Introduction to Exoplanets

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The discovery of planets around other stars, which we call exoplanets, has emerged over the past two decades as a new, vibrant, fruitful field that spans the disciplines of astrophysics, planetary science, and even parts of biology. The study of exoplanets is now an important part of the curriculum for many graduate students, and this volume is intended to bridge the gap between single-article summaries and specialized reviews. This chapter serves as an introduction both to the study of exoplanets and to this book, providing a starting point to new students and researchers entering the field.

1. A BRIEF HISTORY OF DISCOVERY

The search for our place in the cosmos has fascinated human beings for thousands of years. For the first time in human history we have technological capabilities that put us on the verge of answering a hierarchy of pressing questions: "Do other Earths exist?," "Are they common?," and "Do they have signs of life?" The study of exoplanets seeks to understand how planetary systems formed and evolved, and to understand the diversity of planetary system architectures.

The concept that there may be worlds beyond Earth goes back more than 2000 years, with Epicurus (ca. 300 BCE) asserting, "There are infinite worlds both like and unlike this world of ours . . . We must believe that in all worlds there are living creatures and plants and other things we see in this world." The thirteenth-century scholar and philosopher Albertus Magnus stated, "Do there exist many worlds, or is there but a single world? This is one of the most noble and exalted questions in the study of Nature." Italy's Giordano Bruno asserted that "There are countless suns and countless Earths all rotating around their suns in exactly the same way as the seven planets of our system . . . The countless worlds in the universe are no worse and no less inhabited than our Earth" (*Bruno,* 1584). By the time of Newton, entire books were being written on the topic, with Christopher Huygens asserting in his *Cosmotheoros: Or, Conjectures Concerning the Planetary Worlds* (*Huygens,* 1968) that "the Earth may justly liken'd to the planets . . . [which have] gravity . . . and animals not to be imagin'd too unlike ours . . . and even Men . . . [which] chiefly differ from Beasts in the study of Nature . . . [and who] have Astronomy and its subservient Arts: Geometry, Arithmetick [sic], Writing, Opticks [sic]." These thoughts, however modern sounding, remained speculative (C. Beichman, in preparation).

The contemporary search for exoplanets began with astrometry in the mid-nineteenth century, when a dark companion was suspected to orbit the binary star system 70 Ophiuchi (*Jacob,* 1855; *See,* 1896). Although the 70 Ophiuchi "planet" was soon discredited (*Moulton,* 1899), it likely represents the first published claim of a planet beyond the solar system. A century later, reports of massive planets in the 1940s were controversial and after decades of work were finally discarded as spurious signals. In the 1960s, the detection of the now infamous 24-year-period Jupiter-mass planet around Barnard's star was announced (*van de Kamp,* 1963). This and a companion planet turned out to be instrument systematics. The checkered history of exoplanet detection was born [see *Jayawardhana* (2010) and the chapter by Quirrenbach].

A prescient two-page paper by *Struve* (1952) proposed that Jupiter-like planets might exist in orbits as small as 0.02 AU. Struve pointed out that high-precision radial-velocity measurements could discover such short-period planets and transits of such planets could be found from photometric observations. At the time, and for the following decades, almost all astronomers thought that Jupiter-mass planets should copy our solar system and reside in Jupiter-like orbits at 5 AU from the host star. The key in making radial-velocity observations precise enough to search for Jupiter-mass planet companions in Jupiter-like orbits was to change the reference frame from telluric spectral lines in the Earth's atmosphere to an instrument gas cell. *Campbell and Walker* (1979) were the first to make this advancement, enabling an order-of-magnitude increase in radial-velocity precision, and they embarked on a 12-year search for Jupiter-like planets orbiting 21 bright Sun-like stars. In the late 1980s a substellar object orbiting HD 114762 was detected by *Latham et al.* (1989). Latham et al. referred to this object as a brown dwarf, but if it is very close to the minimum mass obtained by radial-velocity measurements of

HD 11742, then it might be just below the upper mass cutoff for planets. For the history and details of the radial-velocity technique, see the chapter by Lovis and Fischer.

