SCI 238 — Introduction to Astronomy

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Winter 2015

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1 Chapter 1 – Our Place in the Universe

1.1 Overview

A naive look at the sky, which seems to rotate around us, implies we live in a **geocentric** Universe, ie. that everything orbits around the Earth. We know now that this is untrue, but the path to this knowledge was a long one.

We can refer to our place in the Universe as our **cosmic address**, this is our **solar system**; which consists of the Sun and all objects that orbit it including rocky **asteroids** and icy **comets**. Our solar system, and all the stars we can see, make up a small portion of the **Milky Way** galaxy.

A **galaxy** is an island of stars in space containing anywhere between a few hundred million to trillions of stars. The Milky Way is a relatively large one, with 100 billion stars. We are located about halfway from the center of the Milky Way (the **galactic center**) to the edge of the **galactic disk**.

In summary: the Earth is a planet in the solar system, which is a collection of objects orbiting a star, which is in the milky way galaxy, which is a part of the **local group** of galaxies, which is part of the **local supercluster** of groups, which is somewhere in the **Universe**.

The local group contains about 40 galaxies, and is one of what we call **galactic clusters** – groups of galaxies with more than a few members. Superclusters are essentially clusters of galactic clusters, as the Universe seems to be arranged ingiant chains and sheets with large divides between them. The local group is on the edge of the local supercluster.

1.2 The Big Bang and the Expanding Universe

We have observed that the Universe seems to be *expanding*, that is, the distance between galaxies is increasing. By extrapolating backwards, we imagine that all matter must ahve existed at the same point in the past and exploded outward in a **Big Bang**. Based on the rate of expansion, we believe this happened approximately 14 billion years ago.

Note that though the distance between galaxies is increasing, the distances between objects within galaxies is *not*.

Most galaxies, including our own, formed within a few billion years of the Big Bang.

1.3 The Birth of Stars

A star is **born** when gravity compresses the material in a cloud of gas and dust until it is dense and hot enough to generate energy through **nuclear fusion**. The star lives so long as it has useable material to fuel its fusion and dies once it runs out.

A star **dies** by blowing much of its remaining content back into space in a **supernova**. This matter eventually becomes new stars and planets.

1.4 Modelling the Universe

1.4.1 Distance

We can imagine our solar system shrunk down to a manageable size. On the **Voyage** scale (a model solar system in Washington, D.C. where sizes are one billionth of the actual size), the Sun is roughly the size of a grapefruit, Jupiter the size of a marble, Earth the size of a pinhead. Obviously the Sun is far larger than any planet, in fact, it has more than 1000 times as much mass as all the planets in our system combined. Note that the planets also vary in size to a large extent: the "permanent" storm on Jupiter known as the **Giant Red Spot** is larger than the Earth.

We can also use this model to describe the distances between objects. On the same scale, the Earth is 15m from the Sun and the distance from the Sun to pluto is 600m. To have enough space for the orbit of each object in the system, we would need a grid of 300 football fields centered around the Sun.

The closest star (Alpha Centauri) is incredibly far away, on this scale it would be the difference between Washington, D.C. and California.

If we reduce this scale by another factor of one billion, we can start thinking about the size of the galaxy. On this scale, each light year is roughly a millimeter and the Milky Way is about the size of a football field. The distance between our star system and Alpha Centauri is smaller than the width of our pinky.

1.4.2 Time

We can also model the time between events by creating a **cosmic calendar**. If we set the Big Bang as January 1^{st} and the present day as Decembre 31^{st}, we can place each major event on specific days. By the age of the universe, each month represents just over a billion years.

On this scale, the Milky Way was formed sometime in February. Our solar system, though was, only formed in September – life on Earth flourished by the end of that month. Recognizeable animals only appeared in mid-December. Dinosaurs first appeared the day after Christmas and died off yesterday. Around 9PM today, early hominids began to walk upright.

The entire history of human civilization, then, occurred in the last half-minute of January 31^{st}.The Egyptians built the pyramids in 11 seconds, Galileo proved the Earth orbited the Sun one second ago, and the average college student was born 0.05 seconds ago.

