occultation of Triton allowed us to determine the air pressure. The base air pressure was about 1.4 Pa, which is about 16.5 μbar. The increase was measured as 19 μbar by some and 40 μbar by others. Triton was also having the warmest summer in 100 years, experiencing a 5 % rise in global temperature. So Triton's temperature increased by about 2 K. Between 1910 and 2010, global warming on Earth accounts for about 1 K. I guess we need to convene an "Intergovernmental Panel on Climate Change on Triton," since Earth is now not the only planet with global warming problems.

Surface Features: Triton is geologically active. Triton has two types of terrain. *Voyager 2* has observed a south polar cap. It found nitrogen ($N(s)$) and methane ($CH_4(s)$) ices scattered about it by impacts and by geysers. The North Pole is expected to be similar, but *Voyager 2* was unable to observe it when it passed Neptune.

Cantaloupe Terrain: The western half of Triton is covered with features termed so-called "cantaloupe terrain." Cantaloupe terrain covers most of Triton's western hemisphere and indeed could cover most of the surface (except for the south polar cap. The north is unknown as no photograph has ever caught it due to lighting conditions, but may or may not be similar to the south cap). Cantaloupe terrain is made of dirty water ice, forming long raised grooves called sulci. The areas between the grooves are known as cavi and are about 3–40 km in diameter. It's thought this is caused by diapirism, the rising of less dense material to the surface through the stratum of other material. When the material comes up to the surface it freezes. This ongoing action also makes impact craters rare and short-lived features. Some of the sulci cross into the south polar area (due to cryovolcanos located there). It is thought the north area must be similar.

Nereid

Overview: Nereid is the third largest moon of Neptune (at 340 km), surpassed by Triton and Proteus. However it was discovered in 1949, 40 years before *Voyager 2* discovered Proteus (Fig. 8.10).

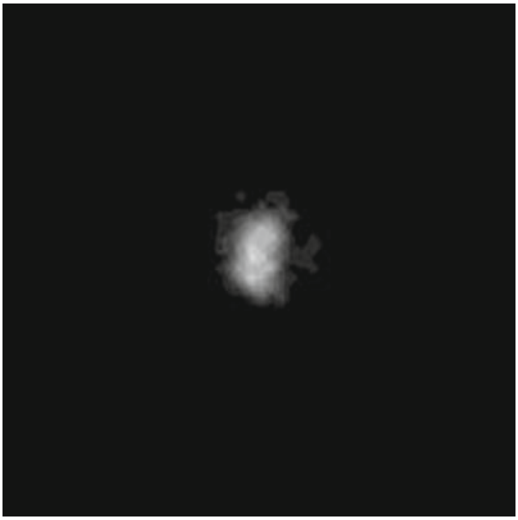

Fig. 8.10 Nereid (Credit: NASA)

Orbit and Capture?: Nereid brings its prograde orbit as close as 1,372,000 kilometers, and as far as 9,655,000 km, meaning it is over 75 % out of round. The eccentric orbit has led to some scientists suggesting it may be a captured KBO or asteroid (a Centaur). Such an orbit does not require a companion; only circular orbits demand such. However its spectrum does not match the typical KBO dwarf planets, nor does it match Pholus, Chiron, or Chariklo (semi-typical Centaurs) which suggests it formed in place around Neptune. It now seems that it did so, and the highly eccentric elliptical orbit was caused by the capture of Triton. The length required by Nereid to make one orbit is 360 days. Halimede may be a fragment of Nereid separated from the parent body in a collision.

Retrograde Irregular Moons

Note: *This is not a true dynamical grouping; I just put them together since there is little significant to say about any of them* (Figs. 8.11 and 8.12).

Core Members and Diameters (*in km*) (*3–4*): Triton (2705.2—while technically a retrograde irregular, captured satellite this certainly deserves separate treatment above), Halimede (62, prototype), Neso (60), Psamathe (40).

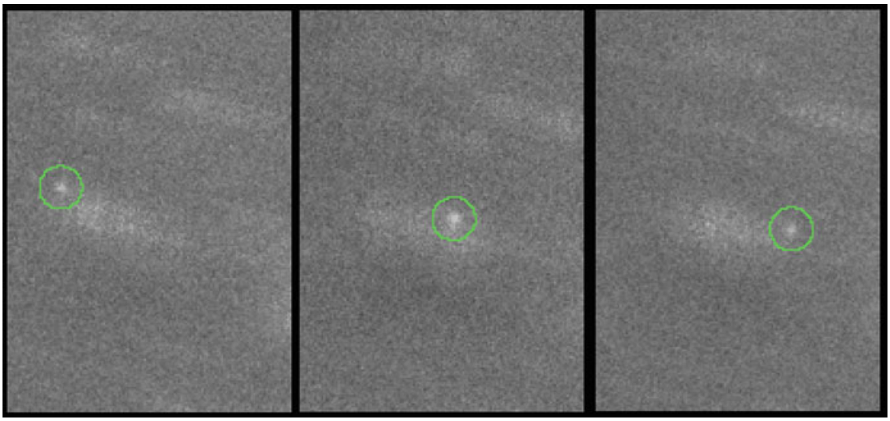

Fig. 8.11 Halimede (Credit: NASA)

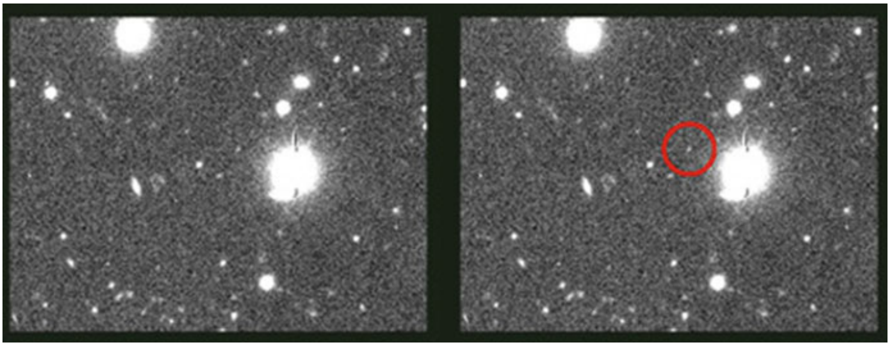

Fig. 8.12 Psamthe (Credit: NASA)

Three retrograde, irregular satellites (excluding Triton).

Halimede: Halimede has been shown to be very similar to Nereid. Numerical simulations show that there is a 41 % chance that it either collided with Nereid in the past or was part of it at one time. If so, these two would be a true dynamic group. Of course, if Triton did tear everything apart and they re-accreted they are all mixed couples.

Neso and Psamathe: These two moons have such similar orbits that the pair may have a common origin in the breakup of a larger moon. If so these two would comprise a true dynamic group. They may also be a mixed-up conglomeration, like Halimede and Nereid.

Psamathe: This moon is similar to Neso, but is lighter and has less gravity. The dynamics suggest this moon is close to being able to escape Neptune using the theoretical stable separation for a body in a retrograde orbit.

Neso: Neso is the most distant satellite from any planet; at 72 million km, it is further from Neptune than Mercury is from the Sun! It also has a period over 26.67 years.

Prograde Irregular Moons

Note: *This is not a true dynamical grouping.*

Core Members and Diameters (in km) (2–3): Nereid (340—while technically a prograde, irregular, and possibly captured satellite, this also deserves brief treatment above), Sao (44), and Laomedeia (42).

Three prograde, irregular satellites (including Nereid).

Sao: Sao is also in a Kozai resonance (see section "Margaret" (Chap. 7) for a full treatment of this.)

9. Distant Minor Planets

The Distant Minor Planets include the cis-Neptunian objects, and the trans-Neptunian objects (TNOs). The TNOs include Kuiper Belt Objects (KBOs), Scattered Disc Objects (SDOs), Detached Objects, and Oort Cloud Objects (OCOs).

Cis-Neptunian Objects

The cis-Neptunian objects include the Centaurs and the Neptune Trojan asteroids. The Centaurs are asteroids with orbits beyond Jupiter and as far as Neptune; no traditional Centaurs are known to have moons. (42355 Typhon does has a moon, even though it is not a traditional Centaur; its orbit is highly eccentric and unstable, and it is an inner-grazer of Neptune. And 10199 Chariklo while lacking a moon does have two rings.) Five of these objects will be discussed: Chariklo; (65489) Ceto; Phorcys; Typhon; and Echidna. The Neptune Trojans are found in the L_4, and L_5 point of Neptune and none are known to have satellites, although with objects so distant and so small, it is possible to just be unaware of them. It is possible, indeed likely (inferred from four of Jupiter's Trojans), that some do have moons.

TNOs

In the outer solar system, 81 trans-Neptunian objects have a moon, two have two moons and one (Pluto) has five (although one is questionable, it begs inclusion here). That is 81 objects and 87 moons.

The trans-Neptunian objects include Kuiper Belt Objects (KBOs), Scattered Disc Objects (SDOs), Detached Objects, and Oort Cloud Objects (OCOs). This latter body's existence is still theoretical, and was proposed in 1950 by Dutch astronomer Jan Oort after the idea was first hypothesized by Estonian astronomer

J.A. Hall III, *Moons of the Solar System*, Astronomers' Universe,
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Ernst Opik in 1932. It is believed to comprise two different regions, a disc-like inner cloud and a spherical outer one. These are thought to be populated by icy planetesimals between roughly 2000 and 100,000 AU from the Sun, a vast expanse of space. Originally closer to the center of the Solar System, gravitational effects from the giant planets would have continually pushed it further out, to the point where it would now be subject to the gravitational pull of the larger galaxy. Presumably this would be the origin place of long-period and Halley-esque comets, as well as Jupiter-family comets and centaurs. However it has yet to be confirmed by observation. If the Oort cloud does exist, which is now thought likely, it would primarily be composed of comets, none of which have moons. There are speculations that a hypothetical red or brown dwarf named Nemesis might reside in the zone of the Oort cloud as well. It was paleontologists and not astronomers who first imagined the existence of Nemesis as a possible undetected companion star, hoping it might explain the Earth's extinction rate periodiocity, but no sky surveys have found any evidence for it.

Trans-Neptunian Objects (TNOs), by the numbers:

- 81 TNOs have satellites
  - 17 TNOs have names (including Pluto, Eris, and Haumea)
  - 23 TNOs have numbers and provisional designations
  - 41 TNOs are not numbered and have only provisional designations
- 3 Centaurs
- 10 Resonant objects
  - 4 Are 1:2 resonant;
  - 2 Are 4:7 resonant
  - 1 Each is 2:5, 3:5, 3:8, and 5:8 resonant
- 52 Are Cubewanos
- 8 Are Plutinos
- 7 Are Scattered Disc Objects (SDOs)
  - 1 Is an SDO Dwarf (Eris)
  - 1 Is an SDO Haumea-class object (Haumea)
- 2 Are Extended Scattered Disc Objects
- 2 Have no known further definition

- Around these 81 TNOs are 87 moons (79+4 for Pluto, +1 for Haumea, +1 for 1999 TC_{36}; Chariklo is not counted in either number)
  - 19 Of the moons are named (Table 9.1).

Many of these (and, arguably, 134340 Pluto included) are actually binary. An object could be called binary if the barycenter (the common center of orbits) lies above the surface of the primary; another definition could be where both bodies are tidally locked to each other (see Charon for a discussion of these); another definition could be purely based on size, such as "anything above 75 %". However, notable objects are notable objects, regardless of what humanity terms them as. Humanity can change Pluto's designation to a planet, dwarf planet, plutino, jack-o-lantern, or jack-in-the-box... but no matter what we call it here on Earth; Pluto will not fall from the sky or pack up and move away from the solar system in disgrace and embarrassment. Pluto is still Pluto even if you call it 134340 Pluto.

Objects (by class) are ordered by number. Also note that many values are so small, and at such distances from the Earth they are uncertain. These numbers are mostly scientist's best guesses.

Centaurs with Moons

JPL considers a Centaur to be a small solar system body (i.e., an asteroid) with an unstable orbit and a semi-major axis between 5.5 and 30.1 AU.

Two Centaurs have moons, and one has a ring system, making it the fifth such object *known* to have a ring (not including Rhea). Primary sizes include 162 and 223 km (42355 Typhon and 65489 Ceto). 10199 Chariklo is 248 km and the largest Centaur confirmed (1995 SN55 may have been larger at 295 km in diameter when it was discovered in September, but as it was 39 AUs it was "lost" in October. JPL estimates it aphelion as 39.1, and DES estimate it at 91 AU, which just shows the poorly understood dynamics of its orbit.) Secondary sizes include 89 and 171 km (Echidna and Phorcys). Separations includes 1618 and 1840 km (42355 Typhon and Echidna, and 65489 Ceti and Phorcys).

Table 9.1 Distant minor planet satellite data

	Class	Subclass	Selected reso-nances	Number	Name	Diameter (primary) (in km)	Moon name or designation	Diameter (secondary) (in km)	Separation (km)
*	Centaur			10199	Chariklo	248	None	–	–
*	Centaur			42355	Typhon	162	Echidna	89	1628
*	Centaur			65489	Ceto	223	Phorcys	171	1840
*	Cubewano			50000	Quaoar	1070	Weywot	81	13,800
	Cubewano			55637	2002 UX25	665		210	4770
*	Cubewano			58534	Logos	82	Zoe	67	8217
*	Cubewano			66652	Borasisi	126	Pabu	103	4528
*	Cubewano			79360	Sila	249	Nunam	236	1777
	Cubewano			80806	2005 CM105	160		121	2700
	Cubewano			82157	2001 FM185	138		120	3130
*	Cubewano			88611	Teharonhiawako	178	Sawiskera	129	27,670
*	Cubewano			120347	Salacia	854	Actaea	286	5619
	Cubewano			123509	2000 WK183	106		101	2366
	Cubewano			134860	2000 OJ67	138		108	2357
	Cubewano			148780	Altjira	246		221	9904
	Cubewano			160091	2000 OL67	153		116	7800
	Cubewano			160256	2002 PD149	186		155	24,400
*	Cubewano			174567	Varda	705	Ilmare	361	4200
	Cubewano			275809	2001 QY297	169		154	9960
	Cubewano			303712	2005 PR21	227		137	3600
	Cubewano			364171	2006 JZ81	122		78	32,300
	Cubewano				1998 WW31	148		123	22,620

	Cubewano	1999 OJ4	75	72	3267
	Cubewano	1999 RT214	100	69	3310
	Cubewano	1999 RY214	125	76	1500
	Cubewano	1999 WV24	110	96	1420
	Cubewano	1999 WW31	148	123	22,620
	Cubewano	1999 XY143	213	179	2670
m	Cubewano	2000 CF105	63.6	50	33,300
	Cubewano	2000 CQ114	132	115	5880
	Cubewano	2000 WT169	205	168	2600
	Cubewano	2001 FL185	142	88	1900
	Cubewano	2001 QC298	235	192	3813
	Cubewano	2001 QQ322	171	156	3890
m	Cubewano	2001 QW322	128	126	102,100
	Cubewano	2001 RZ143	108	90	1560
	Cubewano	2001 XR254	171	140	9310
	Cubewano	2002 VF130	121	105	22,400
	Cubewano	2002 VT130	251	205	2490
	Cubewano	2002 XH91	298	185	19,900
	Cubewano	2003 HG57	156	156	13,200
	Cubewano	2003 QA91	188	180	1900
	Cubewano	2003 QR91	207	189	1790
	Cubewano	2003 QY90	81	80	8549
	Cubewano	2003 TJ58	65	51	3768
	Cubewano	2003 UN284	124	83	55,500
m	Cubewano	2003 WU188	178	129	1300
	Cubewano	2003 YS179	126	110	7830

(continued)

Table 9.1 (continued)

	Class	Subclass	Selected resonances	Number	Name	Diameter (primary) (in km)	Moon name or designation	Diameter (secondary) (in km)	Separation (km)
	Cubewano				2003 YU179	146		80	2000
	Cubewano				2004 PB108	243		132	10,400
	Cubewano				2005 EF298	138		105	3300
	Cubewano				2005 EO304	152.4		78	69,800
	Cubewano				2005 GD187	123		102	7600
	Cubewano				2006 BR284	89.8		71	25,300
	Cubewano				2006 CH69	100		82	27,000
	Plutino		2:3	38628	Huya	406		213	1740
*	Plutino		2:3	47171	1999 TC36	272	S/2007 (47171) 1	251	867
*	Plutino		2:3	47171	1999 TC36	272	S/2001 (47171) 1	132	7411
*	Plutino		2:3	90482	Orcus	917	Vanth	276	9006
*	Plutino		2:3	134340	Pluto	2346	Charon	1207.20	19,573
*	Plutino		2:3	134340	Pluto	2346	Hydra	115	64,736
*	Plutino		2:3	134340	Pluto	2346	Nix	93	48,841
*	Plutino		2:3	134340	Pluto	2346	Kerberos	29	57,731
*	Plutino		2:3	134340	Pluto	2346	Styx	18	42,471
m	Plutino		2:3	139775	2001 QG298	135		117	172
	Plutino		2:3	208996	2003 AZ84	723		72	7200
m	Plutino		2:3	341520	2007 TY430	102		97	21,000
	Plutino		2:3		1998 WV24	110		96	1420
m	RTNO		1:2	26308	1998 SM165	268		81	11,377
m	RTNO		2:5	60621	2000 FE8	146		111	1180

	RTNO		3:8	82075	2000 YW134	216		75	1900
m	RTNO		4:7	119067	2001 KP76	153		146	8900
m	RTNO		1:2	119979	2002 WC 19	440		139	2760
*	RTNO		4:7	385446	Manwë	160	Thorondor	92	6674
	RTNO		1:2		2000 QL251	148		143	5002
m	RTNO		3:5		2001 XP254	108		7	1200
	RTNO		1:2		2003 FE128	178		131	2140
	RTNO		5:8		2005 VZ122	124		49	2300
m	SDO	Extended		48639	1995 TL8	176		80	420
	SDO			60458	2000 CM114	167		128	2200
*	SDO	Haumea	7:12?	136108	Haumea	1379	Hi'Iaka	320	49,880
*	SDO	Haumea	7:12?	136108	Haumea	1379	Namaka	160	25,657
*	SDO	Dwarf	5:17?	136199	Eris	2326	Dysnomia	514	37,580
	SDO	Extended		182933	2002 GZ31	195		123	2060
	SDO			229762	2007 UK126	590		103	3600
m	SDO, RO		1:3		2006 SF369	144		141	3120
	Unknown				2004 KH19	179		129	13,000
	Unknown				hst 5	135		135?	16,400

Moon names are given where they are named. An asterisk indicates a write-up. All asteroids with named moons have been so written. A lowercase "m" indicates a brief mention due to a notable numerical value. Blank values are unknown. In many cases the values used are assumed, derived, or estimated, but in all cases the tables provide the most accurate data that can be found

? Possible values

10199 Chariklo: This Centaur has two rings, nicknamed Oiapoque and Chui (nicknamed after rivers/streams—right now they are still using the formal designations 2013C1R and 2013C2R). The rings are two bands; one is 6–7 km wide, then there is a 9 km gap and then a 2–4 km band. These two orbit at about 400 km. This makes it the only object not a gas giant to have even a semi-stable ring. But how the rings remain stable is unclear. It may be that Chariklo has an as-of-yet undiscovered shepherd moon, like the many such moons Saturn has. (There is also a strong likelihood that 2060 Chiron, a Saturn-crossing Centaur may also have a pair of rings. July 2015 update: According to MIT, 2060 Chiron does have debris encircling it. They may be rings of may be symmetric jets.)