In addition to the radial-velocity planet search method, a technique very different from astrometry and radial velocity was emerging from radio observations of pulsar timing to take advantage of the ultraprecise radiation beaming from millisecond pulsars. Pulsars are neutron stars, remnants of massive stars with $\geq 8\ M_{\odot}$. Pulsar timing aims to detect changes as the host star orbits the planet-star common center of mass. An early, tentative claim of planetary companions to pulsars came in 1970 (*Hills,* 1970). The well-publicized announcement of a pulsar planet by *Bailes et al.* (1991) was retracted after the changes in pulsar timing were ascribed to Earth's own motion about the Sun (*Lyne and Bailes,* 1992). Immediately following the retraction of this claim at a scientific conference, the first two bona fide exoplanets were announced to orbit PSR 1257+12 (*Wolszczan and Frail,* 1992). Dubbed "dead worlds" because of the deadly radiation from the host pulsar, pulsar planets are often ignored in favor of planets orbiting main-sequence stars. The chapter by Wolszczan and Kuchner describes the past, present, and future of pulsar planet searches.

Returning to main-sequence stars, *Walker et al.* (1995) published results of their 12-year search for Jupiter-mass companions to nearby stars. In addition to the conclusion of their own study — that none of the 21 Sun-like stars showed reflex motion corresponding to planets with masses less than 1–3 M_{Jup} (Jupiter masses) for orbital periods less than 15 years — they used other evidence to state that no Jupiter-mass planets in short-period circular orbits had been detected around about 45 Sun-like stars.

Later the same year, an exciting, incredible announcement was made of a 0.5 M_{Jup} planet in a 4.2-day period planet orbiting the Sun-like star 51 Peg (*Mayor and Queloz,* 1995). This first planet to orbit a Sun-like star — at about seven times closer to its star than Mercury is to the Sun — shattered the paradigm of our solar system as the model for planetary architecture. 51 Peg and about 100 other so-called hot Jupiters have changed the foundational concepts of planet formation and evolution. Giant planets were not expected to be found so excruciatingly close to the host star, and must have migrated inward after formation. This 51-Peg discovery is perhaps the most significant discovery in exoplanets because it marked the success of the method used to discover hundreds of exoplanets to date. Had jovian-mass planets orbiting within a few AU of their stars been rare, the field of exoplanets would have gone nowhere until surveys had operated long enough uncover the population of true Jupiters in 12-year-period orbits. The existence of short-period exoplanets allowed for a burst of exoplanet discoveries (following within a couple of years), forming the foundation for the now explosive field of exoplanets.

At the present time, five different exoplanet detection techniques have been used to discover exoplanets (Fig. 1). One of the most surprising aspects of the hundreds of known exoplanets is their broad diversity: a seemingly continuous range of masses and orbital parameters. Planet formation gives birth to planets of a wide range of masses in a wide variety of locations in a protoplanetary disk. Planetary migration allows planets to end up very close to the parent star.

It is fair to say that the blank parts of the mass vs. semimajor axis diagram (Fig. 1) are unpopulated because no exoplanet discovery technique can yet reach low-mass planets with modest to large planet-star separations. In particular, any technique has difficulty discovering Earth analogs.

Ultimately, in the future of exoplanets, we would like an image of an Earth twin as beautiful as the Apollo images of Earth (Fig. 2). For our generation, we are instead limited to imaging exoplanets as spatially unresolved, i.e., as point sources. The Voyager 1 spacecraft viewed Earth in such a way from a distance of more than four billion miles (Fig. 2). Earth's features are hidden in a pale blue dot's tiny speck of light. Even to obtain an image of a pale blue dot, the light from the host star, $\sim 10^{10}$ times as bright as the planet, must be blocked out. This is one of the biggest challenges facing the current generation of astronomers.

This book, *Exoplanets*, aims to introduce principal aspects of exoplanet observation and theory at the graduate student level. The book is organized into five sections. Part I is the introduction, and includes this chapter and a chapter on