1.5 Motion of the Universe

The Earth has a daily rotation (its **spin**) and a yearly **orbit** (or **revolution**) around the Sun.

The Earth rotates each day around its **axis**, the imaginary line from the North to the South pole. It rotates from West to East – counter-clockwise when viewed from above the North pole. The speed is substantial; anywhere other than near the axes, an object whirls around the Earth at a speed greater than 1000km/h.

The Earth's average orbital distance is one **Astronomical Unit** (AU), which is approximately 150 million kilometers. At times, we race around the Sun in excess of one hundred thousand kilometers per hour.

Earth's orbital path defines the **eliptic plane**, and its axis is tilted by 23.5 degrees from a line perpendicular to this plane. The **axis tilt** happens to align our north pole with Polaris, the North Star.

Note that the Earth orbits the Sun in the same direction as it spins around its axis since it was formed from a spinning disk and both of these rotations are a remnant of this.

We also move relative to nearby stars at a rate of $70,000$ kilometers per hour. We rotate around the Milky Way's galactic center once every 230 million years, which implies speeds of (on average) $800,000$ kilometers per hour.

1.6 Dark Matter and Dark Energy

Since stars at different distance from the galactic center orbit at different speeds, we can learn how mass is distributed in the galaxy by measuring the differing speeds. Studies show that the mass of the stars in the galactic disk form only a small percentage of the total mass of the galaxy. Most of the galactic mass, then, seems to be located outside of the visible disk in the galaxy's **halo**. We call this mass **dark matter**, since we have not observed light being emitted from it. Similarly, we find that the bulk of the energy in the universe is **dark energy**. This seems to be the case in all observable galaxies.

1.7 Relative Galactic Movements

Within the local group, some galaxies move toward us and some move away. Outside of the local group, though, this changes; virtually every galaxy outside of the local group seems to be racing away from us at a speed proportional to its distance from us. This is the basis of our theory that of an **expanding universe**: that the space between galaxies is increasing.

Note that we observe this motion by measuring **Doppler shifts**, as detecting any difference in celestial position within our lifetimes is impossible.

2 Chapter 18 – Life in the Universe

- Reasons why life likely might exist elsewhere
  - Life arose quite quickly on Earth, so why not on other planets too
  - Chemicals on young Earth combined readily into complex organic compounds. This may also be true on other exoplanets.
  - We have discovered microorganisms that could survive on other planets in our solar system

- Timeline of development of life on Earth:

Years ago	Event
4.5 billion	Earth and moon form
3.85 billion	Carbon isotope evidence of life
3.5 billion	Oldest microfossil evidence of life
2.5 billion	earliest evidence of oxygen in the atmosphere
410 million	animals colonize land
230 million	mammals and dinosaurs appear

- Requirements for life (on Earth)
  - A source of nutrients
  - Energy to fuel the activities of life
  - Liquid water (* this is the only one that is difficult to achieve)
- Microbes living in extreme conditions (volcanic vents, deserts) imply that if not for a need for water life could exist almost anywhere
- Only likely candidates to have liquid water in our solar system are Mars and some jovian moons (e.g. Europa)
- What properties must a star system have to contain life
  - It must be older than several million years (that's how long life took to form after Earth's formation)
  - The star must not be much bigger than our Sun, because it would die off before life formed (still leaves about 99% of stars)
  - Planets must have stable orbits (far less likely in binary star systems, but not impossible)
  - Bigger star means larger habitable zone (the zone where liquid water could exist)
- A planet's spectra can give us the atmospheric makeup, allows us to look for water vapour, ozone, methane, etc.
- Rare-Earth hypothesis
  - The galaxy has a habitable zone, just like our solar system
  - Star systems further out contain far less non-hydrogen/helium elements, which almost completely compose terrestrial planets
  - Inner systems are subject to far more high supernovae, which would likely irradiate life
  - Leaves only about 10% of solar systems habitable
  - Impact rate in our solar system dropped off quickly, is the same true everywhere? In our solar system this was due to jovian planets ejecting small objects from the inner solar system

- Our atmosphere has been relatively stable due to plate tectonics (which might be rare on other planets) regulating the carbon dioxide, and our large moon regulates our axial tilt