42355 Typhon and Echidna: Named after monster in Greek mythology, Echidna is a medium moon of Typhon at 55 % of the diameter. The primary is 162 km, the secondary 62 km and the separation 1628 km.

65489 Ceto and Phorcys: Named after Greek gods, the Ceto-Phorcys system is more of a binary, as Ceto is 223 km, and Phorcys is 171 km, over 76 % of the primary. The separation is 1840 km.

Cubewanos with Moons

This is pronounced Q-B-1-o(s); after the first one found (15760) 1992 QB_1. They are also called Classical Kuiper Belt Objects; Kuiper being pronounced KĪ-per, with a long i sound.

These objects have low eccentricities, are in the Kuiper belt (40–50 AU, orbiting beyond Neptune), are not controlled by an orbital resonance with Neptune, and do not cross Neptune's orbit. Many also have low-inclination orbits similar to the classical planets.

Fifty-two Cubewanos have satellites. Primary sizes range from 63.6 to 1070 km (2000 CF_{105}, 50000 Quaoar). Secondary sizes range from 50 to 361 km (S/2002 (2000 CF_{105}) 1, Ilmarë). Separations range from 1300 to 102, 100 km (2003 WU_{188}, 2001 QW_{322})

50000 Quaoar and Weywot: Weywot is a tiny moon. It is less the 8 % the diameter of Quaoar, and it is estimated to be only about 1/20th of 1 % of its mass. Quaoar is estimated to be (at the time of this writing) 1070 km, the secondary is 81 km, and the separation is 13,800 km.

58534 Logos and Zoe: Logos and Zoe are of comparable size, and elliptically orbit a barycenter which lies between them. Logos is 82 km, Zoe is less than 82 % at 67 km, and the separation is 8217 km.

66652 Borasisi and Pabu: Borasisi and Pabu are also of comparable size, and also elliptically orbit a barycenter which lies between them. Borasisi is 126 km, Pabu is less than 82 % at 103 km, and the separation is 4528 km.

79360 Sila and Nunam: (Sometime called Sila-Nunam) 79360 Sila is a primary at 249 km, and Nunam is a whopping 94.8 % at 236 km. That is why this is often called the Sila-Nunam system since one is not significantly larger than the other. The separation is 1777 km.

88611 Teharohiawako and Sawiskera: These challenging names come are from the Iroquoian creation myth: the primary is a god of maize, while the secondary is named after his evil twin brother. Teharohiawako is 178 km, Sawiskera is less than 73 % at 129 km and the separation is 27,670 km.

120347 Salacia and Actaea: Salacia is 854 km; Actaea is closer to a real moonlet at only 286 km, only 34 % of the primary. Separation is 5619 km.

174567 Varda and Ilmarë: Varda, like many TNOs has a highly elliptical orbit. It is distant from the sun (since a book should not be too exact), and its next perihelion will occur around late 2096 (Perihelion is about 39.6 AU). Varda is 705 km, Ilmarë is 361 km, just over half its size, and the separation is around 4200 km.

Plutinos with Moons

Unsurprisingly, these were named after Pluto, the first one discovered by quite a margin. Plutinos are Kuiper belt objects in a 2:3 orbital resonance with Neptune.

Eight Plutinos have at least one moon. Primary sizes range from 102 to 2346 km (2007 TY_{430}, 134340 Pluto). Secondary sizes range from 18 to 1207 km (134340 Pluto's "Styx" and "Charon" respectively). Separations range from 172 to 64,736 km (2001 QG_{298}, 134340 Pluto's "Hydra").

47171 1999 TC_{36}, S/2007 (47171) 1, and S/2001 (47171) 1: 47171 (1999 TC_{36}) is 272 km, S/2007 (47171) 1 is 251 km, and S/2001 (47171) 1 is 132 km. The separations are 867 and 7411 km, which is a departure from the asteroid belt triple-body systems where the smaller moon is generally closer.

90482 Orcus and Vanth: Orcus is 917 km, Vanth is 276 km, and the separation is 9006 km. Orcus is the Etruscan god of the underworld, and the Etruscan equivalent of Pluto. Orcus shares some traits with Pluto. As they are both Plutinos, they both share a 2:3 resonance with Neptune, but when one is at perihelion, the other is at aphelion. And vice versa. Orcus is a binary (like the Pluto-Charon system), and like the Pluto system the two objects may be tidally interlocked (see next entry).

134340 Pluto, Charon, Hydra, Nix, Kerberos, and Styx: Pluto is the most well-known and most well studied of the Plutinos and of all KBOs. This is in no small way linked to its discovery 62 years earlier than the second object found (not counting Charon separately). Much of the information found claims Eris is larger, but the best most accurate, up-to-date data I found indicates Pluto is larger if only by a scant 20 km. (This is partly due to the fact the Eris *is* the largest in the scattered disc, but is not a true Plutino. By the same coin, by mass, Eris *is* larger, by about 28 %). According to the best data that could be found (as of July, 2015 including the *New Horizons* early returns) Pluto is 2372 km. Charon is 1207 km, and 19,571 km away. Hydra is 58*34 km, and at 64,738 km, and in a nearly 6:1 resonance with Charon. Nix is 56*26 km and at 48,694 km and in a nearly 4:1 resonance with Charon. Kerberos is 31 km and 57,783 km away, and in a nearly 5:1 resonance with Charon. Styx is 8-28 km, and 42,656 km away, and in a nearly 3:1 resonance with Charon.

In order of size it is Pluto, Charon, Hydra, Nix, Kerberos, and Styx. By discovery date it is Pluto, Charon, Nix/Hydra (same time), Kerberos, Styx. By orbital distance (from Pluto), or increasing orbital resonance, it is Pluto, Charon, Styx, Nix, Kerberos, and Hydra.

Studies indicate Pluto could have stable prograde moons out to 53 % of its Hill radius (the stable zone for orbiting satellites), and stable retrograde moons out to 69 %. Yet all of Pluto's moons are within a mere 3 %, making it a very compact system. Some could say the most compact system known, but now that so many objects have been found in the same area with one or more moons, weirder things may yet be seen. For the same reason I cannot say this system has the most objects, but for now it does (at five satellites). More may yet be discovered around other objects when they are further studied.

Information on the moons is sketchy and will remain such until the New Horizons data has been complete transmitted and analyzed. *New Horizons* successful flew by Pluto around 11:49:57 UTC, was 12,500 km distant and traveling at 13.78 km/s, but full data transmission will take 16 months. Analysis will take even longer.

Charon was identified in 1978. Charon is unusual in that it is not only tidally looked it is tidally interlocked. That is, not only does the same face always face Pluto, but the opposite it true; the same face of Pluto always faces Charon. In fact, if somebody lived on Pluto the moon would always be in the sky if it ever was, and would never move from its spot, nor would its face change much. If somebody lived on the other side of Pluto they would never even know that they had a moon (until they noticed that the stars seemed to move in a very unusual way, almost like the planet was being pulled as if by some unseen force, that caused it to race in small circuits within its own orbit!)

Nix, Hydra, Kerberos, and Styx all share the same orbital plane Charon does, all have orbits nearly circular, and are all far smaller and less studied. Hydra may have variable brightness, since some parts seem to be more reflective than others. There may be a tiny ring system, but more study needs to be done. In fact, Kerberos was discovered while searching for rings. Styx was discovered while looking for hazards for the *New Horizons* probe. (Nix and Hydra were discovered by the Hubble Space Telescope, but until they were discovered no ring was suspected.)

With full New Horizons data, much more will be known about this class of object.

RTNOs with Moons

A resonant trans-Neptunian object is, quite logically, any TNO locked in a mean-motion resonance with Neptune (and there are many of them). They may also be TNOs, and all Plutinos fit into this category as well, as they all have a 2:3 resonance.

Ten RTNOs have satellites. Primary sizes range from 108 to 440 km (2001 XP_{254}, (119979) 2002 WC_{19}). Secondary sizes range from 7 to 146 km (2001 XP_{254}, (119067) 2001 KP_{76}). Separations range from 1180 to 11,377 km ((60621) 2000FE_8, (26308) 1998 SM_{165})

385446 Manwë and Thorondor: Manwë is 160 km, and Thorondor is under 58 % of its primary at only 92 km, and they are separated by 6674 km.

SDOs with Moons

Scattered disc objects have orbit that are eccentric (up to 0.8), inclined (up to 40°), and distant (out to 30 astronomical units). The name refers to the "scattering" of these objects, likely done by the gas giants. Many continue to be perturbed by Neptune.

Six objects in the scattered disc have one satellite, and one has two for a total of seven objects with eight satellites. Primary sizes range from 144 to 2326 km (2006 SF_{369}, 136199 Eris). Secondary sizes range from 80 to 514 km (S/2002 (48639) 1, Dysnomia). Separations range from 420 to 49,880 km (1995 TL_8 and its satellite, and 136108 Haumea and Namaka).

136109 Haumea, Hi'iaka and Namaka: Originally nicknamed "Rudolph" and "Blitzen" before the IAU gave them official names; there is little of any real interest to say about these two that cannot be said about virtually any other moon of the solar system. The primary is 1379 km, the closer is 160 km (11.6 %), and 25,657 km away, the larger one is double the size at 320 km (23.2 %) and 49,880 km away. This is more like the main belt asteroid with the smaller one being notably closer.

136199 Eris and Dysnomia: Eris is 2326 km (and the most massive KBO yet known), Dysnomia is 22.1 % at 514 km, and it is separated by 37,580 km.

II. Projects

10. Logging/Blogging

OBJECTIVE: Keep an observing log of whatever you see (in particular the moons). Logging is one of the most basic and most important things that an astronomer ought to do. Accurate records are essential. According to Montreal amateur astronomer Isabel K. Williamson, "Observations not recorded are not observations." I doubt anyone could say that any better. No matter what way you choose to record your observations, keep a key of how they should be read. That way when people (both you AND others) are seeking something, they can find it later.

WHO CAN DO THIS: Anyone who looks skyward.

REQUIRED MATERIAL: Varies, but it is essential to have something to save records on (i.e., a notebook), and something to keep them with (pencil or paper). You can also use a reliable voice recorder to avoid needing any light besides the screen of one, or its power LED. A telescope changes the quality of the observations you can make (but is not required), and your eyes are your most important tools. A computer can be useful but due to the light output it will probably be more useful after the fact.

What to Record

Entries require a few key parts, and can benefit from others.

Entry record number: Give the entry some identifying record number. If you go out every night for 50 years and make 3 entries that would be over 50,000 entries! You can number them sequentially (12,345), or categorically (P1, #2345, for the 2345th observation in "Project 1"), or a complex date and serial (2014-1-2-3, for the third observation on the second day of the first month of 2014, or January 2nd, 2014, #3), or any other system that allows them to be sorted.

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Target: Most importantly, what are you looking at? Separate this categorically (planet, moon family (if any), subfamily (if any), name of moon/moons.)

Date: Be as specific as possible. But be consistent. If you put down Sunday, August 31st, is that the day you started or the day you finished? If you observe past midnight, it is important. If you consistently use the start date, you'll be fine. If you wish to include both dates, do so. You should probably use the day of the week. Although you can find this out later by putting the date into a spreadsheet (and formatting the spreadsheet cell to tell the day of the week), it is a step you could much easier do now.

Time: Include both the start time and the end time (0123–0321), or each one (0123, 0321), or the start time and a durations (0123, 118 minute or 1 h 58 m). You can use UTC which is most useful when other people look at your records from across the world, but if you are the only one who looks at your record (and you rarely, if ever, leave your home time zone), then you can use local time. (If you become famous later, then your biographer can just subtract or add whatever hours are needed to match universal time).

Location: Your home, your mom's and/or dad's home, your favorite dark observing site, or an observatory (whether physical or online), this is the record of where the observations were made. If they were done from a remote or unusual site, you may also wish to record the latitude and longitude of the observing site.

Project: If this is part of a project (i.e., "My Moon Catalog, Revision two"), you may wish to include a code for such (MC2).

Equipment: What did you use to observe it? Was it visually, binocular, a telescope, or online (see Chaps. 23 and 24)? If it was a scope, was it a reflector or a refractor? Was the type a Schmidt–Cassegrain or Dobsonian (or Muksatov, Newtonian, or dozens of others)? Was it an equatorial or an altazimuth mount? What was the aperture, eyepiece, speed, and focal length? If you used filters, what type? If you got an image, what type of equipment did you use, CCD or DSLR (or smart phone)? How many exposures, how long, and is it stacked or retouched, and in what ways? If you use a variety of instruments, you could just name each instrument (like Christy for your Schmidt–Cassegrain or CCD; Michael for your Muksatov; and Dave for your Dobsonian or DSLR) and then include a special key for the instruments.

Additional categorical information: At this point ask yourself "is there anything else I wish to include that I might wish to sort or filter my records by?" If so, include that. Common items might include RA, Dec (for semi-fixed objects, i.e., stars), Altitude, Azimuth (for things without set coordinates, like moons or comets), direction of the moon in relation to the planet or another object by angular measurement, angular diameter of the item observed, etc.

Specialty: If you are a specialist, record special information, i.e., if you like to make composite images (like photographing moons when they are in the same frame as nebulae or other deep-sky objects), record which deep sky images were shared with the image. If this is the case, the image you make should have an "A" and identically or sequentially numbered "B" reference so you know what you used for each, since you probably did not photograph the items the same (since the moon would be overexposed or the nebula underexposed. This would also surely involve a special project identifier!)

Image/Sketch: Did you image or sketch the object? If so, you should identify the sketch/file with your reference number (you made one, right?).

Capsule: This is the one of the most important categories yet is often neglected. How does what you see speak to you? Is it brighter than you thought, is it a poor object, is it easy to see details such as wispy terrain or tiger stripes, do you see an alien spacecraft near the planet firing laser cannons—whatever it may be, what do YOU see?

If you want to record this on paper, I include a sample log page in Appendix C.

Computers

Computers are wonderful tools, nothing more and nothing less, and it is best to keep a log on a computer spreadsheet. But leave your computer at home. If you do insist on taking it with you, look into a red screen utility. "Red Screen" by astrodigital.net which is simple as can be is free, and other products such as ColorVeil exist. If DIY seems preferable, tape a red filter over the screen. The reason for this is red light won't hurt your dark adaptation. While even with a filter you won't be able to record while you observe, you can always put the data in after the fact.

Some astronomical societies will enable you to record your information on their website. If you do so, be sure to check the terms of their web service, since you may forfeit the rights to call the observations your own after posting them. The data can also be hosted on your own website. This is a good way to go if you do not care about other people using the work you make available.

The master spreadsheet log should be kept on your computer and backed up. It is also possible to employ specialized logging software. Just make sure that you can get your records in a universal format (such as ASCII) in case you use propriety software that the maker later stops supporting or producing at some point. If you are tech-savvy enough, then you can program your own software with forms, bells and ringers and such to record your observations however you wish. You could even make a really nice one that automatically converts times and coordinates systems, and records (or links to) images or scanned sketches.

If you put these on a computer, no matter how you do it, BACK IT UP. I cannot stress this point too much. Back it up on the hard-drive; if you have another computer on that one too, if you have an external hard-drive, on that drive too, and you can also use an online backup system.

11. *c*: The Speed of Light

OBJECTIVE: Consider the speed of light and the distance to nearby and more distant objects, and understand how the moons (Io mostly) are important in this.

WHO CAN DO THIS: Anyone who can do a little math, and can handle the basic functions (division mostly), and scientific notation.

REQUIRED MATERIAL: You may either use a calculator or spreadsheet or do it by hand if you really enjoy math.

Measuring Space with Numbers

Astronomy is a science of numbers. Among other things, they determine:

- How big is the Milky Way? [*]
- How far away is the closest star? [*]
- How many galaxies are there? [125 million?]
- How old is the universe? [13.798 ± 0.037 billion years is the consensus]
- What is Pi? [3.14159265358979323846264338327950…]
- What is the Base Order of Magnitude? [10]
- What is the Distribution of Energy Density? [about 22 % dark matter, about 73 % dark energy, about 5 % baryonic matter]
- What is the Gravitational Constant, G? [6.673e – 11 N m^2/km^2]
- What is the Hubble Constant? [73.8 km/sec/Mpc]

(You'll notice, I did not specify the size of our galaxy or how away the nearest star is.) But perhaps most important for gauging the above information is the number that represents the speed of light, also known as "c". Because the speed of light is now used a common measure for how far away something is, the age and distance of objects in the Universe can't be understood without it. So how was it determined to begin with?

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The Speed of Light: A Brief History

The groundwork was laid in 240 BC by Eratosthenes wanted to figure out the circumference of the Earth. He put a gnomon (a straight rod) in a well in Alexandria and took measurements of its shadow at noon. At another well in Syrene, a measurement was made at the same time of day. By measuring the length of the shadows, and knowing the distance between the two wells, he was able to figure out the circumference of the Earth to within 1.6 % accuracy, or 39,690 km. (Some say, 16.3 %, depending on whether he used the Egyptian stade or the Attic stade for his measurements, but he is credited with the discovery at 1.6 % error.) He had some faulty data (the two wells he used did not lie on the same meridian, he was a bit off on the distance between the two wells with either stade, and the Earth is not a perfect sphere but an oblate spheroid.) If we repeat his experiment today correcting these errors, the error in his method drops to 0.16 %.