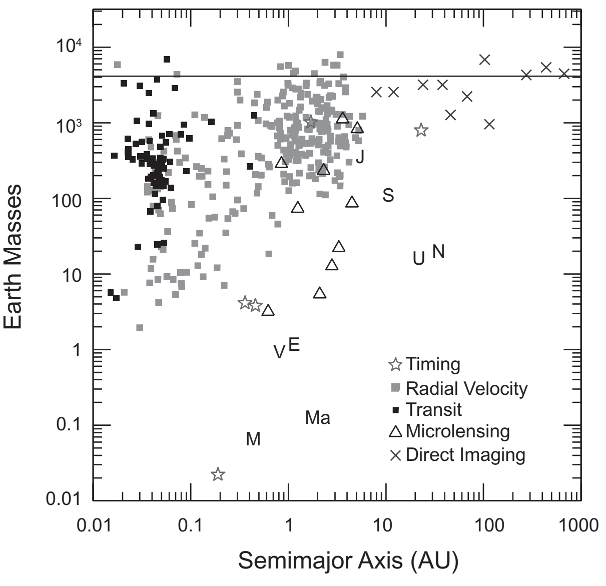

Fig. 1. Known exoplanets as of July 2010. Exoplanets surprisingly are found at a nearly continuous range of masses and semimajor axes. Many different techniques are successful at discovering exoplanets, as indicated by the different symbols. The solar system planets are denoted by the first one or two letters of their name. The horizontal line is the conventional upper limit to a planet mass, 13 M_{Jup} (Jupiter masses). The sloped, lower boundary to the collection of gray squares is due to a selection effect in the radial velocity technique. Data taken from *http://exoplanet.eu/*.

the fundamentals of Keplerian orbits and dynamics. Part II contains exoplanet observing techniques and findings to date, with one chapter per topic and a concluding chapter on the current statistical distribution of exoplanets. The two chapters in Part III discuss orbital dynamics in more detail. Part IV is about exoplanet formation and migration. Part V is about planet interiors and atmospheres. The goal for each chapter is to start with a conceptual introduction followed by a detailed explanation of the foundational equations and methodology. The chapters continue with current research highlights, and conclude with future prospects. The goal of this chapter is to give an introductory overview of the topics covered in *Exoplanets*.

2. WHAT IS A PLANET?

Requirements for membership in the "planet club" received considerable attention in the press when the International Astronomical Union (IAU) "demoted" Pluto during the summer of 2006. But the IAU's still-controversial 2006 definition only covers the four giant planets, the four terrestrial planets, and smaller objects in orbit about our Sun. What about the hundreds of (and rapidly increasing in number) extrasolar "planets" that are the subject of this book?

As larger and more massive objects tend to be easier to detect than smaller ones, the first exoplanets to be found were large, and in many cases more massive than Jupiter. In our solar system, there is a gap of over a factor of 10^3 in mass and more than 10^8 in luminosity between the Sun and its most massive planet. Just as the discoveries of numerous additional small bodies orbiting the Sun have forced astronomers to decide how small an object can be and still be worthy of being classified as a planet, detections of substellar objects orbiting other stars have raised the question of an upper size limit to planethood.

Stars can be defined as objects for which self-sustaining fusion provides sufficient energy for thermal pressure to balance gravity. For solar composition, this yields a lower-mass limit of $\geq 0.075\ M_\odot \approx 80\ M_{Jup}$. The smallest-known stars are a bit less than one-tenth as massive as our Sun. One could simply apply the word "planet" to all sizable substellar objects, but the term "brown dwarf" is generally used to denote bodies that are very similar to stars yet too small to reach internal temperatures necessary for thermonuclear fusion of significant quantities of ordinary hydrogen.

Various delineations of the upper boundary of planethood incorporate formation and/or location requirements on the object in question in addition to limits on its physical properties. A few years before the Pluto planethood debate heated up, the IAU's Working Group on Extrasolar Planets decided upon a provisional definition of the attributes required for an object outside of our solar system to be considered to be a planet. This working definition reads as follows:

1. Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 M_{Jup} for objects of solar metallicity) that orbit stars or stellar remnants are "planets" (no matter how they formed). The minimum mass/size required for an extrasolar object to be considered a planet should be the same as that used in our solar system.

2. Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are "brown dwarfs," no matter how they formed nor where they are located.

3. Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not "planets," but are "subbrown dwarfs" (or whatever name is most appropriate).

Various hesitant qualifying statements surround the above listing (see *http://www.dtm.ciw.edu/boss/IAU/div3/wgesp/* for details), lest anyone think that the definition wasn't drawn up by a committee.

A few comments are in order: This definition incorporates physical properties and location, but not formation; the theorists on the panel generally objected to the inclusion of mode of formation because of modeling uncertainties, whereas some of the observers argued for including formation-based criteria. 1, 2: Deuterium, which contains one proton and one neutron, is almost five orders of magnitude less abundant than ordinary hydrogen (one proton, no neutrons). Deuterium fuses at a substantially lower temperature than does ordinary hydrogen, but even the fusion of the entire inventory of an object's deuterium does not provide a very large amount of energy because of deuterium's low abundance. There is no fine dividing line dividing no-deuterium fusion from all-deuterium fusion, but the mass at which 50% of deuterium eventually fuses is now estimated at 12 M_{Jup}, down from 13 M_{Jup} estimated several years ago when the IAU exoplanet definition was written. 1: The comment regarding the lower-mass limit shows that the panel was aware of the brewing Pluto controversy, but didn't want to take a position on this matter. Note that the inner "planet" of PSR B1257+12 is less massive than any of the eight planets in our solar system, but more massive than Pluto, and it also has (at least mostly) cleared its orbital zone of debris.