- Counter-arguments include
  - Earth is very small and wouldn't need a high abundance of heavy elements to form (relative to the mass of the star)
  - We don't know if a supernova would be harmful to life
  - If the Earth rotated faster it would also regulate our axial tilt without the Moon
  - Large moons could exist other places, ours isn't that rare
  - Life could adapt to a changing axial tilt

- Drake equation: Number of civilizations = $N_{\text{HP}} * f_{\text{life}} * f_{\text{civ}} * f_{\text{now}}$

  $\mathbf{N_{HP}}$ number of habitable planets in the galaxy that *could* have life

  $\mathbf{f_{life}}$ fraction of habitable planets that actually have life

  $\mathbf{f_{civ}}$ fraction of life-bearing planets upon which a civilization capable of interstellar communication *has at some time* arisen

  $\mathbf{f_{now}}$ fraction of civilization-bearing planets that currently have such a civilization

- Fermi paradox: If it's so likely that other civilizations exist than there are some millions of years ahead of us technologically. So where are they? Options: "we're alone", "every other civilization destroyed itself before it could settle the galaxy" or "they haven't revealed themselves to us yet"

3 Assignment 5

Jovian planets __________ than terrestrial planets:

- Are more massive
- Are lower in average density
- Are bigger
- Orbit the Sun farther
- Have more moons
- Have rings

How are Pluto and Eris different from other planets:

- Smaller
- More elliptical orbits
- Less massive

- Similar composition to comets (ice and rock)

Characteristics of planets in our solar system:

- Large bodies have orderly motions
- There are exceptions to most trends
  - Venus spins backwards
  - Uranus rotates on its side (axial tilt $\approx 90°$)
  - The moon is about $\frac{1}{4}$ the size of Earth
- Planets orbit the Sun in the same plane
- Planets closer to the Sun move around their orbits at higher speed than planets farther from the Sun
- All the planet (not counting Pluto) have nearly circular orbits

Small bodies:

- Rocky = asteroids
  - Found in the asteroid belt
- Icy = comets
  - Found in the Kuiper belt (starts around Neptune, extends past Pluto) and Oort cloud (sphere around the solar system, far beyond Pluto)

Detecting extrasolar planets

- Planets are very dim compared to their star, it makes it very hard to image them visually. The angular separation from Earth is also very small.
- We can detect planets by watching how their star "wobbles" due to their gravity (Doppler technique). This technique can only give us the **minimum** mass of the planet (unless it's on the same plane as the Earth)
- Smaller orbital radius of planet results in higher max speed of the star and shorter period of rotation
- Mass of the planets only affects the max speed of the star in its "wobble"
- If the planets orbital plane lie between the Earth and the star we can see eclipses — a slight dip in the stars luminosity
- As of 2008, the most extrasolar planets have been discovered by the Doppler technique
- The Kepler mission mostly looked for eclipses
- Transit technique has the best chance of finding Earth-like planets
- The astrometric technique uses careful measurements of positions of celestial bodies to find planets

Properties of extrasolar planets (discovered so far):

- Some jovian planets have been found closer to their star than Mercury is to the Sun (hot Jupiters)
- Many are on very eccentric orbits
- Jovian planets migrate closer to their star from their original orbits
- Most are larger than Jupiter

Four process that shape planetary surfaces:

- Impact cratering
  - number of impacts per square area about the same for all planets
  - Mostly occurs in the first few hundred million years after formation
  - Primary factor for craters still being visible is if they've been erased, because they were definitely there at some point
- Volcanism
  - Outgassing explains how terrestrial planets got their atmospheres
- Tectonics
  - Happens beneath the *lithosphere*, the rigid layer of rock at the surface of a planet
  - Compression causes mountain ranges
  - Extension (stretching) causes cracks and valleys
  - Earth is the only planet where the lithosphere has been broken into plates
  - Lots of tectonic activity means lots of volcanic activity
  - Can only occur if the interior of the planet is liquid (hot!)
  - Big planets take longer to cool than small ones, so they have tectonic activity for longer
- Erosion
  - Occurs due to surface liquids, ices and gases
  - Liquid water is the best, causes much more pronounced features
  - Canyons (formed by glaciers), dunes, rock formations
  - Planet must be warm enough to have liquids, and big enough to capture an atmosphere

4 Definitions

4.1 Basic Astronomical Objects

- a **star** is a large, glowing ball of gas that generates heat and light through nuclear fusion in its core. Our Sun is a star.