Then, from 1671 to 1676, Ole Rømer, a Danish astronomer who worked at the Royal Observatory in Paris with Cassini set about addressing the problem, which first Galileo and later Cassini had approached but not solved. In the 1600s, Rømer sent his friend Jean Picard to Tycho Brahe's observatory at Uraniborg, on the island of Hven near Copenhagen. By observing Jupiter and calculating the altitude and azimuth to know where it lay in the sky, and knowing where they were on Earth, they could have calculated the distance to Jupiter (which earlier astronomers had already done). What they did instead was observe the eclipses of the moon Io across Jupiter's disc. By knowing the distance from Jupiter to each observatory and measuring when certain events (like first contact, second contact, and so on) happened at each, and correcting for things such as differing angle of viewing, they could calculate that light reached one observatory before it reached the other and by using the distance to Jupiter and some trigonometry, they could figure out how much longer the light took to reach the more distant one. The difference in the time for light from an eclipsing Io to reach the two observatories led him to realize that its speed was finite, and his measurements allowed Christiaan Huygens to calculate the speed. It was the first quantitative measure of light's speed.

So What Is the Speed of Light in a Vacuum?

In this project you will be given the lunar distance and a time or pulse. You will then derive an experimental value for the speed of light. Use a semi-major axis of about 384,399 km or 238,854 miles. If you were to aim a pulse of light at the moon, it would take exactly 2.5644340926 seconds to return (use however much accuracy you would like to in these measurements). So how many meters did the light cross (do not forget to multiple the distance by two before dividing to get the round trip travel), and how many can it cross in one second?

Playing with the Speed of Light

Now by either using your experimental value or by using the values given in Appendix C answer the following questions (all of which have answers in Appendix C.)

1. How long would it take for light to get from New York to Los Angeles?

DISTANCE: **2972 miles**, **4783 km**.

NOTES: This does not actually come out correctly; the speed of light you figured is the speed of light in a vacuum and our planet's atmosphere has certain refraction factors. For these purposes we will figure this as if it were a vacuum.

HINT: Answer in seconds. The answer should be less than 1.

2. How long would it take for light to get from the sun to Mercury at perihelion?

DISTANCE: **46,001,200 km** (**Miles: 28,583,820**).

NOTES: Assume this is a 2D trip so there are no 3D geometric acrobatics. Again, this is not a true vacuum, but assume it is.

HINT: Answer in minutes.

3. How long does it take for the light from the sun to reach the Earth?

DISTANCE: **Use 1 AU or 149,689,000 km** (**Miles: 93,000,000**).

NOTES: Again, this is not a true vacuum, but assume it is.

HINT: Answer in minutes.

4. On 27 Aug 2003, Mars made its closest approach to Earth in almost 60,000 years. It was at 55,758,006 km. If Deimos was on its far side and at apoapsis, how long would the round trip time for a light pulse be?

DISTANCE: Separation distance: 55,758,006 km. Diameter of Mars: 6792.4 km, Deimos at apoapsis: 23,470.9 km. **Round trip distance: 111,576,538.6 km** (**Miles; 69,330,447**).

NOTES: Assume this is a 2D trip so there are no 3D geometric acrobatics. Again, this is not a true vacuum, but assume it is. Ignore the fact that Mars is in the way.

HINT: Answer in minutes.

5. How long would it take for a light pulse from the Earth to complete a round trip to Callisto (Jupiter) at perigee?

DISTANCE: Jupiter at perihelion: 740,573,600 km. Earth at aphelion: 152,098,232. Proposed separation: 588,475,368 km. Diameter of Jupiter: 142,984 km. Callisto at periapsis: 1,869,000 km. **Round trip distance**: **1,180,964,704 km** (**Miles: 73,382,660**).

NOTES: This assumes that Jupiter can be at perihelion while Earth is at aphelion, and that Callisto is at the periapsis, but on the far side. Assume this is a 2D trip so there are no 3D geometric acrobatics. Again, this is not a true vacuum, but assume it is. Ignore the fact that Jupiter is in the way.

HINT: Answer in hours.

6. How long would it take for a light pulse from the Earth to complete a round trip to Rhea (Saturn) at apogee?

DISTANCE: Saturn at aphelion: 1,513,325,783 km. Diameter of the sun: 1,396,684 km. Earth at perihelion: 147,098,290. Diameter of Saturn: 142,984 km. Rhea at average distance: 527,108 km. **Round trip distance: 3,324,981,698 km** (**Miles: 2,066,047,842**).

NOTES: The assumptions regarding the vacuum, etc. again hold.

HINT: Answer in hours.

7. How long would it take for a light pulse to reach Hi'iaka, the moon of dwarf planet Haumea, at perigee (one way)?

DISTANCE: Haumea at perihelion: 5,196,657,071 km. Earth at aphelion: 152,098,232. Proposed separation: 5,044,558,839 km. Diameter of Haumea: 1300 km. Hi'iaka at average distance: 49,880 km. **One-way distance: 5,044,610,019 km** (**Miles: 3,134,575,342**).

HINT: Answer in hours.

8. How long would it take for a light pulse from the Earth to complete a round trip to the outermost major moon of Uranus, Oberon, at perigee?

DISTANCE: Uranus at perihelion: 2,735,118,100 km. Earth at aphelion: 152,098,232. Proposed separation: 2,583,019,868 km. Diameter of Uranus: 50,734 km. Oberon at average distance: 583,520 km. **Round trip distance: 5,167,307,880 km** (**Miles: 3,210,816,258**).

HINT: Answer in hours.

9. How long would it take for a light pulse from the Earth to complete a round trip to Neptune's moon Proteus at apogee?

DISTANCE: Neptune at aphelion: 4,537,580,900 km. Diameter of the sun: 1,396,684 km. Earth at perihelion: 147,098,290. Diameter of Neptune: 49,244 km. Proteus at apoapsis: 117,709 km. **Round trip distance: 9,372,485,654 km** (**Miles: 5,823,792,585**).

HINT: Answer in hours.

Bonus Questions

A parsec is defined at the distance at which something has 1 arc second of parallax.

(If you do not understand parallax, consider this. Look at two objects, a foreground and background one (or you could even use your hand or finger for the foreground one). Look at the two with one eye. Then close it and look at it with the other eye—see how it seems to shift? It is kind of like that. Think of an astronomer comparing a "close" star to more distant stars. You measure the star against the background when Earth is at one position. You wait until the Earth is at the furthest point in its orbital path from there (about 6 months), and do the same measurement. A star close by will shift. The closest stars shifts just over 0.75 arc seconds. Distant stars also shift, but after you pass a certain threshold, parallax can no longer be used due to the extreme sensitivity of instruments and things like atmospheric effects that make star twinkle.)

In fact, even the word "parsec" is a portmanteau of "Parallax Second".

The equivalent is 3.26156 light-years.

10. How long would it take for the light from the sun to reach Vulcan?

DISTANCE: **Use 0.15 AU, 22,450,349 km, or 13,950,000 miles**.

NOTES: Vulcan, a planet inferior to Mercury, is not thought to exist anymore, and if it does, it must be smaller than 6 km, or 3.5 miles.

HINT: Answer in minutes.

11. How long would it take for a light pulse to make a round trip to Alpha Centauri Bb S/1 (if Alpha Centauri Bb has a moon)?

DISTANCE: **1.3368 parsecs each way**.

NOTES: Interstellar space is more of a vacuum than stellar space.

HINT: Answer in years.

12. Using your results for light speed, when did Supernovae 1987A actually explode? Where was human development then? (Hint: Ignore the effects of dark energy).

DISTANCE: **Use 51.4 kiloparsecs**.

NOTES: Now that we are dealing with intergalactic space, this is very close to a true vacuum.

HINT: Answer in years

13. GRB 090423 is the earliest object ever detected. It has a progenitor star. Even gamma rays must obey the speed of light. Ignoring the expanding effects of dark energy when was this burst emitted? How old was the universe?

DISTANCE: **Use about 4 gigaparsecs**.

NOTES: Ignore the effects of dark energy.

HINT: Answer in years.

Now, go to Appendix C and check all your answers.

12. Telescopic Moon Targets

OBJECTIVE: Observe the moons with equipment or the naked eye.

WHO CAN DO THIS: Anyone with any level of equipment, from the naked eye to a binocular or a telescope.

REQUIRED MATERIAL: Any sort of visual aid.

Observation

When I was young, adults told me they loved astronomy since it was, "One of the last sciences based on pure observation." This foundation has been improved by math, telescopes, probes, and so on, but all of these things either improve our ability to observe, or confirm the prediction(s) based on our observation(s). So what can be seen from the Earth? In large part, it depends greatly on your equipment. (See Appendix A for a list.)

The first part of this process if you are using any equipment, is to test the equipment is to test your scope. If you have an electronic go-to scope (sometimes denigrated by being called dial-a-star), you can make using any equipment, is to test the equipment. your own list of stars to find your own limiting magnitude. Most astronomy magazines have advice for how to test your equipment. They describe what type of scope to use so you can find your limiting magnitude quickly and easily, while seeing objects you might not otherwise look at. After that, look at the object data tables for Jupiter, Saturn, and other satellite data. You should be able to spot anything lower than your limiting magnitude.

OBJECTIVE: See the Galilean moons without the help of visual aid.

WHO CAN DO THIS: In my opinion, anyone with really, really good eyes.

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REQUIRED MATERIAL: Really, really good eyes, patience, fortitude, and luck sure helps.

Jupiter and Its Moons

Jupiter is really easy to see in the night sky. The brightest star, Sirius, the Dogstar is −1.47. Jupiter varies between −1.61 and −2.94. The only brighter permanent, natural things at night are Venus (−3.82 to −4.89), and the full moon (mean −12.74). The ISS is usually around −5.9, but artificial, and some comets get to −10, but are temporary.

So Jupiter is comparatively easy to find by the naked eye. But is it possible to see any of Jupiter's moons without visual aids? Some of them have magnitudes of 5.02, 5.29, 4.61, and 5.65 (all at opposition). It seems like they should be visible if your eyes are good, so why aren't they?

The answers are age, darkness, distance, and glare. Let's handle these one by one.

Age and Vision

As people age, their eyes become less sensitive to the dimmest of dim objects and these do count in this category. It is a relatively easy task to make a table of objects for benchmark brightness. If you assemble such a chart, you should record the limiting magnitude in your logs, and as specialized information, you could even make a project recording the limiting magnitude and use a spreadsheet (or just graph paper) to construct a chart to see if there are patterns. With a spreadsheet you can even use some equations and multiple columns to set up automated weekly and monthly averages and use specific as well as "best fit" lines to see if there are any patterns that recur at variable time scales.

The need to wear corrective glasses can also render the moons invisible, as the correction is rarely 20/20. In young people, better visions (usually about 20/16 or 20/12), and smaller retinas allow for better resolution of the objects. Some people also claim they have better than 20/20 vision after procedures such as LASIK, but evidence is lacking to verify such claims.

Darkness

Darkness adaptation is usually not acquired unless you have the patience to stand outside in the dark and be careful as you let what light to enter your eyes (common enemies are security lights, vehicle headlights, the self-same planets and especially the full moon). These are enemies every astronomer has to deal with, but be especially careful if you seek for the moons not to be hit in the eye by Jupiter. It will ruin all your scant chances.

Of course most dedicated observers know where a dark-sky sight can be found. If you are going to load up the car and trek out to one, you can use this as part of your adapting. You can try for Jupiter before setting up your scope. Make notes (use a voice recorder, not a notebook, since even a red light will hurt your chances), and then view Jupiter through your scope later.

Distance

Distance is one of the factors making it difficult—not the distance between us and the inner moons, but the distance between Jupiter and the inner moons.

Let's take a brief look at the trigonometry. The angular diameter equation is "$\delta = 2 \arctan (d/2D)$", where δ is the separation, d is the actual diameter, and D is the actual distance expressed in the same units. However when dealing with a circular object which is closer, and to which the distance is known, it is also acceptable (and probably better) to use "$\delta = 2 \arcsin (d_{act}/2D)$."

Recall that arctan refers to the ratio of opposite/adjacent, and arcsin refers to the ratio opposite/hypotenuse—this however requires that you know the actual diameter, since you must use d_{act}. Due to the use of d_{act} this is rarely used except in close spherical objects since arctan is tangent to the surface of a sphere where arcsin uses the center.

According to the Jupiter satellite data table the apoapsis distances are 423,400 km; 676,938 km; 1,071,600 km; and

1,897,000 km. Therefore, there are (under perfect conditions) angular sperations of 0.000722, 0.00115, 0.00182, 0.00322 degrees or 2.6, 4.1, 6.6, and 11.6 arc seconds. However some published numbers point to as much as 24.9 arc seconds of separation of Callisto at best viewing, I was not able to mathematically verify this suggestion (but then I did not include a radius for Jupiter or Callisto, introducing an error less than 0.03 %).

Due to the spatial placement of rods (optic cells sensitive to light, but not color), visual acuity (the ability to see and resolve) is much better in bright light than dim light. In dim light, the ability to resolve is about 25 arc minutes at 20/20 vision.

Glare

This is the biggest enemy to seeing the moons.

For argument's sake, say Jupiter is at its minimum brightness of −1.6, and use the brightest moon (Ganymede) at 4.61. This is a difference of 6.21, a difference in brightness of $2.512^{6.21}$ or over 300! The moon cannot be seen unless the glare can be eliminated.

Trying It Out

If you are brave enough to still be willing to try this challenging task, first find a dark site, and find a corkscrew diagram of the Galilean moons.

The best thing to do is find a place where Jupiter is blocked by a narrow object, say a telephone pole or tree branch. Remember that the moons will be ridiculously close to the planet.

Now, you will need to do something which few children can do; sit still. Place Jupiter behind that pole and sit stock-still. Since you may need to sit still for 15 minutes (since you will need to look at Jupiter to block it), you will need to sit still; however since the Earth sits still for no man, you may need to adjust the blocking, and a slip can ruin your shot.

Finally, avert your vision. Many seasoned observers can explain the best way to do this, but if you do not know, do not look directly at where you expect to see the moons. Look just to the side and you may see some sort of fleeing ghost. If so, you have found your quarry. Congratulations are in order. Be sure to note this momentous night in your log book. Most likely, the moons possible to spot in this way are limited to Ganymede and Callisto, as they will be the furthest away from the planet's glare.

13. Life on Moon Worlds

An Alternative Lifestyle?

Humanity may not always live on Earth. We may at one time try to colonize Venus or Mars. And if we wished to explore beyond the asteroid belt, stations on the outer planet's moons would be required. So what might that entail? This project only requires a dose of imagination.

Habitability Concerns

Let's go through the condition of living in alphabetical order.

The ***albedo*** is of note. The light reflecting from the surface of some moons with high Bond albedos (meaning, as with Enceladus, that 99 % of the light that hits it is reflected), would be virtually blinding except for the fact that the sun is smaller at that distance, with an angular diameter of 3″, about a tenth of its size from Earth. Saturn on the other hand would be 29°40′ (on average). This light would also be reflected at least from the side that faces it. (See rotation, below).

The ***apparent magnitude*** would not be important to you, but while we are on the subject, stargazing would be little changed. The stars will be about the same brightness, and the constellations would not be (perceptible) changed. However the planet's positions would all be vastly different and the phases of inferior would be different from a different vantage point. (i.e.: On a moon of Saturn, Jupiter, Mars and Earth would also go through phases). There will also be a glowing blue dot, dimming somewhat from the more distant planets. The blue dot is a little place we like to call Earth. Drop by and visit some time.

Some of the moons have ***axial tilt***, and some do not. More tilt means more pronounced seasons. Without weather patterns (requiring an atmosphere) this would primarily affect the

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temperature. Consider Uranus; the North Pole is pointed to the sun for one quarter of the year, the sun is on the horizon for half, and the South Pole points to it for one quarter with every Uranian year being 84 years. A long winter! Of course, moons orbit planets, not the sun, but if they orbit in the perfect ecliptic plane the effect is the same. In that case, the seasons would change four times every time the planet orbits the sun, since that is the source of the seasons—most planet do not heat the surface of their moon significantly, except for Io, and maybe Europa. With greater distance from the sun seasons would be much more minor, being out-shadowed by the difference between day and night. Axial tilt also defines how long day and night are, but there is more on this in the "Temporal Concerns" section, next.

Most moons do not have an ***atmosphere*** or ***surface pressure***. The few that do are so thin and so cold that it is nothing you would want to breathe even with diatomic oxygen. Humans have trouble breathing the atmosphere atop high mountains (and some of us even have trouble on lower mountains), but compared to the atmosphere on the majority of moons, that would be easy. There are exceptions (most notably Titan), but these are the exceptions not the rule. I still don't think you would want to breathe the Titanian atmosphere being 95+ % diatomic nitrogen at −179.5 °C, and with pressure almost twice our own. Pressure would also have various effects, but I would assume that anyone on a moon would have their own atmosphere and pressure since otherwise you would asphyxiate, not be able to breathe due to air pressure, you'd suffer from ear squeeze, the bends, explosive decompression, rapid freeze drying, and other lethal and grizzly effects.

Dimensions, ***density***, ***mass***, and ***volume*** are primarily important because of G; mass is a constituent of gravity. People who saw Neil Armstrong walk on the moon could see how gingerly he could jump and land in the low gravity. Alan Shepard (Apollo 14) walked on the moon and smuggled a pair of golf balls with him to (humorously) show the effects of low gravity. This then, in turn, affects ***equatorial surface gravity***, and ***escape velocity***.

Eccentric orbits (long ellipses) cause extreme seasons, but the eccentricity of the moon is little important, since it is eccentric around the planet. This is not dangerous unless the moon can get dangerous amounts of radiation from the parent planet (like Io or

Europa), but why would humans be there in an unshielded environment (unless a ship crashed with survivors)?

Eccentricity also has the same effect it has on a planet. According to Kepler's Second Law of planetary motion (most translations state that as "a line joining a planet and the Sun sweeps out equal areas during equal intervals of time") a planet (or any orbiting body) would have to accelerate and decelerate over time if the eccentricity is significant. Most planets have (relatively) low eccentricities, but moon orbits are a hodgepodge of various ellipses. If a moon accelerates and decelerates, then the celestial objects would appear to do likewise.

Inclination is one of the more unusual things to get used to. Some moons have perfect ecliptical orbits and on such places the planet and other moons transit the sun all the time, and inferior moons transit the planet all the time too. One of the most highly inclined moons is Triton (Neptune). Its orbit is practically polar.

There are two conditions for the primary planet. If your moon is not tidally locked, the planet would (appear to) rise and set like the sun, or indeed any other celestial body. If the moon is tidally locked like most, the planet would not rise or set but would either always be in the sky or always be on the horizon or never appear at all, depending on where you were on the moon.

This is also probably a good place to mention that there would be other moons in the sky. If you were on the satellite of a gas giant, there would virtually always be a moon in the sky. You likely could not see the tiny ones, but the bigger ones would be more magnificent than ours may be (depending on the size of the sun and the Bond albedo).

The ***surface area*** would not be very important except for futuristic real estate agents.

The ***surface temperature*** would be cold (at least in our solar system, since our moon is closest to the sun). But if you have a self-contained atmospheric apparatus (see atmosphere), I assume (and hope) it would keep you within the norms of human temperature, too.