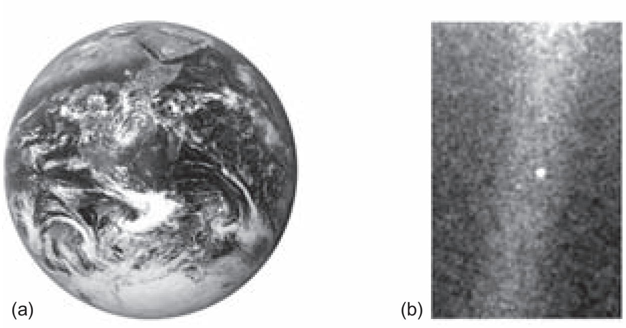

Fig. 2. Earth as viewed from space. **(a)** Image from NASA's Apollo 17 spacecraft in 1972. **(b)** Image from Voyager 1 at a distance of more than four billion miles. Earth lies in the center of a band caused by scattered sunlight in the camera optics.

3. PLANETARY DYNAMICS

By analyzing Tycho Brahe's careful observations of the orbits of the planets, Johannes Kepler deduced the following three laws of planetary motion:

1. All planets move along elliptical paths with the Sun at one focus.

2. A line connecting a planet and the Sun sweeps out equal areas ΔA in equal periods of time Δt

$$\frac{\Delta A}{\Delta t} = \text{constant} \tag{1}$$

Note that the value of this constant differs from one planet to the next.

3. The square of a planet's orbital period about the Sun (in years) is equal to the cube of its semimajor axis.

Although Kepler's laws were originally found from careful observation of planetary motion, they were subsequently shown to be derivable from Newton's laws of motion together with his universal law of gravity.

Newton's analysis corrected some small errors in Kepler's laws, and generalized them to apply to objects not orbiting the Sun. Two mutually gravitating bodies of masses m_1 and m_2 travel on elliptical paths about their mutual center of mass, with an orbital period T given by

$$T^2 = \frac{4\pi^2 a^3}{G(m_1 + m_2)} \tag{2}$$

where a refers to the semimajor axis of relative orbit of the two bodies and G is the universal gravitational constant. The majority of known exoplanets have been found by tracking the small variations in their star's velocity as they moves in response to the planet's gravitational influence (see chapter by Lovis and Fischer).

Newton's laws imply that all massive bodies have influence on one another, so that in systems with more than two bodies, orbits are not perfect ellipses. The planet Neptune was discovered by studying deviations of the path of Uranus from an ellipse that could not be accounted for by the perturbations of the then-known planets. Analogous deviations have been used to precisely specify the masses and orbital inclinations of the two largest planets known to orbit the pulsar PSR B1257+12 (see chapter by Wolszczan and Kuchner), as well as the two resonant giant planets orbiting the small main-sequence star GJ 876 (*Correia et al.,* 2010).

Newton demonstrated that the gravitational force exerted by a spherically symmetric body is equivalent to that of a point particle of the same mass. However, rotation and other processes can cause deviations from spherical symmetry, and these asymmetries affect orbits, especially for bodies whose separations are not substantially larger than their sizes. General relativity implies differences from elliptical trajectories that are most profound for orbits close to massive bodies.

Astrophysical bodies are neither perfectly rigid nor perfectly fluid. Tidal forces can deform a body, and since the strength of the tidal force increases with proximity, so does the amount of deformation. These variations produce flexing in a body traveling on an eccentric orbit, which can dissipate energy as heat within the body at the expense of damping the orbital eccentricity. Moreover, a tidally deformed body exerts a different gravitational force as a result of its nonspherical distribution of mass. For example, the Moon raises tides on Earth, producing a tidal bulge. This bulge points almost along the Earth-Moon line, but as Earth cannot respond instantaneously to the pull of the Moon, Earth's rotation carries the bulge slightly ahead of the Earth-Moon line. The resulting skewed mass distribution within Earth exerts a torque on the Moon, causing its orbit to expand (at the rate of a few centimeters per year) and Earth's rotation to slow.