- a **planet** is a moderately large object that orbits a star and shines primarily by reflecting light from its star. According to a definition approved in 2006, an object can be considered a planet only if it (1) orbits a star; (2) is large enough for its own gravity to make it round; and (3) has cleared most other objects from its orbital path. An object that meets the first two criteria but has not cleared its orbital path, like Pluto, is designated a dwarf planet.
- a **moon (or satellite)** is an object that orbits a planet. The term satellite can refer to any object orbiting another object. asteroid A relatively small and rocky object that orbits a star.
- a **comet** is a relatively small and ice-rich object that orbits a star.
- a **extrasolar planet** is a planet that orbits a star that is not our Sun

4.2 Collections of Astronomical Objects

- a **solar system** is the Sun and all the material that orbits it, including the planets, dwarf planets, and small solar system bodies. Although the term solar system technically refers only to our own star system (solar means of the Sun), it is often applied to other star systems as well.
- a **star system** is a star (sometimes more than one star) and any planets and other materials that orbit it.
- a **galaxy** is a great island of stars in space, containing from a few hundred million to a trillion or more stars, all held together by gravity and orbiting a common center.
- a **cluster (or group) of galaxies** is a collection of galaxies bound together by gravity. Small collections (up to a few dozen galaxies) are generally called groups, while larger collections are called clusters.
- a **supercluster** is a gigantic region of space where many individual galaxies and many groups and clusters of galaxies are packed more closely together than elsewhere in the universe.
- the **universe (or cosmos)** are the sum total of all matter and energy – that is, all galaxies and everything between them. observable universe The portion of the entire universe that can be seen from Earth, at least in principle. The observable universe is probably only a tiny portion of the entire universe.

4.3 Astronomical Distance Units

- an **astronomical unit (AU)** is the average distance between Earth and the Sun, which is about 150 million kilometers. More technically, 1 AU is the length of the semimajor axis of Earths orbit.
- a **light-year** is the distance that light can travel in 1 year, which is about 9.46 trillion kilometers.

4.4 Terms Relating to Motion

rotation is the spinning of an object around its axis. For example, Earth rotates once each day around its axis, which is an imaginary line connecting the North Pole to the South Pole.

orbit (revolution) is the orbital motion of one object around another. For example, Earth orbits around the Sun once each year.

expansion (of the universe) is the increase in the average distance between galaxies as time progresses. Note that while the universe as a whole is expanding, individual galaxies and galaxy clusters do not expand.

Doppler shift light is **bluer** if the object is moving **towards** the Earth, it is **redder** if the object is moving **away** from the Earth

4.5 Telescopes

Diffraction limit The angular resolution before interference of light itself causes problems

5 Formulae and Values

The **speed of light** is approximately $300,000$ km/h. A **light-year** is the distance light can travel in one year: $9.46 * 10^{12}$ km, or roughly 10 trillion. Note that based on the speed of light, and since the universe formed roughly 14 billion years ago, the distance of 14 billion light-years forms the boundary of the **observable universe**. Note that this does not place a size limit on the entire universe, only on the portion that we can (and will ever be able to) see.

Our solar system was formed 4.5 billion years ago, when about 2% of the galaxy's original Hydrogen and Helium had been converted to heavier elements. Thus the cloud which formed our galaxy was roughly 98% Hydrogen and Helium. The 2% of other materials form the core of the rocky planets in our systems, ie. the Earth.

The **Andromeda galaxy** is roughly 2.5 million light-years away and about $100,000$ light-years in diameter. **Sirius**, the brightest star visible in the night sky, is 8 light-years away. **Alpha Centauri**, the closest star system to our own (a three star system), is 4.4 light-years away.