Temporal Concerns

There are a number of temporal effects of living on the satellite of a planet.

Of all of these, the ***average orbital speed*** is probably the least noticeable on a day-to-day basis, at least on its own accord, but I will cover other effects of this below.

Axial tilt also defines how long day and night are, but there is more on this in the next section. Earth has just under 23.5° of tilt, and the Arctic and Antarctic circles define areas where the sun does not rise or set for most of the year. In other places nights and days get longer and shorter (which leads to two equinoxes and two solstices per year), while on the equator every night is at equinox, with equal periods of light and dark. On a planet like Mercury with less than a 10,000th of a degree of tilt, it is an equinox no matter where you are every day!

The ***orbital period*** and ***rotation period*** are very likely two of the most important things to be known before moving to a moon. The year and day have definite effects on the Earth, and the calendar month is important to some people, but few non-astronomers even know that the lunar month and calendar month are not the same. The sidereal month is 27.32166 days, the synodic month is 29.53059 days, the tropical month 27.32158 days, the anomalistic month is 27.55455 days on average, and the draconic month or nodal month is 27.21222 days on average. Many non-astronomers round it to 28 if they care at all.

So you need some new definitions. First is the rotation period, what we Earthlings call the day. The day on the moon would still be its rotation, but many moons are tidally locked to their planets. The Pluto-Charon system and some other binary systems are co-tidally locked with the planets also locked to the moon; from both, the same face of the other always appears and there are defined "far sides."

Finally is the year, which could be defined as the time it takes for the moon's planet to go around the sun or as the period of time for the body you are on to complete one orbit of its own primary.

Everything else—hours, weeks, etc.—can be converted to local time, or one can use an absolute Earth time (a 24th of a Earth Day, 7 Earth Days) as a reference.

Vacation Among the Stars

So now that you have a primer on what to expect, all you need to do is get in your spaceship, point it to your new home, and go stake a claim. Some of the moons have things more extreme than anything you could accomplish on Earth. So, assuming you would be immune to (or protected from) the heat, cold, radiation, and so forth, consider visiting the following.

Io

Surf's Up

If you could survive the heat, you could surf the lava flows on Io. You start off sitting in the caldera in your invulnerable inner-tube, surrounded by not just magma, but magma with a high content of magnesium (which makes it hotter than most of Earth's magma). When it erupts, the lava shoots up, you fly into the air 500 km, and then you ride down in a 500 km long glide!

Saturn

Mountain Climbing on Mimas

Back in the day, some people wanted to climb Everest, and some wanted to reach the peak just above 29,000 ft (over 8500 m). (And some people wanted/want to climb it without bottled oxygen.)

Of course, if you want a REAL challenge why not head out to "Mount Herschel." The floor is 10–12 km deep, and the central peak rises 6–8 km. Bottled oxygen a necessity for this ascent in more ways than one!

Ring Spotting on Daphnis

Daphnis is only 8 km wide, and in its orbit it moves vertically by about 17 km. It lies within the 42 km wide Keeler Gap in Saturn's A Ring, so on either side of the moon, the rings are a mere 24 km away. Without delving into more discussions of angular diameter, I think we can safely assume you would have an awesome front row view of the rings, day or day. (I cannot say day or night since so close to the rings there would always be plenty of light reflected from them, except when in total shadow by Saturn.)

Spelunking on Hyperion

Spelunking is also called caving. It is climbing or crawling down into a cave and exploring it for any one of any number of reasons.

Look at Hyperion. Hyperion has a porosity of 0.46, meaning it is 46 % empty space. There must be huge networks of caves running through all parts of the satellite. And as Hyperion is only 121.57 kilometers in diameter and 10.2 km deep, it is far too small to have achieved a differentiated interior. This means that on Hyperion there is no separate core where heat would be built up, though it would be possible to find a place where the force of gravity is equal in all directions, something which people who explore caves on Earth never have to deal with. There would of course be hazards, beyond the standard loss of light or provisions. The rotation of the moon constantly changes resulting in it being termed as chaotic in its rotation, the only body so termed, and on the surface there is a crater over 10 km deep. Your terminal velocity may be less, but going splat which will hurt no matter what moon you are on!

So if you are looking for a challenging spelunk, try making a map of Hyperion's cave network sometime.

Stalking the Wild Tiger… Stripes

The Grand Canyon is 446 km long, 29 km wide, and over 1800 meters deep. Enceladus' "tiger stripes" average 130 km long, 2 km wide, and 500 meters deep. Not too big compared to the Grand Canyon. (But if you want large, go to Mars and explore Valles Marineris; 4000 km long, 200 km wide, and up to 7 km deep, making the Grand Canyon not so grand; more like *le grand ditch*.) However, there is more than one tiger stripe and each is spaced about 35 kilometers apart. And how many Grand Canyon enthusiasts can claim that it creates a ring of debris around the Earth? On Enceladus, their "ditches" are thought to do just that.

Uranus

BASM Jumping on Miranda

On Earth some people like to go BASE jumping. BASE stands for buildings, antennas, spans (bridges), and earth (cliff). In August of 2014 the record jump was off Cerro El Plomo (part of the same Chilean range which houses Cerro Paranal), with a height of 4100 meters or 13,500 feet.

But on Miranda you could go BASM jumping: building, air, space, and Miranda. The ice cliffs on Miranda are large enough that they could be observed by *Voyager 2* when it flew by in 1986. And the largest cliff, Verona Rupes is a 20-kilometer-high chevron-shaped tectonic feature. That is over four times as high as Cerro El Plomo! And consider Earth's surface gravity of 9.807 m/s^2 (or simply "g"). On Miranda the surface gravity is only 0.079 m/s^2, and there is no air to resist your fall. It would take over 2 minutes of free fall to gain the same velocity as you would in one second on Earth! It would regardless take a long time to reach the ground.

But, man, what a rush!

Triton

Triton Is Not Completely Without Its Own Charms

Since it arrived in Neptune's orbit it can be credited with flinging its likely original companion clear of the planetary neighborhood, ripping smaller moons to shreds, and dooming them to slow lingering deaths. The payback for its acts will arrive in about 3.6 billion years. Remember how exciting it was to watch Shoemaker-Levy 9 crash into Jupiter? Imagine that with a 1300 km moon!

14. Citizen Science

OBJECTIVE: Get involved!

WHO CAN DO THIS: Anyone with a computer.

REQUIRED MATERIAL: A computer, a broadband connection, a decent graphics cards, and some free processing time

Distributed Computing

The recent wealth of space science data is proving too much of a good thing in some regards. Simply put, there is a lot more data collected compared to what used to be and there are not enough properly trained people to analyze it. The astronomers have too few eyes, and too few computers, amid continuing economic crises and constant funding cuts. That is where citizen science can step in to make up the gap in analysis.

Distributed computing is one of the best ways to do this. It functions in a similar way to a telescope array, where a large number of smaller telescopes are able to act as a much larger telescope. In distributed computing, the data that needs to be examined are separated into smaller pieces and processed on individual computers. The first major project to use distributed computing was called distributed.net which has projects trying to break ciphers and unsolved mathematical projects. The second, an astronomy venture, was SETI@home.

Using a software suite called BOINC, anyone with a computer can sign up to work on SETI@home. Your computer, during idle time, will download information from various SETI systems, then crunch the numbers looking for what the SETI scientists want to find (signals of a possible intelligent origin) before sending the data back to them. When your computer is idle, it can use 100 % of your processor, but if you are using your computer, you can set it up to use from 99 to 0 % of your total CPU power. SETI@home can

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also be customized to only use your computer at certain hours of the day or to use only use a certain amount of memory; once the settings are chosen, the data processing happens automatically.

In the years since SETI@home was launched, many other similar programs have been started. BOINC also works toward creating an enhanced 3D map of the Milky Way (MilkyWay@home) and calculating dust grains to see which model of the universe works best (Cosmology@home). Information and their project list can be found at http://boinc.berkeley.edu/projects.php.

Citizen Science

For a more challenging project, ways to take advantage of people's superior pattern recognition and critical thinking skills also exist. Rather than simply provide processing support for number crunching, you can access observed data collected from various missions and telescopes and analyze it firsthand. Users can download an image from Spitzer Space Telescope data and deploy the built-in web tools, to identify visual bubbles, bright red spots, and bright yellow spots—anything in the image field. Spitzer includes a forum to discuss an image before submitting it. The same unmarked image goes to other people who do the same visual analysis and tagging. The more repeated, confirmed marks on an image the more important the image becomes, and it is moved up in the queue. Few marks or inconsistent ones would move the image down on the queue. Then the professional astronomers examine the crowdsourced input. The eyes that see these images are redundant to find consistency: the more users mark an image, the better the results are. Additionally as a participant it is possible to be among the first to view Spitzer images, a very special position. The range of projects is staggering with new ones being launched all the time, and the simplicity of them is great since anyone can do it.

To connect citizen science to the subject of this book, Moon Zoo at https://www.zooniverse.org/ provides high-resolution images of our own moon's surface (from the Lunar Reconnaissance Orbiter, LRO) to volunteers who count craters and map variation in age of lunar rocks. There is also Galaxy Zoo, radio galaxies, asteroids, “sun spotter,” “Higgs Hunters,” “Galaxy Zoo mergers,” “Galaxy Zoo Supernovae,” “SETI Live,” and more.

Remote Observing

While many amateur astronomers cannot realistically buy a home observatory, e-observing can fill the gap and provide greater magnifying power than is possible for mere backyard planet spotting. Sites like iTelescope Networks, LightBuckets, Mount Wilson Observatory, Cherry Mountain Observatory, Rent-a-scope, New Mexico Skies Remote Telescope Hosting, Bradford Robotic Telescope, and more allow for the rental of higher-powered scopes. After creating an account, buying a package, and reserving some time, you have your choice of apertures between 6 and 20 inches. You also have a choice of CCD cameras from small, fast ones for wide field sky images to big CCDs for images of faint objects like nebula, deep sky galaxies, or comets. Remote observing offers sites and instruments around the globe, making it possible to look at Polaris with one telescope and see Canopus on the same night. The mounts are good quality and the optics are well cared for, with no need to worry about collimating and aligning. Each telescope has controls for things such as guiding, filters, binning, and more, with the ability to preview the effects beforehand. There is a web page for each telescope giving all of the operating details you could want on each one, and any image you take is your own. Users have full legal copyright and privileges once the image is transferred to them.

Google Moon

If analyzing telescope data or doing remote observing seems too complicated, there is yet another option. In addition to stunning views of the Earth, a map or the Martian surface and an all sky map useful to any astronomer, Google Earth comes with a Moon mode as well. At the top of the Google Earth bar, click the small icon of Saturn, and from the drop-down menu select “Moon”. Soon you will have an image of the moon, which allow you to zoom to any level and rotate (near side, far side, west or east, north pole, south pole). Users can control the direction they are facing, pan the camera, and control the tilt, which goes as far as a ground level view. The bar on the bottom gives useful information, like coordinates of the mouse pointer and the height of the current view. You may wish to play with the Layer option, which offers the following in Moon mode:

- Featured Satellite Imagery (Click on a square to bring up a photo and an article)
- Place Names (useful to know what you are looking at)
- Global Maps:
  - Visible Imagery (Mostly Clementine images—what you see in the night sky)
- Colored Terrain (SELENE imagery, which shows the differing topographies on the lunar surface. useful on the far side where the crust is much thicker)
  - Lunar Orbiter Mosaic (from the Lunar Orbiter mission of the 1960s which blows the visible imagery right off the charts)
- Moon Gallery:
  - Apollo Missions (self-explanatory)
  - Guided Tours
  - Historic Maps

    USGS Geologic Maps
    USAF Topographic Maps

  - Human Artifacts by nation of origin

If you have a scroll wheel mouse (or if you use the slider on the right), you can zoom into the moon. Some of the places are not very high resolution in true sight, but in LO most places are exceptional. You can get stunning views from as close as just a few miles. If you wish to, you can even zoom all way in, and get a ground view from most places on the moon, and look up at the stars! You can also go the Apollo (or anything else) landing sites and see a model of where the item was, and (from the ground) see what the astronauts saw. You can also control the orientation tool. Some areas are also available in very high resolution imagery taken from the Apollo missions (you can see the ribbon at the top and some others) and Tycho is a wonderful image taken from Selene (zoom in and it will load up), and Mare Moscoviense (again give it a little zoom). To find these HR images is like an Easter egg hunt.

Don't forget to check out the Sky map too. A word of warning: if you turn on all the layers, you will be overwhelmed. You may want to keep very careful tabs on how much you want open here. If you see something very weird, you may want to check to see if you have the "Historical Sky Maps" > "Rumsey Star Maps" > "Cassini Overlay" turned on which uses the original star charts which Cassini illustrated. It is interesting but only works if you are viewing under about 12 arc degrees, a fairly tight zoom.

The program is not perfect, however. Something you should be aware of includes the search for common terms. For instance, if you search for "Grimaldi" you will get "Grimaldi" and "Rimae Grimaldi." Selecting Grimaldi here will bring you back the same thing and not the crater (but if you select Rimae Grimaldi, it will start to zoom in and you end up pretty close to both, so this is usually a fairly minor if annoying issue.) Also the Lunar Orbiter imagery is not complete. There is a large area missing on the south of the far side of the moon. Also it has a limited search feature. If you search for lots and lots of terms in row, it will eventually stop returning results until you shut it down and start it up again. It is a wonderful way to explore Luna on cloudy nights.

Appendix A
Luna and Telescopes

Exploring Luna's surface is one of the easiest things to do in this book. You have a few options when you do this. It has the advantage of being the only moon visible to the naked eyes. (You might be able to just see the Galilean moons, but you would hardly be able to do anything beyond just see them.) So the next step is to consider an instrument.

Be aware, this is not a general purpose guide. If you want one, look at the local library or bookseller for a copy of "NightWatch" as the book is excellent, has a sturdy plastic spiral for easy hands-free use and will serve you in more ways than just binoculars for many years to come. That being said all my recommendations in this chapter are for viewing ONLY OUR MOON. Most other moons will be pinpricks, so if you can see them at all you did the best you could. If you also wish to view nebula, galaxies, birds, be rude to your neighbors, and so forth, do your homework.

Binoculars

The first option is to go with binoculars. These come in a variety of sizes, which is listed as two numbers. The first is magnification and the second is aperture size (in mm). Common sizes include 7×35, 7×42, 8×40, 9×50 or even 10×50. For dim object you will want the bigger sizes, but the moon is not a dim object. Even a 7×35 will produce some pretty spectacular views.

If you do buy binoculars, go with a good company. More on this is under telescopes.

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If you intend to use binoculars you should ask yourself how. Some people try to stand up and use them and feel light-headed pretty quick as well as arm pain. Some people like to lie in a lawn chair and do it which makes it easier but not easy. The best choice here is to use a sturdy tripod (most binoculars have a mounting hole in the bottom), and to get a pair of 45° or 90° diagonals (required for standing, and standing is certainly easier). If you are a do-it-yourself-er you can even build a custom mount, that will hold the binoculars in place so you can look in them and then look away without touching them. For instance, you could mount them over the head of a reclining lawn chair, or even mount them on a swing table that pivots around you on an upright lawn chair (and with a large enough table you can have a guidebook or sketchbook too.) One thing that you may see at some more recent star parties is to use an inflatable pool dinghy, as it provides better neck and shoulder support them most lawn furniture does.

(Larger magnification gives a narrower field of view, but we are discussing the moon.)

If you are using a tripod you can also use big binoculars. What is big? 10×50, 11×80, 15×80, 16×70, and 20×80 all exist. 10×50s can weigh less than 2 lbs./0.75 kg. 11×80 can weigh 5 lbs./2.25 kg or more! I don't think you want to hold a 2 or 3 kg dumbbell over your eyes for an hour or more.

Telescopes

If you want to get a lot of magnification, you may need to use a telescope. I evaluate telescopes for three criteria: price, light site viewing, and quality for moon seeing.

Now, the most important thing if considering a telescope is quality.

I bought a "Galileo"-brand telescope with some impressive accessories off one of those home shopping TV stations for about $100. It came with an 8 mm eyepiece, and two others, a Barlow and sun projection plates. The tube was of inferior quality the objective lens was substandard. The 8 mm eyepiece has a small lens that was not fitted properly. The tripod was a steel tripod, with inline screws for the legs, and actually was of pretty good quality, at least for an altazimuth. I could see the moon and the Pleiades, and project the sun but that was about it. The whole shebang was sold at a moving sale for about $15 (since the tripod was of good quality).

Buy a telescope from a good company. Who is good? Meade, Celestron, Astro-physics, Televue, and Vixen. There are others too, but the best place to ask is a local planetarium if you are lucky enough to live near one, or you could go to any university. If they do not have an astronomy department try Physics. Avoid telescopes from Chinese factories (since they make 90 % of the trash scopes), but some Japanese companies also make a very good selection. Takahashi and Caton are well known. And yes, you do get what you pay for. If you pay 15,000 for a Meade, you will get more than the $100 "Department store XYZ Christmas Special."

It also helps if you have an assistant. Telescope stores are better than department stores. If you make friends at star parties or astronomy clubs, one of them may wish to help you on your way. Books can also be helpful.

Also give a thought to accessories. Your tripod should be sturdy, but an altazimuth is often sufficient for the moon. Erecting prisms can be useful if you are using a refractor. Reflectors often do not require them. Neutral-color lunar filter are essential for bright moons, like the type you will come up against during full moon. If you intend to image you will need a CCD or DSLR, but there are entire books just on the subject of astrophotography. Computer controls will likely not be required; if the moon is up, you can usually tell without a computer telling you… If you have an equatorial, you can have a motor drive follow the moon, but an equatorial is not required for lunar viewing, neither do you require setting circles. A motorized focuser should be used if you have one and wish to. This is a person-to-person decision.

So, what type of scope is best for the viewing the moon from a bright site which does not require a second or third mortgage?

Apochromatic Refractors

Ratings: ***Price***: *2*; ***Performance***: *10*; ***Light***: *7* (***Overall***: *6.3/10, due to price, 8.5 otherwise*)

In the 3–7″ (80–180 mm) range these provide the best result. This is the preferred choice *if you can afford one.* This works well in a bright site, and outperforms achromatics in a dark site. If you are limited to mostly urban viewing this is still a good choice. A good one can run from $2000–3000 for a 100 mm apochromatic with sturdy equatorial mount. This is the best, but out of price for most—this would be fine if the planets and moons were you career choice.