The basic dynamics of the two-body problem are described in the chapter by Murray and Correia. The chapter by Fabrycky describes planetary perturbations, the principal effects of stellar oblateness, general relativity, and tidal forces as they apply to exoplanet research. The chapter by Correia goes into more detail on tidal evolution.

4. OBSERVATIONAL TECHNIQUES

Exoplanets are being discovered with several different detection techniques (Fig. 1). Each technique has its own selection effects in mass (or radius) and semimajor axis parameter space. Here we introduce and compare the different planet-finding techniques.

Radial velocity: In the presence of a planet, a star orbits the planet-star common center of mass. The star's motion can be described by three components: one along the observer's line-of-sight to the star, and two components on the plane of the sky. The radial-velocity technique measures the star's line-of-sight motion with a selection effect toward more-massive planets close to the star. Radial velocity is the most mature of the planet-finding techniques, giving it the advantage of being able to push to relatively low planetary masses around bright stars. The major disadvantage of the radial-velocity technique is that only an exoplanet's minimum mass (given by $M_p \sin i$, where M_p is the planet mass and i is the orbital inclination) is measured because the orbital inclination of the planet orbit is undetermined. The radial-velocity technique is described in the chapter by Lovis and Fischer.

Astrometry: Astrometry measures the position of stars by the two components of motion in the plane of the sky. The main advantage of astrometric measurements is that they can provide the planetary mass (without the sin i factor inherent in radial-velocity searches) and all planetary orbital parameters. Although the astrometry technique has a long history, with the first claimed exoplanet detections in the mid-nineteenth century, astrometry has yet to discover an exoplanet (as of 2010). For details, see the chapter by Quirrenbach.

Timing: Timing techniques for exoplanet detection include both pulsar timing (*Wolszczan and Frail,* 1992) and time perturbations of stars with stable oscillation periods (e.g., *Silvotti et al.,* 2007) (see the chapter by Wolszczan and

Kuchner for details). Because the planet detection techniques radial velocity, astrometry, and timing infer the presence of the planet from the star's orbital motion, only the planet's mass and orbital elements can be derived.

Gravitational microlensing: Gravitational microlensing occurs when a foreground star happens to pass very close to the observer's line of sight to a more distant background star. The foreground star acts as a lens, magnifying the background source star, as a function of time, by an amount that depends on the angular separation between the lens star and source star. If a planet is orbiting the lens star, the lightcurve may be further perturbed, resulting in a characteristic, short-lived signature of an exoplanet and yielding the planet mass and planet-star physical separation. The major weakness of the microlensing planet-finding technique is that the lensing occurence is a one-time event that will never repeat. The advantages of the current state of microlensing over other planet-finding techniques (except for pulsar timing) is the sensitivity to low planetary masses (potentially to Earth's mass) at relatively large planet-star separation, aiding in understanding the statistical distribution of exoplanets (see Fig. 1). The theoretical and observational foundation for microlensing is laid out in the chapter by Gaudi.

We now turn to the two planet-finding techniques that can also be used to observe physical characteristics beyond planetary mass.

Transits: Exoplanet transits (or primary eclipses) occur when a planet passes in front of its star as seen from Earth. When the planet goes behind the star, the event is called an occultation or secondary eclipse. (The term "transit" is used for small bodies going in front of larger bodies, "occultation" for larger bodies going in front of smaller bodies, and "eclipse" for bodies of about the same size moving in front of each other.) Most transiting planets have been discovered from transit surveys searching large numbers of stars for the characteristic drop in brightness that is indicative of a planet transit. Transiting exoplanets are also detected via follow-up photometric observations to known radial-velocity planets and these tend to be orbiting bright stars, favorable for additional observations. Transits are described in the chapter by Winn.

For an exoplanet to show transits, the exoplanet-star orbit must be aligned with the observer. For a random orientation of stellar inclinations (for zero eccentricity and $R_p \ll R_\star$), the probability, p, to transit is

$$p = R_\star/a \tag{3}$$

where R_p is the planet radius, $R_\star$ is the stellar radius, and a is the planet's semimajor axis. So, for example, while transits for planets in 1 AU circular orbits are rare (1/215), transits of hot planets in short-period orbits are more common. Transits of short-period planets also occur at shorter time intervals, and thus limited observing programs are more likely to detect them. The major limitation for exoplanet transit searches is, therefore, the huge bias toward short-period planets (Fig. 1).