- $E_k = \frac{1}{2}mv^2$
- $v = \lambda f$
- Energy $= hf = \frac{hc}{\lambda}$
- $v_{\text{radial}} = \frac{\Delta\lambda}{\lambda}\ c$
- $F = G\frac{m_1 m_2}{r^2}$
- $p^2 = \frac{4\pi^2}{(M_1+M_2)*G}\ a^3$ (in our solar system years^2 = A.U.^{3})
- $L = 4\pi^2 R^2 \sigma_{SB} T^4$

- Angular separation (rad) $= \frac{\text{semi-major axis (AU)}}{\text{distance parsecs}}$
- $r_{\text{planet}} \approx r_{\text{star}} * \sqrt{\text{fraction of light blocked}}$
- Eccentricity of an ellipse: $e = \frac{f}{a}$ where f is the distance from the center to a focus
- momentum = mass $*$ velocity
- $\text{SA}_{\text{sphere}} = 4\pi r^2$
- $\lambda_{\text{peak}} T = 2.898 * 10^{-3} m \cdot K$
- Time dilation: $t' = t * \sqrt{1 - \left(\frac{v}{c}\right)^2}$
- Length contraction: $l' = l * \sqrt{1 - \left(\frac{v}{c}\right)^2}$
- Mass increase: $m' = \dfrac{m}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$

6 Data

Speed of light $2.998 * 10^8 m/s$

Light year $9.461 * 10^{15}$ m = 63 241 AU

Average Earth-Moon distance 385 000 km

Average Earth-Sun distance (1 AU) $1.4959 * 10^{11}$ m

Diameter of the Sun $1.391 * 10^6$ km

Planck's constant (h) $6.626 * 10^{-34} J \cdot s = 4.136 * 10^{-15} eV \cdot s$

StefanBoltzmann constant $5.67 * 10^{-8} \frac{W}{m^2 K^4}$

Gravitational constant $6.673 * 10^{-11} N \cdot (m/kg)^2$

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Mass (10^{24} kg)	0.330	4.87	5.97	0.073	0.642	1898	568	86.8	102	0.0131
Diameter (km)	4879	12,104	12,756	3475	6792	142,984	120,536	51,118	49,528	2390
Density (kg/m^3)	5427	5243	5514	3340	3933	1326	687	1271	1638	1830
Gravity (m/s^2)	3.7	8.9	9.8	1.6	3.7	23.1	9.0	8.7	11.0	0.6
Escape Velocity (km/s)	4.3	10.4	11.2	2.4	5.0	59.5	35.5	21.3	23.5	1.1
Rotation Period (hours)	1407.6	-5832.5	23.9	655.7	24.6	9.9	10.7	-17.2	16.1	-153.3
Length of Day (hours)	4222.6	2802.0	24.0	708.7	24.7	9.9	10.7	17.2	16.1	153.3
Distance from Sun (10^6 km)	57.9	108.2	149.6	0.384*	227.9	778.6	1433.5	2872.5	4495.1	5870.0
Perihelion (10^6 km)	46.0	107.5	147.1	0.363*	206.6	740.5	1352.6	2741.3	4444.5	4435.0
Aphelion (10^6 km)	69.8	108.9	152.1	0.406*	249.2	816.6	1514.5	3003.6	4545.7	7304.3
Orbital Period (days)	88.0	224.7	365.2	27.3	687.0	4331	10,747	30,589	59,800	90,588
Orbital Velocity (km/s)	47.4	35.0	29.8	1.0	24.1	13.1	9.7	6.8	5.4	4.7
Orbital Inclination (degrees)	7.0	3.4	0.0	5.1	1.9	1.3	2.5	0.8	1.8	17.2
Orbital Eccentricity	0.205	0.007	0.017	0.055	0.094	0.049	0.057	0.046	0.011	0.244
Axial Tilt (degrees)	0.01	177.4	23.4	6.7	25.2	3.1	26.7	97.8	28.3	122.5
Mean Temperature (C)	167	464**	15	-20	-65	-110	-140	-195	-200	-225
Surface Pressure (bars)	0	92	1	0	0.01	Unknown	Unknown	Unknown	Unknown	0
Number of Moons	0	0	1	0	2	67	62	27	14	5
Ring System?	No	No	No	No	No	Yes	Yes	Yes	Yes	No
Global Magnetic Field?	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Unknown

* From the Earth

** Due to intense greenhouse effect of thick atmosphere