Maksutov-Cassegrains

Ratings: ***Price***: *ETX*: *7*; *Questar*: *0*; ***Performance***: *9*; ***Light***: *8* (***Overall***: *ETX*: *8/10, Questar*: *5.7/10 due to price*)

In the 3.5–7″ (85–180 mm) range these provide excellent results (second only to Apochromatic Refractors) if you have a good model. This works good-very good in a bright site. Price will limit you. The Meade ETX will stay under $1000. A well-maintained Questar will cost about $4000.

Achromatic Refractors

Ratings: ***Price***: *5–9*; ***Performance***: *9*; ***Light***: *7* (***Overall***: *7.7/10*)

In the 2.4–4″ (60–100 mm) range these provide excellent results (for the moon). You may wish to use a longer focal length, f/9–f/16. You telescope dealer or assistant (if he knows what he is doing) will be able to help you with this. This works well in a bright site, but underperforms in a dark site. These run from $500–$1000 (at the upper end with a sturdy mount). Small ones can be under $500 but check the mount. These can run from $1000–$1500 for top quality models (like a Meade or Celestron 4″ with an equatorial mount.)

Small Newtonian Reflector, Equatorial Mount

Ratings: ***Price***: *9*; ***Performance***: *7*; ***Light***: *7* (***Overall***: *7.7/10*)

In the 4–8″ (100–200 mm) range these provide good results (for moons). This works well in any site. You may get a small one for under $500 but check the mount.

Schmidt-Cassegrains

Ratings: ***Price***: *0–5*; ***Performance***: *7*; ***Light***: *7* (***Overall***: *5.5/10*)

In the 4–8″ (100–200 mm) range these provide good results. This works well in any site. These run up $1000–$1500 or can be $1500–$2500. Look at the options you're paying for (since computer control is likely included on the higher priced ones). 8″ ones can even run up to $4000.

Large Newtonian Reflector, Equatorial Mount

Ratings: ***Price***: *5*; ***Performance***: *7*; ***Light***: *4* (***Overall***: *5.3/10*)

In the >10″ (>250 mm) range these provide good result. Use a focal length of f/6–f/8 for best results. This is rather limited in bright sites. These will probably run you $500–$1000

Small Newtonian Reflector, Dobsonian Mount

Ratings: ***Price***: *9*; ***Performance***: *6*; ***Light***: *7* (***Overall***: *7.3/10*)

In the 4–8″ (100–200 mm) range these provide good results, but the mounts are not designed for viewing moons and planets—they don't move too easily. This works well in any site. These cost under $500.

Large Newtonian Reflector, Dobsonian Mount

Ratings: ***Price***: *3–7*; ***Performance***: *1*; ***Light***: *4* (*Overall*: *3.3/10*)

In the >10″ (>250 mm) range these perform poor or very poorly, the mounts are not designed for viewing moons and planets even more so than the small ones. This is rather limited in bright sites. These run from $500–$1000. The largest cost $1500–$2500. For moons, this is not recommended, and for our moon, this is right out.

Notable Lunar Features

There are so many lunar features to include; it seems more appropriate than to put them all in the text than in an appendix (as was originally planned). See Chap. 2 for a table of 176 items, 165 of which can bee seen, and extensive descriptive notes. (A map was to have been included, but at the last minute it was removed to the poor reproduction quality You can download a very high resolution map from https://www.hq.nasa.gov/alsj/LPC-1.html. it is available in 4 and 11 mb format and some computers cannot handle the 11, and when I downloaded this file the extension was ".jp2", which you will need to change to ".jpg" for it to open easily).

Appendix B
Lunar Mission Highlights

Mankind has thus far only visited one object beyond the Earth and that is Luna, our own moon (or at least 72 % of Russians (in the context of "ethnic group"), and 80–94 % of Americans believe we did). As there are hundreds if not thousands of books covering the Apollo missions from every viewpoint and in every detail, only a brief overview of mission highlights appears here.

Also please note that while I have great respect for all the brave Apollo astronauts, 1 and 8–10 were technical and test missions. Here, I cover only the landed lunar science missions 11–17 (and Apollo 13 briefly as it was intended to land.)

I have also converted the coordinates from decimal to degree/arc minute format (and rounded to the nearest arc minute) (Figs. B.1 and B.2).

APOLLO 11

"The Eagle has landed…"

Crew: *Neil Armstrong, Commander*; *Edwin E. Aldrin Jr., Lunar Module Pilot* (Eagle, LM-5), *Michael Collins, Command Module Pilot* (Columbia, CSM-107)

Primary objective:

- Complete a national goal set by President John F. Kennedy on May 25, 1961: perform a crewed lunar landing and return to Earth before 1970 (before the decade is out).

Additional flight objectives:

- Scientific exploration by the lunar module crew;
- Deployment of a television camera to transmit signals to Earth;
- Deployment of a solar wind composition experiment, seismic experiment package and a Lunar Laser Ranging experiment;
- Gather samples of lunar-surface materials for return to Earth;

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Fig. B.1 Apollo Logo. The logo of the Apollo project (the project, not any mission specifically). (Credit: NASA)

Fig. B.2 Apollo 16 Landing Panorama. This is a composite image of the Apollo 16 landing site. Years earlier on Apollo 11, Buzz Aldrin called the lunar surface "magnificent desolation." This image shows the type of surface typical of most lunar landings. (Credit: NASA)

- Both astronauts were told to extensively photograph the lunar terrain, the deployed scientific equipment, the LM spacecraft, and each other, both with still and motion picture cameras.
- Fly a "free-return" trajectory, which would enable, if necessary, a ready abort of the mission when the combined command and service module/lunar module, or CSM/LM, prepared for insertion into lunar orbit. (The trajectory would occur by firing the service propulsion subsystem, or SPS, engine so as to merely circle behind the moon and emerge in a trans-Earth return trajectory, much like Apollo 13 had to do.)

Additional information:

- Lunar Location: Sea of Tranquility
- Lunar Coordinates: 0°43′ north, 23°38′ east
- Length of EVA: 2 hours, 31 minutes 40 seconds
- Returned Sample Payload: 21.5 kg (47.5 lb)
- Maximum Separation (from LM): 66 meters (217 feet)

Patch:

Figure B.3

Fig. B.3 Apollo 11 Logo (Credit: NASA)

APOLLO 12

"The Pinpoint Mission…"

Crew: *Charles Conrad Jr., Commander*; *Alan L. Bean, Lunar Module Pilot* (Intrepid, LM-6); *Richard F. Gordon Jr., Command Module Pilot* (Yankee Clipper, CM-108)

Primary objectives:

- An extensive series of lunar exploration tasks by the lunar module crew.
- Deployment of the Apollo Lunar Surface Experiments Package, or ALSEP, to gather seismic, scientific and engineering data throughout a long period of time

Additional flight objectives:

- Selenological inspection;
- Surveys and samples in landing areas;
- Development of techniques for precision-landing capabilities;
- Further evaluations of the human capability to work in the lunar environment for a prolonged period of time;
- Deployment and retrieval of other scientific experiments;
- Photography of candidate exploration sites for future missions.

- Retrieve portions of the *Surveyor 3* spacecraft, which had soft-landed on the moon April 20, 1967, a short distance from the selected landing site of Apollo 12.
- In addition, the Apollo 12 flight plan called for the LM ascent stage to provide a measured seismic stimulus for the ALSEP seismic experiment. Following crew return to the command and service module, or CSM, a controlled burn of the remaining propellants in the empty ascent stage caused the stage to crash into the moon, providing a measurable seismic shock impulse.

Additional information:

- Lunar Location: Ocean of Storms
- Lunar Coordinates: 3°2′ south, 23°25′ west
- (Surveyor III Coordinates: 3°2′ south, 23°28′ west, 0.16 km (0.1 mi. directly))
- Length of First EVA: 3 hours, 56 minutes, 03 seconds
- Length of Second EVA: 3 hours, 49 minutes, 15 seconds
- Total Length of all EVAs: 2 for a total 7 hours, 45 minutes, 18 seconds
- Returned Sample Payload: 34.35 kg (75.7 lb)
- Maximum Separation (from LM): 446 meters (1362 feet)

Patch:
Figure B.4

FIG. B.4 Apollo 12 Logo (Credit: NASA)

APOLLO 13

"Houston, we have a problem…"[1]

Crew: *James A. Lovell Jr., Commander*; *Fred W. Haise Jr., Lunar Module Pilot* (Aquarius, LM-7); *John L. Swigert Jr.* (Odyssey, CM-109)

Apollo 13 was supposed to land in the Fra Mauro area. An explosion on board forced Apollo 13 to circle the moon without landing. The Fra Mauro site was reassigned to Apollo 14.

Additional information:

Intended Lunar Location: Fra Mauro

Patch:

Figure B.5

Fig. B.5 Apollo 13 Logo (Credit: NASA)

[1] While this is taken directly from the NASA website it is in error. The actual quote is "Houston, we've had a problem"

APOLLO 14

"Shepard, back in space…"

Crew: *Alan B. Shepard Jr., Commander*; *Edgar D. Mitchell, Lunar Module Pilot* (Antares, LM-8); *Stuart A. Roosa, Command Module Pilot* (Kitty Hawk, CM-110)

Primary objective:

- Explore the Fra Mauro region centered around deployment of the Apollo Lunar Surface Scientific Experiments Package, or ALSEP;

Additional flight objectives:

- Lunar field geology investigations;
- Collection of surface material samples for return to Earth;
- Deployment of other scientific instruments, not part of ALSEP;
- Orbital science involving high-resolution photography of candidate future landing sites;
- Photography of deep-space phenomena, such as Zodiacal Light and Gegenschein;
- Communications tests using S-band and VHF signals to determine reflective properties of the lunar surface;
- Engineering and operational evaluation of hardware and techniques;
- Tests to determine variations in S-band signals; and
- Photography of surface details from 60 nautical miles in altitude.

Additional information:

- Lunar Location: Fra Mauro
- Lunar Coordinates: 3°39′ south, 17°29′ west
- Length of First EVA: 4 hours, 47 minutes, 50 seconds
- Length of Second EVA: 4 hours, 34 minutes, 41 seconds
- Total Length of all EVAs: 2 for a total 9 hours, 22 minutes, 31 seconds
- Returned Sample Payload: 42.28 kg (93.2 lb)
- Maximum Separation (from LM): 1.37 km (0.85 miles)

Patch:

Figure B.6

APOLLO 15

"Climb aboard the Lunar Rover…"

Crew: *David R. Scott, Commander*; *James B. Irwin, Lunar Module Pilot* (Falcon, LM-10); *Alfred M. Worden. Command Module Pilot* (Endeavor, CM-112)

Fig. B.6 Apollo 14 Logo (Credit: NASA)

Apollo 15 was the first of the Apollo "J" missions capable of a longer stay time on the moon and greater surface mobility.

General objectives:

- Explore the Hadley-Apennine region,
- Set up and activate lunar surface scientific experiments,
- Make engineering evaluations of new Apollo equipment (including the Lunar Roving Vehicle),
- Conduct lunar orbital experiments and photographic tasks.

Specific objectives:

- Exploration and geological investigations at the Hadley-Apennine landing site, enhanced by the addition of the Lunar Roving Vehicle, or LRV.
- Setup of the Apollo Lunar Surface Experiments Package, or ALSEP, was the third in a trio of operating ALSEPs (Apollos 12, 14, and 15).
- Orbital science experiments were concentrated in an array of instruments and cameras in the scientific instrument module, or SIM, bay.
- Engineering and operational objectives included evaluation of modifications to the lunar module, or LM, made for carrying a heavier payload and for a lunar stay time of almost 3 days.
- Changes to the Apollo spacesuit and to the portable life support system, or PLSS, were evaluated, and performance of the Lunar Roving Vehicle and the other new J-mission equipment that went with it—lunar communications relay unit, or LCRU, and the ground-controlled television assembly, or GCTA.

- The launching of a Particles and Fields, or P&F, subsatellite into lunar orbit by the command and service module, or CSM, shortly before beginning the return-to-Earth portion of the mission. (The subsatellite was designed to investigate the moon's mass, gravitational variations, the particle composition of space near the moon and the interaction of the moon's magnetic field with that of Earth.)

Additional information:

- Lunar Location: Hadley-Apennine
- Lunar Coordinates: 26°5′ north, 3°40′ east
- Length of Standup EVA: 33 minutes, 7 seconds (In this they did not leave. They depressurized the LM and took photograph from the top docking hatch.)
- Length of First EVA: 6 hours, 32 minutes, 42 seconds
- Length of Second EVA: 7 hours, 12 minutes, 14 seconds
- Length of Third EVA: 4 hours, 49 minutes, 50 seconds
- Total Length of all EVAs: 4 for a total 19 hours, 7 minutes, 53 seconds
- Returned Payload: 77 kg (170 lb)
- Maximum Separation (from LM): 5 km (3.2 miles)
- Lunar Rover Mileage: 27.9 km (17.3 mi)

Patch:
Figure B.7

Fig. B.7 Apollo 15 Logo (Credit: NASA)

APOLLO 16

"Explore the Highlands…"

Crew: *John W. Young, Commander*; *Charles M. Duke Jr., Lunar Module Pilot* (Orion, LM-11); *Thomas K. Mattingly II, Command Module Pilot* (Casper, CM-113)

Primary Objectives:

- Inspect, survey, and sample materials and surface features at a selected landing site in the Descartes highlands region;
- Place and activate surface experiments; and
- Conduct in-flight experiments and photographic tasks from lunar orbit.

Additional objectives:

- Performance of experiments requiring zero gravity and
- Engineering evaluation of spacecraft and equipment.

Equipment:

- The fourth Apollo Lunar Surface Experiments Package, or ALSEP,
- Orbital science experiments were concentrated in an array of instruments and cameras in the scientific instrument module, or SIM, bay. Handheld Hasselblad 70 mm still and Mauer 16 mm motion cameras were used by the crew.
- Minor changes in surface extravehicular activity, or EVA, equipment were evaluated—a stronger clutch spring in the television camera drive mechanism to eliminate aiming problems experienced on Apollo 15, longer seat belts on the Lunar Roving Vehicle for better astronaut retention, continuous fluting of drill bits to eliminate bit binding due to extract jamming, and the addition of a treadle and jack to aid in drill core removal from the lunar subsurface.
- An ultraviolet stellar camera to return photography of the Earth and celestial regions in spectral bands not seen from Earth.
- Evaluation of the lunar rover through a "Grand Prix" exercise consisting of S-turns, hairpin turns and hard stops also was to be conducted.
- Another subsatellite launched into lunar orbit from the command and service module, or CSM, shortly before trans-Earth injection. (Again, the objective of the Particles and Fields, or P&F, subsatellite was to investigate the moon's mass, gravitational variations, the particle composition of space near the moon, and interaction of the moon's magnetic field with that of Earth.)

Fig. B.8 Apollo 16 Logo (Credit: NASA)

Additional information:

- Lunar Location: Descartes Highlands
- Lunar Coordinates: 8°58′ south, 15°31′ east
- Length of First EVA: 7 hours, 11 minutes, 02 seconds
- Length of Second EVA: 7 hours, 23 minutes, 09 seconds
- Length of Third EVA: 5 hours, 40 minutes, 03 seconds
- Total Length of all EVAs: three total for a combined 20 hours, 14 minutes, 14 seconds
- Returned Payload: 95.71 kg (211.0 lb)
- Maximum Separation (from LM): 4.5 km (2.75 mi.)
- Lunar Rover Mileage: 26.7 km (16.6 mi)

Patch:
Figure B.8

APOLLO 17

"We came in peace for all mankind…"

Crew: *Eugene A. Cernan, Commander*; *Harrison H. Schmitt, Lunar Module Pilot* (Challenger, LM-12); *Ronald E. Evans, Command Module Pilot* (America, Cm-114)

General objectives:

- Scientific objectives:
  - Geological surveying and sampling of materials and surface features in a preselected area of the Taurus–Littrow region;
  - Deploying and activating surface experiments;
  - Conducting in-flight experiments and photographic tasks during lunar orbit and trans-Earth coast.
  - Deploy a Apollo Lunar Surface Experiments Package, or ALSEP, with experiments in:

    Heat flow;
    Lunar seismic profiling, or LSP;
    Lunar surface gravimeter, or LSG;
    Lunar atmospheric composition experiment, or LACE; and
    Lunar ejecta and meteorites, or LEAM.

  - The mission also included lunar sampling and lunar orbital experiments.

- Biomedical experiments:
  - Biostack II experiment
  - BIOCORE experiment.

Additional information:

- Lunar Location: Taurus–Littrow
- Lunar Coordinates: 20°10′ north, 30°46′ east
- Length of First EVA: 7 hours, 11 minutes, 53 seconds
- Length of Second EVA: 7 hours, 36 minutes, 56 seconds
- Length of Third EVA: 7 hours, 15 minutes, 8 seconds
- Total Length of all EVAs: three total (on the surface), totaling 22 hours, 3 minutes, 57 seconds (Note: I write on the surface as there was also a space walk of just over an hour on the return trip to earth.)
- Returned Payload: 110.52 kg (243.7 lb)
- Maximum Separation (from LM): 7.5 km (4.7 miles)
- Lunar Rover Mileage: 35.74 km (22.21 mi)

Patch:
Figure B.9

Robotic Lunar Missions

Humans have also sent many robotic missions to the moon. They deserve some mention too. These are ordered by nation and then by year.

Fig. B.9 Apollo 17 Logo (Credit: NASA)

In all of the following descriptions, all locations have been converted from the decimal coordinates most commonly used and rounded to the nearest arc minute.

USA

Pioneer

- **Probes**: **Pioneers 0–4**,
- **Administrators**: varied
  - Pioneer 0 was undertaken by the United State Air Force.
  - Pioneer 1–4 was undertaken by NASA.
- **Years**: 1958–1959
- **Profiles**: Varied
  - Pioneers 0–2 were orbiters.
  - Pioneers 3 and 4 were flybys.
- **Performance**: On the whole it would be called a failure, but all space programs in the 1950s (and anything as challenging a space program) are at the end of a road paved with failures:

- Pioneer 0 (fail): (Thor-Able 1) failed 77 seconds after launch, and was destroyed.
- Pioneer 1 (fail): (Thor-Able 2) missed the moon due to a third stage partial failure.
- Pioneer 2 (fail): (Thor-Able 3) missed the moon, and reentered the Earth's atmosphere due to a third stage partial failure.
- Pioneer 3 (fail): (Juno II rocket) missed the moon due to a launch failure.
- Pioneer 4 (partial success): (Juno II rocket) did successfully launch and flew by the moon, at 60,000 km.