Transits are not just used for discovering planets. Follow-up observations of transits and eclipses provide a huge amount of information that cannot be obtained from radial-velocity data alone. The size of the planet relative to the size of the star can be measured from the transit lightcurve. The orientation of the planet's orbit relative to the sky plane and relative to the stellar rotation axis can be determined. Transit time anomalies or perturbations in other eclipse properties may indicate the presence of additional planets or moons. A transiting exoplanet's atmosphere can be measured in several ways in the combined light of the planet-star system: during transit, during secondary eclipse, and even around the orbit phase curves. The richness of investigations for transiting exoplanets is described in the chapter by Winn and in the chapters in Part V.

Direct imaging: Direct imaging means taking a snapshot of an exoplanet by spatially separating the planet and star on the sky. More generally, direct detection refers to the ability to distinguish the light emergent from a particular celestial object from that of any other. Stars by virtue of nuclear fusion in their core are much brighter than planets, making the main challenge of direct imaging not the actual spatial separation, but rather the elimination of the scattered or diffracted light from the central star in the telescope optics.

Direct imaging of planets is currently limited to big, bright, young, or massive substellar objects and/or objects located far from their stars (e.g., *Marois et al.,* 2008; *Kalas et al.,* 2008). Four or five or more orders of magnitude improvement in planet-star contrast is needed to reach solar-system-like, solar-system-aged exoplanets. This is the weakness of the direct imaging exoplanet discovery technique — the technical challenges and the complexity of overcoming the large planet-star contrast, the physics of diffracted light, and the engineering needed to mitigate scattered light in the telescope optics.

Direct imaging is advantageous over other exoplanet discovery techniques because of the science it enables. First and foremost, if a direct image (i.e., photometry) can be taken of a planet, if adequate photons are available, so can a spectrum. In addition to exoplanet spectra, the orbit of the planet may be measured, more accurately as combined with astrometry or even radial-velocity measurements. Any circumstellar disks present in a planetary system can also be imaged (see the chapter by Roberge and Kamp). One of the exciting aspects of direct imaging is the fast-paced development of many new coronagraph concepts that have specifically been developed for exoplanet observations, and cannot be found in any optics textbooks. See the chapter by Traub and Oppenheimer for a thorough foundation of the physics and future of direct imaging.

5. PLANET FORMATION

Studies of planetary formation are intimately connected with those of exoplanets. Prevailing views on planet formation have been influential in directing exoplanet studies, although the directions provided have not always been optimal. More than 98% of the planets now known orbit stars other than our Sun, so exoplanet data provide constraints on models of planetary growth. While for exoplanets, we have the numbers, we have much more data on the planets and smaller objects in our solar system, and at present these "local" data remain the primary drivers for planet-formation models. Note that the set of known exoplanets is highly biased based on detectability, whereas our own solar system is not a truly random sample, since we wouldn't reside here if it didn't contain a planet suitable for life to evolve to the point of asking these questions.

Modern theories of star and planet formation are based upon observations of planets and smaller bodies within our own solar system, exoplanets, and young stars and their environments. Terrestrial planets are thought to grow via pairwise accretion of initially small solid bodies known as planetesimals, until the spacing of planetary orbits becomes large enough that the configuration is stable for the age of the system. According to most models, giant planets begin their growth as do terrestrial planets, but they become massive enough that they are able to accumulate substantial amounts of gas before the protoplanetary disk dissipates. These models predict that rocky planets should form in orbit about most single stars. It is uncertain whether or not gas giant planet formation is common, because most protoplanetary disks may dissipate before solid planetary cores can grow large enough to gravitationally trap substantial quantities of gas.

A potential hazard to planetary systems is radial decay of planetary orbits resulting from interactions with material within the disk. Protoplanetary disks are built of the same material as are stars, and thus are initially ~99% hydrogen and helium. In the first few million years of a planetary system's life, some of this gas is still present and provides a large sink/source of angular momentum for (proto)planets. From theoretical consideration, the gravitational interaction between a planet and a massive disk in which it is embedded — Type I migration — ought under most circumstances to bring about a net loss of orbital angular momentum from the planet and decay of its orbit for planets on the order of a few Earth masses. A sufficiently massive planet exerts strong enough torques on the disk to open a gap, thereby locking the planet into the subsequent viscous evolution of the disk in what is called the Type II mode of migration.