- **Payload**: Lunar radiation experiment (Geiger–Müller tube), lunar cameras.
  - Unfortunately, Pioneer 4 was the only one at the right trajectory to take photos, and was not close enough for the photoelectric sensor to be triggered so no photos were actually taken.
- **Brief**: Pioneer 10 (Jupiter) and 11 (Jupiter, Saturn) are the most well-known Pioneer mission, but the first few missions were aimed at the moon. After the national Advisory Committee for Aeronautics (NACA) was succeeded by The National Aeronautics and Space Administration (NASA) the work of exploration went to them (although the first probe, Pioneer 0 was operated by USAF). The Thor-Able rocket system did not fulfill the goal of the mission, but the Juno II rocket performed somewhat better. As the goal was mostly to reach escape velocity there was very little actual science performed.

Pioneer P

- **Probes**: **Pioneers P-1**, **P-3**, **P-30, P-31**
- **Administrator**: NASA
- **Years**: 1959–1960
- **Profile**: Orbiters
- **Performance**: Total Failure
  - Pioneer P-1 (fail): (Thor-Able 4A) launcher lost during pre-launch test.
  - Pioneer P-3 (fail): (Thor-Able 4) lost during launch.
  - Pioneer P-30 (fail): (Atlas-Able 5) failed to achieve lunar orbit.
  - Pioneer P-31 (fail): (Atlas-Able 5B) lost in upper stage failure.
- **Payload**: Lunar radiation experiment (Geiger–Müller tube), lunar photography.
- **Brief**: This was a subset of the Pioneer probes.

Ranger

- **Probes**: **Ranger 3–9**
- **Administrator**: NASA
- **Years**: 1962–1965
- **Profiles**: Impacters
- **Performance**: Again a failure (as a whole). Only 33 % performed well.
  - (Ranger 1 and 2 (fail) were block 1 Atlas-Agena rockets, and they both lived short, low-Earth orbits, due to the poor rockets.)
  - Ranger 3 (fail): (block 2) missed the moon.
  - Ranger 4 (fail): (block 2) failed and impacted.
  - Ranger 5 (fail): (block 2) missed the moon.
  - Ranger 6 (mostly fail): (block 3) impacted, but the camera had failed.
  - Ranger 7 (success): (block 3) impacted Mare Cognitum
  - Ranger 8 (success): (block 3) impacted Mare Tranquillitatis
  - Ranger 9 (success): (block 3) impacted Alphonsus crater
- **Payload**: Lunar cameras.
  - Ranger 7: Over 4300 pictures
  - Ranger 8: Over 7000 pictures
  - Ranger 9: Over 5800 pictures
- **Brief**: Ranger probes gave scientists their first good look at the moon so they could see what terrains there were on the moon. They found maria (seas) were actually seas of sand, and they found that there were also some significant highland areas and craters as well.
- **Locations**:
  - 4: Crashed near Ioffe, 15°30′ S, 130°42′ W (far side)
  - 6: Crashed near Maclear in Mare Tranquillitatis, 9°24′ N, 21°30′ E
  - 7: Impacted in Mare Cognitum, 10°21′ S, 20°35′ W
  - 8: Impacted in Mare Tranquillitatis, 2°43′N, 24°37′ E
  - 9: Impacted in Alphonsus crater, 12°50′ S, 2°22′ E

Surveyor

- **Probes**: **Surveyor 1–7**
- **Administrator**: NASA
- **Years**: 1966–1968
- **Profiles**: Landers

- **Performance**: On the whole, mediocre (1–4: Mediocre. 5–7: Excellent):
  - Surveyor 1 (success): Soft landed on Oceanus Procellarum.
  - Surveyor 2 (fail): Crashed near Copernicus crater (see location below).
  - Surveyor 3 (success): Soft landed on Oceanus Procellarum.

    Due to an error its engines did not shut off so it "landed" a few times. This however damaged its TV/camera equipment.
  - Surveyor 4 (fail): Crashed on Sinus Medii.
  - Surveyor 5 (success): Soft landed on Mare Tranquillitatis.
  - Surveyor 6 (success): Soft landed on Sinus Medii.

    Surveyor 6 was intentionally lifted off and landed again.
  - Surveyor 7 (success): Soft landed near Tycho crater.
- **Payload**: Lunar cameras, Landing strut strain gauges (1, 4), Soil mechanics surface sampler (3, 4, 7), Alpha-scattering surface analyzer (5. 6, 7)
  - Surveyor 1: Over 11,225 pictures
  - Surveyor 3: Over 6300 pictures
  - Surveyor 5: Over 18,000 pictures (day 1), over 1025 pictures (day 2), and over 50 pictures (day 4). The first-day pictures were of notable higher quality due to the cold lunar night affecting the camera equipment.
  - Surveyor 6: Over 29,900 pictures!
  - Surveyor 7: Over 20,950 pictures (day 1), and 45 pictures (day 2)
- **Brief**: They surveyor missions were supposed to soft-land, and photograph the lunar surface on approach and after landing. They were also supposed to test the soil to determine the properties of the lunar surface. They were also supposed to determine the abundance of the major elements of the surface.
- **Locations**:
  - 1: Soft landed on Oceanus Procellarum, 2°14′ S, 43°13′ W
  - 2: Crashed near Lelande, between Fra Mauro and Sinus Medii, 4° S, 11° W (Precise location unknown)

    The standard line is that is crashed near Copernicus crater. Best data indicates it crashed much closer to Leland crater; in fact it seem to have crashed over 450 km from the rim of Copernicus, 250 km from Leland
  - 3: Soft landed on Oceanus Procellarum, 2°56′ S, 23°20′ W

    This is the final location.
  - 4: Crashed on Sinus Medii, 0°27′ N, 1°23′ W
  - 5: Soft landed on Mare Tranquillitatis, 1°25′ N, 23°11′ E

- 6: Soft landed on Sinus Medii, 0°29′ N, 1°24′ W

  This is the initial location.

  The final location is only 2.5 meters to the west.

  This is 770 meters away from Surveyor 4
- 7: Soft landed near Tycho, 41°1′ S, 11°25′ W

Lunar Orbiter

- **Probes**: **Lunar Orbiter 1–5**
- **Administrator**: NASA
- **Years**: 1966–1967 (concurrent with Surveyor)
- **Profiles**: Orbiters
- **Performance**: Good:
  - Lunar Orbiter 1 (success)
  - Lunar Orbiter 2 (success)
  - Lunar Orbiter 3 (partial success)
  - Lunar Orbiter 4 (partial success)
  - Lunar Orbiter 5 (success)
- **Payload**: Photographic equipment
  - Total: Over 99 % of the surface of the moon mapped, with over 2175 high resolution images (1 square meter resolution), and over 875 medium resolution (but wider-angle) images.
- **Brief**: Each orbiter had a task:
  - LO 1–3: Apollo landing site survey
  - LO 4: General mapping
  - LO 5: Mapping and High-resolution surveying
  - In addition each one was equipped to photograph smooth areas, collect selenodetic data, radiation intensity data, and micrometeorite impact data.
- **Locations**:
  - 1: Impacted near Mandel'shtam, 6°42′ N, 162° E (far side)
  - 2: Impacted near King (and the five named peaks in this 76 km crater), 3° N, 119° E (far side)
  - 3: Impacted near Mees, 14°18′ N, 97°42′ W (far side)
  - (4 went down, but the location is unknown. They suspect that is hit the moon somewhere between 22° W and 30° W, but more precision is not possible. LRO has yet to find its wreckage, or we yet have yet to identify any debris as such)
  - 5: Impacted near Schlüter, 2°47′ S, 83°6′ W

Apollo occurred at about this point, but as it was not a robotic mission and as it has been extensively covered above, there is no need to cover it again.

Mariner

- **Probe**: **Mariner 10**
- **Administrator**: NASA
- **Year**: 1973
- **Profiles**: Flyby
- **Performance**: Successful
- **Payload**: Lunar camera
  - There was much more, but this was all that pertained to the lunar phase of the mission.
- **Brief**: Mariner is usually associated with its primary mission to Mercury and Venus, but it did use its camera to take five photomosiacs of Earth and six of the moon, including the first pictures of the north Polar Regions.

Clementine

- **Probe**: **Clementine** (Deep Space Program Science Experiment (DSPSE))
- **Administrators**: NASA in conjunction with (now defunct) BMDO (the Ballistic Missile Defense Organization).
- **Year**: 1994
- **Profiles**: Orbiter
- **Performance**: Successful
  - The lunar mission was perfect.
  - Due to a computer failure after leaving lunar orbit the other mission to NEA 1620 Geographos was cancelled.
- **Payload**:
  - Charged Particle Telescope (CPT),
  - UltraViolet/VISible camera (UV/Vis),
  - Near-InfraRed CCD camera (NIR),
  - Laser Image Detection And Ranging system (LIDAR), and a
  - HIgh-RESolution camera (HIRES)
- **Brief**: Clementine revolutionized our views of the moon. The moon was imaged at various wavelengths, including UV and IR, and charged particle measurements were taken. The entire surface underwent spectral imaging, the surface mineralogy was assessed, altimeter readings were taken, and gravity data were gathered on the near side.

Lunar Prospector

- **Probe**: **Lunar Prospector**
- **Administrator**: NASA
- **Years**: 1998–1999
- **Profile**: Orbiter/Impacter
- **Performance**: Successful
- **Payload**:
  - Gamma-Ray Spectrometer (GRS),
  - Neutron Spectrometer (NS),
  - The Alpha Particle Spectrometer (APS),
  - Doppler Gravity Experiment (DGE), and a
  - Electron Reflectometer and MAGnetometer (MAG/ER).
- **Brief**: Lunar prospector was designed for a low polar orbit of the moon, and was intended to map the surface composition, investigate possible polar ice deposits, measure magnetic and gravity fields, and study lunar outgassing. At the end of its mission it was purposefully crashed in hopes of sending a plume of ice from the impact site into space (of which, no plume was observed).
- **Location**:
  - Impacted near Shoemaker, 87°49′ S, 42°21′ E (while technically on the near side this is very close to the South Pole.)

Lunar Reconnaissance Orbiter (LRO)

- **Probes**: **LRO**
- **Administrator**: NASA
- **Year**: 2009 (ongoing)
- **Profiles**: Orbiters
- **Performance**: Successful
- **Payload**:
  - Cosmic Ray Telescope for The Effects of Radiation (CRaTER),
  - Diviner Lunar Radiometer Experiment (DLRE),
  - Lyman Alpha Mapping Project (LAMP),
  - Lunar Exploration Neutron Detector (LEND),
  - Lunar Orbiter Laser Altimeter (LOLA), and a
  - Luna Reconnaissance Orbiter Camera (LROC).
- **Brief**: LRO was tasked with characterizing the global lunar radiation environment, (and its biological impact), measure surface thermal emissions to provide information for future surface operations, seek water ice in permanently shadowed craters, using distant stars UV

light, create a precise model of the lunar topography and geodetic grid, and to measure requirements of landing sites and polar illumination. It also provides a high resolution map of the moon's surface.

Lunar Crater Observation and Sensing Satellite (LCROSS)

- **Probes**: **LCROSS Shepherding Spacecraft**, **LCROSS Centaur Upper Stage**
- **Administrators**: NASA/Ames Research Center
- **Year**: 2009
- **Profiles**: Impacter
- **Performance**: Below anticipations but successful.
- **Payload**: LCROSS had
  - One visible camera,
  - Two near-infrared cameras,
  - Two mid-infrared cameras,
  - One visible spectrometer
  - Two near-infrared spectrometers, and
  - A photometer.
- **Brief**: The Centaur Upper Stage was supposed to crash first and send a plume of material up (expected to be more than 350 metric tons, creating a crater 20 meters wide and 4 meters deep). The Shepherding Spacecraft would them fly through this plume and send data back to Earth before its own impact (150 metric tons and a crater 14 meters wide and 2 meters deep) and plume (which could be observed by LRO, Hubble, and from the Earth). In the end neither plume was observable from the Earth even through powerful telescopes with adaptive optics like the Hale telescope. In 2009, it was determined there was detectable water during the Shepherding Spacecraft descent.
- **Locations**:
  - SS: Impacted near Cabeus, 84°′44′ S, 49°22′ E
  - CUS: Impacted near Cabeus, 84°′41′ S, 48°44′ E

Time History of Events and Macroscale Interactions during Substorms (THEMIS)

- **Probes**: **Acceleration**, **Reconnection**, **Turbulence and Electrodynamics of the Moon's Interaction with the Sun**. (ARTEMIS P1 and P2)
- **Administrator**: NASA
- **Years**: 2010–2011
- **Profiles**: Orbiters

- **Performance**: Since THEMIS was a separate mission, the re-tasked satellites are like a bonus.
- **Payload**: Both spacecraft had the same instruments:
  - Electric Field Instrument (EFI)
  - FluxGate Magnetometer (FGM)
  - Search-coil Magnetometer (SCM)
  - ElectroStatic Analyzer (ESA)
  - Solid State Telescope (SST)
  - Digital Fields Board (DFB)
- **Brief**: The THEMIS mission was to study the energy releases from Earth's magnetosphere known as substorms, which affect auroras. ARTEMIS does the same type of studies (magnetic field studies) at the moon. At the time when it was done our moon was the only one known to have any electromagnetic field (although in 2015 it was discovered that Hyperion seemed to have a weak one too.)

Gravity Recovery and Interior Laboratory (GRAIL)

- **Probes**: **GRAIL**
- **Administrator**: NASA/JPL
- **Years**: 2011–2012
- **Profiles**:
  - Two Orbiters
  - Two Impacters
- **Performance**: Excellent
- **Payload**: Gravity Recovery and Climate Experiment (GRACE)
- **Brief**: GRAIL performed well, and gathered useful data for gravity mapping as well as giving us an idea of the moon's interior. It was also used to help us predict what type of fuel consumption need and what fuel requirements future missions will have.
- **Location**:
- Impacted near Mouchez, 75°′37′ N, 26°38′ W (On the near side, but very far north)

Lunar Atmosphere and Dust Environment Explorer (LADEE)

- **Probes**: **LADEE**
- **Administrator**: NASA
- **Years**: 2013–2014
- **Profiles**: Orbiter
- **Performance**: Successful

- **Payload**:
  - Neutral Mass Spectrometer (NMS)
  - UV-Vis Spectrometer (UVS)
  - Lunar Dust EXperiment (LDEX)
- **Brief**: LADEE measured neutral atoms and molecules in the exosphere, measured the dust in the exosphere with a spectrometer, and directly measured the dust in the exosphere.
- **Locations**:
- Impacted near Sundman, 10°′48′ N, 91°42′ W (far side. Technically, this is extreme eastern limb during time of favorable libration, but there would not be enough visible for anyone to see.)

Soviet/Russian

Note: *Due to the fact that many of these program were administrated under the Soviet Space Program which ran from the 1930–1991, during the height of the Cold War and the Space Race, some of this information is not necessarily true. Indeed, even as late as 2002 we found out new evidence concerning the fate of Laika aboard Sputnik 2. I did try to include the best information to be had on these missions as of the time of publication.*

Luna Programs

- **Programs**: Luna E, Luna, Cosmos, Lunokhod

Luna E

- **Probes**:
  - Luna E-1 No. 1, Luna E-1 No. 2, Luna E-1 No. 3,
  - Luna E-1A, No, 1,
  - Luna E-3 No. 1, Luna E-3 No. 2,
  - Luna E-6 No. 2, Luna E-6 No. 3, Luna E-6 No. 6, Luna E-6 No. 5, Luna E-6 No. 8
- **Administrator**: Soviet Space Program
- **Years**: Varied:
  - Luna E-1, No. *: 1958
  - Luna E-1A, No. 1: 1959
  - Luna E-3, No. *: 1960
  - Luna E-6, No. *: 1963–1965

- **Profiles**: Varied:
  - Luna E-1, No. *, Luna E-1A, No. 1: Imapacters
  - Luna E-3, No. *: Flyby
  - Luna E-6, No. *: Lander
- **Performance**: Total Failure. (The E-prefix seems to be a standard Soviet convention for the Early probes that failed. Later ones were given the name Luna)
  - Luna E-1 No. 1: Lost during launch, 92 seconds passed before disintegration.
  - Luna E-1 No. 2: Lost during launch, 104 seconds passed before disintegration.
  - Luna E-1 No. 3: Lost during launch, 245 seconds passed before hydrogen peroxide pump seizure.
  - Luna E-1A, No. 1: Lost during launch, 153 second before intentional destruction (by Range Safety, due to a severe gyroscope problem)
  - Luna E-3 No. 1: Lost during launch the upper stage cutoff was premature, because the fuel tank was only half full.
  - Luna E-3 No. 2: Lost during launch, a booster only reached 75 % of its intended thrust
  - Luna E-6 No. 2: Launched but into a useless orbit due to an upper stage error.
  - Luna E-6 No. 3: Lost during launch, due to a gyroscope error.
  - Luna E-6 No. 6: Lost during launch, disintegration.
  - Luna E-6 No. 5: Lost during launch, 340 seconds passed before an upper stage malfunction and cutoff.
  - Luna E-6 No. 8: Lost during launch, a nitrogen pipeline in the oxide tank depressurized resulting in engine cutoff (third stage)
- **Payload**: Varied:
  - Luna E-1 No. * Luna E-1A, No. 1: None. These were intended to impact so that there would be a man-made object on the moon.
  - Luna E-3: Circumlunar imagery equipment.
  - Luna E-6: Camera and radiation detectors.
- **Brief**: The Luna E-1 and E-1A missions were designed to impact the moon. The Luna E-3 probes were designed to image the moon, and the Luna E-6 was intended to soft-land, image and measure radiation for future manned missions.

Luna

- **Probes**: **Luna 1** (**previously E-1 No. 4**), **2–24**
- **Administrator**: Soviet Space Program
- **Years**: 1959–1976

- **Profiles**: Varied:
  - Luna 1 and 2: Impacters
  - Luna 3: Flyby
  - Luna 4–9, 13, 17, 21: Landers
  - Luna 10–12, 14, 19, 22: Orbiters
  - Luna 15 and 16, 18, 20, 23, and 24: Sample Return
- **Performance**: 73 % successful, more during later missions.
  - Luna 1 (fail): Missed impact with moon, heliocentric orbit. It did however manage to make a flyby at 5995 km something which no spacecraft had yet done,
  - Luna 2 (success): Impacted with moon, becoming first man-made object to do so.
  - Luna 3 (success): Orbited the moon becoming first object to do so. Returned image of far side.
  - Luna 4 and 6 (fail): Flyby, due to failed course corrections
  - Luna 5 (fail): Crashed at Sea of Clouds
  - Luna 7 and 8 (fail): Crashed at Oceanus Procellarum
  - Luna 9 (success): Achieved soft landing. Returned 5 black and white panoramic photographs,
  - Luna 10 (success): First object to orbit the moon (first artificial lunar satellite).
  - Luna 11, 12, 14, 19, 21, 22: Successful
  - Luna 13 (success): Landed at Oceanus Procellarum.
  - Luna 15 (fail): Which was a soil return mission, crashed into a mountain at Mare Crisium a few minutes after Neil Armstrong and Buzz Aldrin had landed.
  - Luna 16 and 20 and 24 (success): Sample collected and returned. Total 0.326 kg (0.718 lbs. on Earth).
  - Luna 17 and 21 (success): Carried rovers (see Lunokhod, below)
  - Luna 18 (fail): Crashed near the Sea of Fertility.
  - Luna 23 (partial success): a sample drill failed
  - Luna 24 (success): Returned the first sample where water was detected.
- **Payload**: Varied: (I have condensed answers where possible, but in many cases there are gaps in my data. In some cases you can guess that a certain item was carried (i.e., if 6–9 have an instrument as well as 11–14, you could infer 10 probably had one). I only list items where a high amount of certainty exists.)
  - Cherenkov Detectors: 1–2
  - Cosmic Ray Detector: 19
  - Dynamograph: 13
  - Gamma-ray Spectrometer: 10–11, 14, 19

- Gas Discharge Counters: 10 (5), 14 (5)
- Geiger Counters: 1–2
- Imaging System for Lunar Photography: 11, 17, 19

  11 returned no usable images due to a misorientation, due to a foreign object in one of the attitude control thrusters.

- Infrared Detector: 10, 14
- Infrared Radiometer: 11
- Ion Traps/Charged Particle Traps: 10 (2), 14 (2)
- Laser Reflector: 17, 21
- Low-energy X-ray photon Counter: 10, 14
- Magnetometer: 1–2, 10–11, 14, 19, 21
- Meteoroid Detector: 11, 19
- Micrometeorite Detectors: 1–2
- Odometer/Speedometer: 17, 21
- Piezoelectric Micrometeorite Detector: 10, 14
- Photodetector: 21
- Photographic Equipment: 3–4, 12–13, 21

  3: 29 photos, 12–17 of which were transmitted, including far side photos, of which 6 frames were released.
  4: No photos taken
  12: 2 high resolution photos were all that was released
  13: 5 panoramas of Oceanus Procellarum

- R-1 Transmission Experiment: 11
- Radiation Densimeter: 13
- Radiation Detector 9, 11, 15–19, 21, 23–24 (probably on all 15–24, as 20 and 22 are not listed)
- Radio Altimeter: 18–19, 23–24
- Remote Arm for Sample Collection: 15–16, 18, 23–24 (with an improved drill)
- Scintillation Counters: 1, 2
- Soil-measuring Penetrometer: 13, 17, 21
- Stereo Imaging System: 15–16, 18, 23–24
- Visible/Ultraviolet Photometer: 21
- X-ray Spectrometer: 17, 21
- X-ray Telescope: 17, 21
- (No information is included on 5–8 since they all failed, and their payload is therefore of little consideration. I had no payload data on 20 and 22.)

• **Brief**:

  - 1: Discovered some high-energy particles in the Van Allen belts. Released a cloud of sodium which allowed us to observe the effects of a gas in space. Discovered the lack of a lunar magnetosphere (which was later found to be incorrect). Observed solar wind.

- 2: Discovered time variations in electron flux and energy spectrum in Van Allen belts.
- 3: Photographed lunar far side (which were released soon after they were received)
- 4–8: Failed
- 9: Photographs taken from lunar surface (which were not released, but as they were transmitted in a familiar format to Radiofax, an internationally agreed upon system to transmit photos for newspapers, and which were able to be deciphered by anyone who could receive the radio transmissions, like the Daily Express or the Jodrell Bank Observatory).
- 10: Gathered data on the strength of the moon's magnetic field, radiation belts, lunar rocks (basalt), cosmic radiation, and micrometeoroid density. Also discovered mass concentration on the moons, which explained why maria distort lunar orbital trajectories (which is also often credited to the Lunar Orbiters series).
- 11: Studied lunar gamma and X-ray emissions in order to determine the moon's chemical makeup, studied lunar gravitation anomalies, the concentration of meteor streams, and the intensity of hard corpuscular radiation in the lunar environs.
- 12: Beside the two high resolution photographs (part of Luna 11's mission), little data are available. Although it seems to have contained a test motor that later was used on the Lunokhod rovers.
- 13: Measured soil properties and radiation densities.
- 14: Studies lunar–terrestrial mass interaction, propagation and stability of radio communications, solar charged particles and cosmic rays, and lunar motions.
- 15: Study lunar gravitation, and chemical composition of lunar rocks. Also photograph the lunar surface.
- 16: Returned a soil sample (101 grams, about 3.6 oz.)
- 17: The most significant thing Luna 17 did was deliver the Lunokhod 1 rover, which is covered in greater detail below.
- 18: Although the Soviet claimed this to be a failure, the continuous-wave radio altimeter did report on the mean density of the lunar topsoil.
- 19: Extended study of gravitational fields, and further study of the mass concentrations (see Luna 10, above) Also studied lunar radiation, the gamma-active lunar surface and the solar wind.
- 20: Collected and returned sample (55 grams or 1.9 oz.). This sample was different. It was collected in the highlands and was about 50–60 % Anorthosite (which is largely light-colored feldspar, much like Earth granite), where as the lowland was mostly dark-colored basalt.
- 21: The most significant thing Luna 21 did was deliver the Lunokhod 2 rover, which is covered in greater detail below. Although it did have an impressive instrument package, and it did collect images, examine the level of lunar light, determine the feasibility of astronomy

from the moon, do laser ranging experiments, observe solar X-rays, measure local magnetic fields, and study the mechanic of lunar soil.
- 22: The ship did imaging, and studied the magnetic field in detail from orbit. It also studied surface gamma-ray emissions, composition of lunar surface rocks, the gravitational field, micrometeorites, and cosmic rays.
- 23: This craft landed, but tipped onto its side damaging its drill which was the primary mission. (Luna 16 and 20 gather material from 0.3 meter (about a foot)). This lander was supposed to drill down to 2.5 (about 8 feet).
- 24: Return third and final sample (170 grams, or about 6 oz. from about 2 meters or 6.5 feet) When this sample was examined water was detected (it was only about 0.2 grams or about 0.1 % by mass, but it was ten times above the detectors minimum threshold level).

• **Locations**:
  - 2: Impacted near Autolycus, Sinus Lunicus (which actually means "Lunik Bay," as Luna 2 was called Lunik 2 in parody of Sputnik in the West), 29°6′ N, 0° E
  - 5: Crashed near Lansberg, Mare Insularum, 8° N, 23° W
  - 7: Crashed near Marius, Oceanus Procellarum, 9°48′ N, 47°48′ W
  - 8: Crashed on Oceanus Procellarum, 9°6′ N, 63°18′ W
  - 9: Landed on Oceanus Procellarum, 7°5′ N, 64°22′ W
  - 10, 11, 12, 14, 15, 19, 22: Crashed

    Many of these were just left in lunar orbit,. It can only be assumed that their orbit decayed with time, but the Soviet did not track these so it is uncertain exactly where they impacted.

  - 13: Landed 125 km from Seleucus in Oceanus Procellarum, 18°52′ N, 62°3′ W
  - 16: Landed near Dorsa Andrusov, Mare Fecunditatis, 0°41′ S, 56°18′ E
  - 17: Landed near Promontorium (headland promontory, or "cape") Heraclides, just outside of Sinus Iridum, on the very outskirts of Mare Imbrium, 38°17′ N, 35° W
  - 18, 20: Near Ameghino:

    These two "landed" less than 2 km from each other
    18 Crashed at 3°34′ N, 56°30′ E
    20 Landed at 3°34′ N, 56°30′ E

  - 21: Near (what is now known as) the Tangled Hills (Kholm Vstrechne), and near Le Monnier (a crater that looks much more like a bay, or Sinus), at the edge of Mare Serenitatis. 25°51′ N, 30°27′ E
  - 23, 24: The best data lists both as the same place: Near Fahrenheit, Mare Crisium, 12°45′ N, 62°30′ E (23 is uncertain), but these are the numbers published for 24

Lunokhod

- **Probes**: **Lunokhod 1** and **2**
- **Administrators**: Soviet Space Program
- **Years**: 1970–1973
- **Profiles**: Rovers
- **Performance**: Excellent
  - Lunokhod 1 was intended to drive for 3 months (3 lunar days). It actually operated for 11 months.
  - Lunkhod 2 worked for 4 months. It eventually failed due to overheating.
- **Payload′**:
  - Lunokhod 1: Antenna (cone-shaped), directional helical antenna, four cameras, soil test apparatus, X-ray spectrometer, X-ray telescope, cosmic ray detector, laser device (batteries, solar recharging panel, and a radioisotope heater to withstand lunar nights).
  - Lunokhod 2: three cameras, four panoramic cameras, soil test apparatus, solar X-ray experiment, astrophotometer (to measure ultraviolet and visible light levels), a magnetometer, radiometer, photodetector, and a laser corner reflector (supplied by France).
- **Brief**:
  - Lunokhod 1 operated for 11 months, 8 months more than intended, (setting the bar high for rovers like *Opportunity* which was intended to operate for 90 days and now over 10 years!) On the first day it returned 14 close-up pictures, and 12 panoramas. During its lifetime it returned 20,000 images, and 206 high-resolution panoramas. It performed 25 lunar soil analyses, using its RIFMA X-ray fluorescence spectrometer and using its pentameter at 500 different locations. The total journey covered 10.54 km.
  - Lunokhod 2 operated for 4 months. On the first day it took pictures before rolling out. It also took photos of the lander. On May 9, it seems that the open solar panel hit a wall of soft dirt near a crater, which covered part of the rover. When the solar lid was closed the soil insulated it, which trapped the heat supplied by its radioisotope thermal generator. It seems to have lost contact when it overheated. While initial estimate was that it covered 37 km, and later estimate placed it at over 42 km, the accepted figure is now at 39 km.
- **Locations**:
  - 1: Luna 17 landed near Promontorium (headland promontory, or "cape") Heraclides, just outside of Sinus Iridum, on the very outskirts of Mare Im. This separate the two by 3 arc minutes (distance as driven 10.54 km)brium, 38°17′ N, 35° W. Lunokhod 1 is at 38°14′ N, 35° W (rounded to the nearest arc minute)

  - 2: Luna 24 landed near (what is now known as) the Tangled Hills (Kholm Vstrechne), and near Le Monnier, at the edge of Mare Serenitatis. 25°51′ N, 30°27′ E. Lunkhod 2 is at (as close as can be determined and rounded to the nearest arc minute) at 25°47′ N, 30°55′ E, a separation of about 28 arc minutes, and a final distance (distance direct (not driven) of 14.55 km.)

Cosmos (Specifically, Cosmos Are Failed Luna Missions)

- **Probes**: **Cosmos 60**, **111**, **300**, **305**
- **Administrators**: Soviet Space Program
- **Years**: 1965–1969 (these are failed Luna missions)
- **Profiles**: Varied
  - Cosmos 60 was a Lander.
  - Cosmos 111 was an Orbiter
  - Cosmos 300 and 305 were Sample Return
- **Performance**: Total Failure. The Cosmos name seems to be is a standard Soviet convention for Luna probes that failed to leave earth orbit.
  - Cosmos 60 (fail): Due to a failure in the ship's power supply, it failed to leave Earth orbit.
  - Cosmos 111 (fail): The upper stage lost roll control and failed to send the ship into lunar orbit.
  - Cosmos 300 (fail): The upper stage engine blocks failed, stranding the ship in Earth orbit.
  - Cosmos 305 (fail): The upper stage engine blocks failed, stranding the ship in Earth orbit.
- **Payload**:
  - 60: See Luna E-6
  - 111: See Luna 10
  - 300 and 305: See Luna 16
- **Brief**: These are all similar to the comparable Luna mission, but failed to leave Earth orbit. As I said I believe Cosmos to just be a name for Luna that failed in this way.

Zond, etc.

- **Probes**: **Zond 3–10, Cosmos 146, 154, Zond 1967A, 1967B, 1968A, 1968B, 1969A, L1S-1, L1S-2**
- **Administrator**: Soviet Space Program
- **Years**: 1965–1970
- **Profiles**:

- Zond 3/7/8, Cosmos 146/154, Zond 1967A/B, 1968 A/B, 1969A were Flybys
- Zond 4/5/6, L1S-1, L1S-2 were Orbiters

- **Performance**: In general a failure. 39 % success rate (excluding Cosmos 146, Zond 9 and 10).
  - Zond 3 (success): Lunar flyby successful (9200 km)
  - Cosmos 146 (unknown): Soyuz 7K-L1P, launched by Proton in planned elliptical Earth orbit.
  - Cosmos 154 (fail): Soyuz 7K-L1P, launched by Proton, but failed to reach planned translunar orbit.
  - Zond 1967A (fail): 60 seconds, off course, escape tower used successfully, rocket crashed.
  - Zond 1967B (fail): Second stage failure, off course, escape tower used successfully, rocket crashed.
  - Zond 4 (partially successful): Test mission.
  - Zond 1968A (fail): 260 seconds, second stage failure
  - Zond 1968B (fail): Engines detonated on pad, killing 3
  - Zond 5 (success): Orbited the moon. Biological payload. Landed on Earth safely.
  - Zond 6 (success): Orbited the moon.
  - Zond 1969A (fail): Stage 2 shtdown 25 second early. Flight abort, safe recovery.
  - Zond L1S-1 (fail): First stage failure, Capsule escape system fired 70 seconds after launch for a safe recovery.
  - Zond L1S-2 (fail): First stage failure, Capsule escape system used for a safe recovery.
  - Zond 7 (success): Flyby (1984.6 km)
  - Zond 8 (success): Flyby (1110.4 km)
  - Zond 9, 10 (both cancelled)

- **Payload**:
  - 3: Camera, magnetometer, UV (covering 0.19–0.35 μm) and infrared (3–4 μm) spectrograph, radiation sensors, radio telescope, micrometeoroid instrument, experimental ion engine

    23 photograph, 3 UV spectra

  - 4: Test mission. It was the first Soviet space vehicle with a computer. It was called the "Argon 11" and weighed 34 kg.
  - 5: Its payload included two Russian tortoises, wine flies, meal worms, plants, seeds, bacteria, and other unspecified biological matter.
  - 6: Cosmic ray detector, micrometeoroid detector, photographic equipment, and an unspecified biological payload (probably similar to the Zond 5).

  - 7: Photographic equipment (including color)
  - 8: Photographic equipment. There was a scientific payload, but I have no data.

- **Brief**:

  - Zond 3 took some pictures, as did 7 and 8
  - Zond 4 was a test mission. It left Earth atmosphere reaching an apogee of 354,00 km, but at 180 degrees away from the moon. It reentered and was supposed to leave the atmosphere again, but the guidance system failed. Since it would not land on Soviet soil, it was set to self-destruct, which it did 10–15 km up and about 180–200 km off the coast of Guinea, Africa.
  - Zond 7, like all the Zond missions had as one of its goals was to serve as a precursor to manned flight. Zond 7 was the first one that, if it had been manned, would have allowed the cosmonauts to survive the Earth landing.

Luna-Glob

This mission, planned for 2014, has now been pushed back to 2018. It is a lunar exploration program by the Russian Federal Space Agency, and is a precursor to a planned full robotic lunar colony. This lunar base was planned for sometime after 2020 and some people connected to the project believe it could be completed as soon as 2037. As this mission is still in the planning and design stages I choose to not cover it in any more detail than this.

All Others

Hitan (Japan)

- **Probes**: **Hiten**, **Hagoromo**
- **Administrator**: Institute of Space and Astronautical Sciences (ISAS)
- **Year**: 1990
- **Profile**: Orbiter/Impacter
- **Performance**: Successful

  - Hiten was the first probe since 1976 to visit the moon.
  - Hiten was the first probe to use the low energy transfer, a procedure for attaining orbit that requires no delta-v (change in velocity), and use far less fuel than delta-v maneuvers ("burns"). It was also the first lunar probe launched by neither the USA nor USSR.

- Hiten carried the Hagaromo Impacter; its transmitter failed, but Earth observers were able to observe the probe do the first aerobraking procedure (which flies the vehicle through a high atmosphere, the drag of which reduces the velocity). This has been repeated on many missions since.

- **Payload**: The only scientific instrument carried aboard the Hiten was the Munich Dust Counter.
- **Brief**: Hiten was more a technology test mission, covering some technologies that have proven valuable since (Aerobraking, low energy transfers, and so on). The Munich Dust Counter examined the amount of dust in the Lagrange points (specifically L_4 and L_5), but found no increase over the background amounts.
- **Locations**:
  - Hagoromo: After the ninth swing-by and two aerobraking maneuvers, its mission completed, contact was lost.
  - Hiten: Near Stevinus, in Vallis Snellius, 34°18′ S, 55°36′ E

Small Missions for Advanced Research in Technology-1 (SMART-1) (ESA)

- **Probes**: **SMART-1**
- **Administrator**: ESA
- **Years**: 2004–2006
- **Profile**: Technology/Orbiter
- **Performance**: Successful
- **Payload**:
  - Advanced Moon micro-Imager Experiment (AMIE),
  - Demonstration of a Compact X-Ray Spectrometer (D-CIXS),
  - X-ray Solar Monitor (XSM),
  - Smart-1 InfraRed spectrometer (SIR),
  - Electric Propulsion Diagnostic Package (EPDP)*,
  - Spacecraft Potential, Electron and Dust Experiment (SPEDE), and
  - the Ka band tracking, telemetry and control (KATE).
  - *Note that EPDP, while not technically a scientific item as much as a diagnostic tool, is important as this was the first probe to use an Ion Drive (Ion propulsion) in a practical application.*

- **Brief**: SMART-1 found calcium in Mare Crsium and searched for a peak of eternal light (PEL, a place on the moon where sun always shines. These are the best places for solar collectors to be deployed since they have the most amount of time in the light, and the shortest periods of darkness.)
- **Location**: In Lacus Excellentiae (Lake of Excellence), 34°14′ S, 46°12′ W

SELenogical and ENgineering Explorer (SELENE, or Kaguya) (Japan)

- **Probes**: **SELENE** (**aka Kaguya**), **Okina**, **Ouna**
- **Administrator**: Japan Aerospace eXploration Agency (JAXA)
  - *JAXA was formed in 2003 from a combination of NAtional Space Development Agency of Japan (NASDA), National Aerospace Laboratory of Japan (NAL), and ISAS (from above).*
- **Years**: 2007–2009
- **Profiles**: Orbiter/Impacter
- **Performance**: Successful
- **Payload**:
  - X-Ray Spectrometer (XRS)
  - Gamma Ray Spectrometer (GRS)
  - Multi-band Imager (MI)
  - Spectral Profiler (SP)
  - Terrain Camera (TC)
  - Lunar Radar Sounder (LRS)
  - Laser ALTimeter (LALT)
  - Lunar MAGnetometer (LMAG)
  - Charged Particle Spectrometer (CPS)
  - Plasma energy Angle and Composition Experiment (PACE)
  - Radio Science (RS)
  - Upper-atmosphere and Plasma Imager (UPI)
  - Relay SATellite aboard Okina (RSAT)
  - VLBI RADio source aboard Okina and Ouna (VRAD)
  - a High Definition TeleVision camera (HDTV)
  - Also aboard was a 28 cm * 16 cm (11″×6.3″) sheet of paper, with 412,627 names and messages printed at 70 μm.
- **Brief**:
  - Kaguya was the main craft. Okina was a small relay, and Ouna was for the VLBI.
  - Kaguya carried the TC, XRS, LMAG, SP, MI, LALT, LRS, GRS, CPS, PACE, UPO, RSAT, and VRAD with the stated goal of obtaining scientific data of the lunar origin and evolution and to develop the technology for the future lunar exploration (according to the JAXA website).
  - Kaguya gave us improved lunar topographic maps, a detailed gravity map of the far side of the moon, and an optical observation of the permanently shadowed interior of the Shackleton crater (so near the south pole, the bottom never gets light (and has ice), and some parts of the top are close to a PEL, see the SMART-1 brief above).