Planets more massive than Earth have the potential to suffer the most rapid orbital decay, and may be able to sweep up smaller planets in their path. Planet formation may be an enormously wasteful process, which dumps a steady stream of growing protoplanets onto the primary, and the end result is whatever happens to be left over when the gas fades away.

Significant postformation migration is quite likely to be responsible for the large number of exoplanets detected on close-in orbits. In multiple-planet systems, convergent migration of planets can be invoked to explain resonant capture, and either convergent or divergent migration can lead to eccentricity excitation. As the nebular gas dissipates, it is likely that the tables are eventually turned; the planets, heretofore at the mercy of the gas, assert themselves and serve as anchors to slow down the viscous evolution of the last remains of the disk. Interactions between planets and the planetesimal disk can also lead to significant planetary migration; such migration can account for the orbital distribution of the small bodies within our solar system beyond Neptune. The present observational and theoretical "state of the art" requires us to use a liberal amount of conjecture in attempting to sketch a coherent picture of planet migration. However, it seems equally clear that migration is intimately linked with the formation of the planetary system, and a complete picture of the latter will require a full understanding of the former.

The arrangement of material within the section on circumstellar disks and planet formation is pedagogical rather than chronological. The first chapter, by Roberge and Kamp, covers disks, both of the protoplanetary variety and postformation debris disk. Chambers then reviews terrestrial planet formation, concentrating on data from our solar system and numerical models that attempt to reproduce these observational constraints. As observations of terrestrial exoplanets start to provide significant information on typical planetary system properties, they may well affect the direction of research in this area. Although the formation and most of the migration of giant planets are thought to predate the latter phases of terrestrial planet growth, the physics of the early stages of core-nucleated accretion of gas giants is the same as that of terrestrial planet formation, making the presentation of terrestrial planet formation first more conceptually straightforward. D'Angelo et al. review growth of giant planets, introducing both the prevailing core-nucleated accretion model and the alternative disk instability model. Part IV concludes with a fairly technical chapter by Lubow and Ida reviewing current models of planetary migration.

6. PLANET INTERIORS AND ATMOSPHERES

6.1. Interiors

The diversity of planet interior compositions is large, but can be summarized in a simplified fashion via their bulk composition as a function of rock, ice, or gas components (see Fig. 3). In the solar system, there is a definite relationship between the relative abundances of rock-ice-gas and planet mass. Small planets ($M \leq 1\ M_\oplus$) are rocky. Intermediate-sized planets (~14–18 $M_\oplus$) are thought to be dominated in mass by astrophysical ices and rock with H/He envelopes that are minor components by mass but dominant by volume. Larger planets are predominantly composed of hydrogen and helium. Whether or not exoplanets also follow this pattern is one of the most significant questions of exoplanet formation, migration, and evolution.

Measured exoplanet masses and radii (and hence densities) can be used to estimate the composition of an exoplanet. The mass vs. radius diagram, populated with exoplanets and illustrative theoretical models, provides such a basic picture of exoplanet compositions (Fig. 4). Most prominent are the collection of giant planets in the top right corner of the diagram. These planets are so large for their mass (i.e., have such low densities) that they must be composed mostly of hydrogen and helium gas. The collection of giant planets is interesting because of their spread of masses and radii well beyond Jupiter's. Some Jupiter-mass planets are over

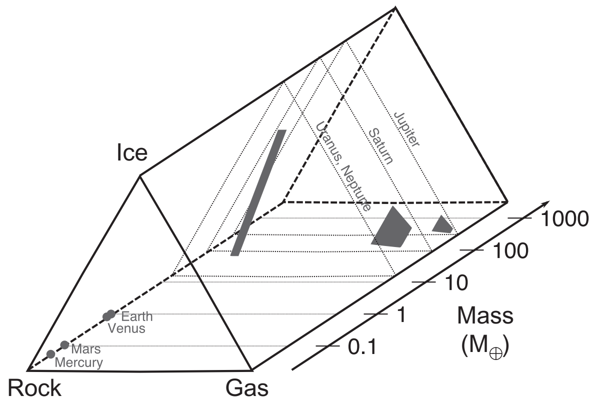

Fig. 3. Schematic diagram illustrating the range of possible planet primordial bulk compositions for exoplanets. In this figure "gas" refers to primordial H and He accreted from the nebula, "ice" refers to ice-forming materials, and "rock" refers to refractory materials. Constraints on the current compositions of the solar system planets are shown and denoted by their first initial. Exoplanets might appear anywhere in this diagram. Adapted from the chapter by Chambers and from *Rogers and Seager* (2010).