- **Locations**:
  - Okina: 90 km south of Van den Bergn, 28°13′ N, 159°2′ W (far side)
  - Kaguya: On the edge of an unnamed crater not too far from Gill, 65°30′ S, 80°30′ E.

Chinese Lunar Exploration Program (China)

- **Probes**: **Chang'e 1**, **2**, **3**, **5-T1**, **4**, **5**, **6**
- **Administrator**: China National Space Administration (CNSA).
- **Years**: 2007–2020 (planned)
- **Profiles**: Varied
  - 1: Orbiter/Impacter
  - 2: Orbiter
  - 3: Lander
  - 5-T1: Flyby
  - 4: Rover
  - 5 and 6: Sample Return
- **Performance**: Successful-Excellent, thus far:
  - 1, 3: Success
  - 2, 5-T1: Success and an extended mission
  - 4–6: *Not yet attempted*
- **Payload**: Varied
  - 1: Stereo camera, laser altimeter, imaging spectrometer, gamma and X-ray spectrometer, microwave radiometer, and a high energy particle detector.
  - 2: Similar to the Chang'e 1 payload, but with upgraded equipment (better resolution camera, more accurate (and faster) laser altimeter, etc.)
  - 3: Lunar-based Ultraviolet Telescope (LUT), Extreme UltraViolet camera (EUV), lander camera, soil probe, and Yutu (a rover, see separate entry, below).
  - 5-T1: This was primarily a test mission to test spacecraft system as well as a capsule return for a lunar sample return mission scheduled for 2017 (Chang'e 5). It had a small camera to photograph the landing zone for Chang'e 5, a radio beacon, a radiation dosimeter, and a radiation exposure experiment with bacteria and plants.
  - 4, 5, 6: Not yet launched

    4, 6: *No data*
    5: (Unverified data suggest it will carry landing cameras, optical cameras, a mineral spectrometer, a soil gas analyzer, a soil composition analyzer, a sampling sectional thermodetector, and robotic drilling rig.)

- **Brief**:
  - Chang'e is from Heng'e, the Chinese goddess of the moon.
  - 1: Chang'e 1 is credited with the most accurate 3D map or the lunar surface, and the first passive, multichannel, microwave remote sensing of the moon. It examined the abundance of various chemical on the moon's surface. It probed the soil and assessed its depth; it also examined the environment between the moon and the Earth examining things such as solar wind. It was also considered an achievement for China, being their first probe. (I leave the political implications of this to authors who specialize in such things.)
  - 2: Chang'e 2 published the best resolution map of the moon up to that point. It then moved to the L_2 point to test the tracking and control software. It then performed a flyby of 4719 Toutalis and photographed it in close-up (the first time an asteroid was photographed with a resolution of 10 meters per pixel.)
  - 3: Chang'e 3 was a soft lander, and it deployed a rover, mostly as a precursor to sample return missions. See more information under Yutu below
  - 5-T1: The best data available suggests the mission was successful. Xiaofei, the return pod, was safely deployed and recovered. Beyond that result are not forthcoming.
  - 4, 5, 6: Not yet launched
- **Locations**:
  - 1: Far from any notable features in Mare Fecunditatis, 1°30′ S, 52°22′ E
  - 3: In Mare Imbrium, 44°7′ N, 19°31′ W

Yutu (China)

- **Probe**: **Yutu**
- **Administrator**: China National Space Administration (CNSA).
- **Years**: 2013–2014 (planned)
- **Profile**: Rover
- **Performance**: Partial
- **Payload**:
  - Ground-Penetrating Radar (GPR)
  - Spectrometers (Including Infrared, and Alpha Particles X-ray)
  - Stereo cameras
  - UV Camera and Telescope (still operating)
- **Brief**:
  - Yutu is literally translated as "Jade Rabbit" which is what the Chinese Dynastic writers refer to the rabbit in the moon as.

The "Rabbit n the Moon" is as common to the peoples of the East as the "Man in the Moon" is to the peoples of the West. It is also a companion to Chang'e (Heng'e) which seems only appropriate.

- On 14 Dec, it was deployed and by 17 Dec all instrument expect the spectrometer had been activated.
- Between 16 Dec and 20 Dec the rover did not move. The sunlit side of the rover was operating at 100 °C. Meanwhile, the side in shadow was below 0 °C. This caused the rover to partially power down.
- This did not cause it to stop taking pictures when it was still operating on full power.
- During its second day due to "mechanical control abnormality," a "complicated lunar surface environment" (according to The Planetary Society), it "could not prepare for the [2-week] oncoming lunar night." When night came, the mast was up and the solar panels were not folded.
- On the third lunar day the rover was declared inoperable and a loss. But one (Earth) day later, they got a signal from Yutu. However, the abnormality that it suffered the previous lunar day (which would soon be discovered to be a circuit malfunction in its driving unit) still impaired it.
- It was intended to operate for 3 months (December 2013–March 2014). As of March 2015 it still operates, but it is also still immobile, and it cannot close up properly for the lunar night. The extreme 2-week lunar nights cause some ability to be lost each night, but even with the degradation it still continues to send back data (i.e., The UV Camera and Telescope still operate)

- **Location**: In Mare Imbrium, 44°7′ N, 19°31′ W

Chandrayaan (India)

- **Probe**: **Chandrayaan-1**
- **Administrator**: Indian Space Research Organization
- **Years**: 2008–2009.
- **Profile**: Orbiter/Impacter
- **Performance**: Good. Duration-wise, 42 %; objective-wise (claimed to be) 95 %.
- **Payload**:

  - Terrain Mapping Camera (TMC)
  - Hyper Spectral IMager (HySI)
  - Lunar Laser Ranging Instrument (LLRI)
  - High-Energy aj/gamma/X-ray spectrometer (HEX)
  - Moon Impact Probe (MIP, see below)
  - X-ray fluorescence spectrometer (C1XS)
  - The Sub-keV Atom Reflective Analyzer (SARA)

  - Moon Mineralogy Mapper (M^3)
  - Near InfraRed Spectrometer (SIR-2)
  - Synthetic Aperture Radar (Mini-SAR)
  - RAdiation DOse Monitor experiment (RADOM-7)

- **Brief**: A number of objectives were accomplished:

  - M^3 confirmed the magma ocean hypothesis, showing that the moon was completely molten at one time.
  - TMC produced more than 70,000 3D images, including image of Apollo 15 landing site.
  - TMC and HySI covered 70 %, and M^3 and SIR-2 covered 95 %, providing us with mineralogy data on the lunar surface.
  - LLRI, HEX, and Min-SAR provided ISRO and the USA interests with unspecified interesting data on the understudied polar region of the moon. Over 200 orbits were made pole over the poles.
  - C1XS detected more than 2 dozen weak solar flares. RADOM-7 also monitored these.
  - Interactions between the solar wind and the moon's weak field have been studied.
  - C1XS detected titanium, confirmed calcium, and measured magnesium, aluminum, and iron at the surface.
  - Chandrayaan-1 had a 2 year mission profile, but after 312 days contact was lost for reasons unknown. The most recent data seem to indicate that a power supply failed due to overheating. It completed 10 months of a 2 year mission, but during that time it did complete 95 % of its objectives.

Moon Impact Probe (India)

- **Probe**: **Moon Impact Probe**
- **Administrators**: ISRO
- **Year**: 2008
- **Profiles**: Imapcter
- **Performance**: Success
- **Payload**: MIP carried three instruments:

  - Radar Altimeter
  - Video Imaging System
  - Mass Spectrometer based payload CHACE

- **Brief**: MIP was supposed to crash into Shackleton crater throwing up underground material which Chandrayaan-1 could then scan for water. This was completed successfully. Water was detected by Chandrayaan-1, but there are many articles on this subject and the implications.
- **Location**: Shackleton Crater, 89° S, 30° W

Appendix C
Resources and Answers

Chapter 15: Sample Log Page

On the next page you will find a sample log page which you may photocopy for you own use if you wish.

Chapter 16: Answers

The speed of light is 299,792,458 meters/second, or 186,282.034457 miles/second. This converts to a speed of 17,987,547,480 meters/minute, or 11,176,943.8231 miles/hour.

(Some more recent research indicates that the speed of light may not be as fixed as many think; some research talks about it changing by a matter of femtoseconds it takes to cross each meter due to the effects of photons interacting with other particles (i.e., electrons) and their path being altered by these electrons, but for this we will use these accepted values.)

You can be as accurate or inaccurate as you wish. I included far more accuracy than was needed.

1. 0.0159543370673 sec.
2. 2.55739144267 min.
3. 8.32181264102 min.
4. 6.20298785724 min.
5. 1.09424284153 hours
6. 3.0808180879 hours
7. 4.67416882393 hours
8. 4.78785660445 hours
9. 8.68423526926 hours

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Bonus Answers: *I gave the distances for these in parsecs since if I gave the distance in light years that would make things far too simple. After all the term "light-year" is how far light travels in 1 year, so for light to cross 500 light-years takes 500 years!*

10/Bonus 1. 1.24810505851 minutes
11/Bonus 2. 8.720106816 years

If we colonized Alpha Centauri without breaking the light speed barrier (as science fiction writers predict we will), it would take radio waves (a form of light)

Entry record number: ______________________
Project: ______________________
Target: ______________________
Date: ____________ Time: ____________
Location: ____________ Lat/Long: ________/________
Equipment: ______________________
Additional categorical information: ______________________
____
Specialist Notes: ______________________
Image/Sketch: ______________________
Capsule: ______________________
____

- -

Entry record number: ______________________
Project: ______________________
Target: ______________________
Date: ____________ Time: ____________
Location: ____________ Lat/Long: ________/________
Equipment: ______________________
Additional categorical information: ______________________
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Specialist Notes: ______________________
Image/Sketch: ______________________
Capsule: ______________________
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Entry record number: ______________________
Project: ______________________
Target: ______________________
Date: ____________ Time: ____________
Location: ____________ Lat/Long: ________/________
Equipment: ______________________
Additional categorical information: ______________________
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Specialist Notes: ______________________
Image/Sketch: ______________________
Capsule: ______________________
____

4 years to reach us telling us they made it and 4 years for us to reply. (Of course, if most science fiction writers are right, by the time they got there, there would be a ship there that had left Earth later, traveled faster, and arrived there earlier).

12/Bonus 3. Light travel time of 167,644.184 years In 165,629.184 B.C.E., it was 35,000 years after the oldest anatomically modern human fossils (Omo 1 and Omo 2). It was 5000 years before "humans" became *Homo sapiens idaltu*, living in Ethiopia, in the Awash River region, in the Herto village. This will be when burial rituals will be first established and they will seem to reach anatomical and behavioral modernity (including the use of red ochre and fishing). This is also 15,000 years before "Mitochondrial Eve"

13/Bonus 4. Light emission 13,046,240,000 years ago, but the error at this point is too great for an age to be reliable due to the red shift and dark energy interactions. This predicts an age of the universe between 751,000 and 380,000,000 years of age. So the second part of the question is not really able to be answered without more information, but it seems to be before reionization ended, and more than 8.5 billion years prior to our solar system forming.

Glossary

Adjective Alternative ways to represent possessives or partitives (i.e., Jupiter's gravity vs. the Jovian gravity. Ganymede's limb vs. the Ganymedian (or Ganymedean) limb.)

Albedo The reflecting power of a surface, given on a scale of 0–1, with 0 being no reflection at all, and 1 being a perfect mirror. (For those of you out there who are experts, this is the Bond not the visual geometric albedo, so 1 is an upper limit; Enceledus is therefore 0.99, not 1.4)

Alternative Names Astronomy has called different objects by different classifications throughout out all of its history. It is no different with moons. Many older ones are identified (if in no other alterative way), by the name of the planet and a roman numeral representing the order of their discovery. The newer ones will have had or still do have an IAU provisional name (i.e., S/2000 J11, a 4 km moon of Jupiter.)

Apoapsis This value is the maximum distance the object goes from the barycenter or "orbital focus." For most moons this is center of the planet they orbit, but not all (i.e., Charon's barycenter is above Pluto's surface, as is its own). For co-orbitals this is the same as aphelion. (Aphelion is the sun specifically.) This is a distance, measured in kilometers.

Apparent magnitude How bright the object appears (usually at opposition.) Measured in astronomical magnitude.

Average orbital speed This is the speed ate at which the body orbits the barycenter (usually the parent body, but see the Pluto-Charon dilemma in Chap. 9). Also see 90 Antiope in Chap. 4. Measured in kilometers per second.

Axial tilt This measure, sometime called obliquity, is the tilt of a rotating object in reference to its orbital plane. (Note that if an object has a retrograde spin, such as Venus, it appears upside down, and this number is close to 180°; for instance 177° for Venus). Measured in degrees (or °).

Composition (Atmosphere) This lists the known constituents of the satellite's atmosphere if any.

Dimensions Since radii are obviously different when measured pole to pole and around the equator unless the eccentricity is 0, most every object (especially asteroids) will not have a single mean radius, but will have three measures. In keeping with the "e" notation being used I also use an asterisk to represent multiplication for these sizes.

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(i.e., 433 Eros is 34.4 * 11.2 * 11.2 km.) Measured in kilometers. Only one number will be listed for objects which are roughly spherical (hydrostatic equilibrium) or for which data are incomplete/inconclusive.

Discovered by The person or group generally credited with the discovery

Discovery date As close as can be determined. Sometime discoveries and announcements may not match. For instance, Galileo discovered the (later called) Galilean moons in January. His results were not published until March of that year. They may have been seen before that as well (but that is another discussion later in this book). Also sometimes there may be more than one date. This is for object which were lost (i.e., Jupiter's moon Themisto was "lost" for 25 years—at only 4 km, we did not get accurate orbital data in 1975. It was found again in 2000, and its orbit was nailed down. Now we know where to look.)

Eccentricity This refers to how non-circular an orbit is. An eccentricity of 0 means the orbit is a perfect circle. A 1 means it is not an orbit (as it means "open"), but a parabola around a point (and not fit for this book; check a book about comets). Greater than 1 is possible, which is a hyperbola (also not fit for this book).

Equatorial surface gravity This is the gravity and is measured as a form of acceleration. It is measured in meters per second per second or meter per second squared (m/s^2, which defines how many m/s you gain per second, as a form of acceleration). It may also be measured in "g" (which is Earth's gravity at the equator, 9.80665 m/s^2. This is not to be confused with "G", the gravitation constant of all objects with mass > 0.)

Escape velocity The speed at which an object needs to move to break free of a source of gravity (which is any object in the universe with mass > 0.) This is a speed, and measured in kilometers per second.

Inclination This is the tilt of an objects orbit usually in reference to the parent body. Measured in degrees (or °). It may be measured to the ecliptic (in some cases and if so, it is mentioned).

Mass This is similar to weight (how heavy something is) with the exception that mass does not depend on gravity (which weight does). When an object is in space it loses weight (weightlessness), but retains the same mass. Measured in kilograms.

Mean density This is the mass of the object divided by the volume. The density in this book is the mean density in grams/cubic centimeter (or g/cm^3).

Orbital period This how long it takes for one object to orbit another. Depending on the object this could be measured in seconds or centuries, even millennia. (The Sun's orbit around the galactic center is about 250 million years!) Often it will be hours or days or given in hour minute second format (i.e., 12 h 30 m 30 s).

Periapsis This value is the minimum distance the object goes from the barycenter or "orbital focus." For most moons this is center of the planet they orbit. For co-orbitals this is the same as perihelion. (Perihelion is the sun specifically.) This is a distance, measured in kilometers.

Rotation period This is how long it takes a body to rotate once. Some objects will be listed as synchronous. This is like our moon, which always has one face toward us (tidal locking). It rotates in the same time as it orbits, so we cannot see more than 59 %. This is very common.

Satellite of This assumes a normal orbit. (Normal being defined her as with the barycenter inside an object such as a planet.) If the barycenter is not within an object (i.e., 90 Antipiope/90 Antiope 1, or Pluto/Charon) more information will be given in the descriptive text that follows.

Semi-major axis This is how far the object orbits from the object it orbits at the longest distance. It is a measure of distance (this is not the same apoapsis, which is distance from the barycenter or "orbital focus." If it is measured over the eccentric anomaly, then you get the semi-major axis. But the semi-major axis and the apoapsis would be the same if the barycenter were on the surface of said object in which case the object would pivot about that point, which would be very unusual except in case of tidally interlocked object such as in the Pluto-Charon system. But this does not intend to be a textbook on celestial mechanics). This is a distance. It is usually in kilometers (km), but in some cases may be expressed in other metric measurements.

Surface area This is the surface area of the object, if that measure is known. For spheres this tends to be somewhat easy but for irregular moons, this gets very complex, and often a range is the best that can be given. I give this measure in square kilometers or in comparison.

Surface pressure If there is an atmosphere, there will be some pressure. Many moons are just trace or none. Titan is one notable exception. If there is more than a trace, I give this measure in Pascals (between micro and kilo (µPa and kPa). If you are unfamiliar with this measure, Earth's surface pressure is 101.325 kPa, that is to say 101,325 Newtons per square meter.)

Surface temperature (**temp**) Obviously this will very depending on whether the temperature is the mean, maximum or minimum. It is measured in Kelvins (and thus I do not use the symbol for degrees as it is now technically incorrect, even though many still do so).

Volume Put simply this is how big something in cubic area. This is a measure in cubic kilometers.

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