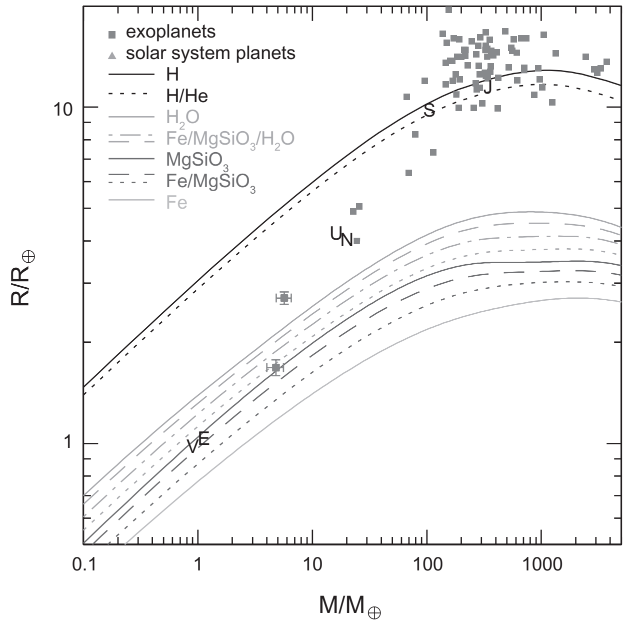

Fig. 4. Mass-radius relationships for cold planets. The solid lines are homogeneous planets. From top to bottom the homogeneous planets are hydrogen, a hydrogen-helium mixture with 25% helium by mass (dotted line), water ice, silicate ($MgSiO_3$ perovskite), and iron (Fe ε). The nonsolid lines are differentiated planets, and are described from top to bottom. The top dashed line is for water planets with 75% water ice, a 22% silicate shell, and a 3% iron core; the dot-dashed line is for water planets with 45% water ice, a 48.5% silicate shell, and a 6.5% iron core (similar to Ganymede); and the dotted line is for water planets with 25% water ice, a 52.5% silicate shell, and a 22.5% iron core. The next lower dashed line is for silicate planets with 32.5% by mass iron cores and 67.5% silicate mantles (similar to Earth), and the adjacent dotted line is for silicate planets with 70% by mass iron core and 30% silicate mantles (similar to Mercury). Solar system planets are shown and denoted by their first intial. The squares designate the transiting exoplanets; mass and radius uncertainties are suppressed for clarity except for the low-mass planets CoRoT 7b and GJ 1214b. Note that electron degeneracy pressure becomes important at high mass, causing the planet radius to become constant and even decrease for increasing mass. Following *Seager et al.* (2007).

1.5 times Jupiter's radius, defying explanation of the large size (see the chapter by Fortney et al. for potential explanations). Some giant planets are up to 10 times more massive than Jupiter but with almost the same size. Such planets are explained as having electron degeneracy pressure in the core, whereby pressure-ionized atoms enable the nuclei to squeeze closer together. This means that a more-massive planet has higher compression in the core and the resulting planet size is similar to that of a less-massive planet.

Moving down in planet mass and radius in Fig. 4, to those with masses between Saturn and Neptune, are planets with no solar system counterparts, exemplifying the diversity of exoplanet interior composition. Planets similar in size and mass to Neptune may be composed mostly of ices plus some rock, with a ~10–15% H/He envelope — or they may alternately have a large rocky interior with a more-massive H/He envelope. Of significant interest are the super Earths, loosely defined as rocky planets significantly more massive than Earth. Super Earths may include planets suitable for life as we know it and are amenable for future observational searches for atmospheric biosignature gases. In the conventional sense, a habitable planet is one with some surface liquid water, because all life on Earth requires liquid water. In contrast to terrestrial planets, giant and Neptune-sized planets enshrouded by gas envelopes have no solid or liquid surfaces to support life as we know it and their temperatures just below the deep atmosphere rapidly become too hot for the complex molecules necessary for life to exist.

To understand planet interiors in more detail, or to use the measured mass and radius to constrain the planet interior composition, models are used. The equations that describe a planetary interior are conservation of mass; hydrostatic equilibrium (a balance between gravity and pressure gradients); the equation of state (describing the relationship betweeen density, pressure, and temperature for a given material in thermodynamic equilibrium); and energy transport (commonly described by an adiabat). For giant planets, conservation of energy in the form of the change in luminosity as a function of planetary radius is also used. Details of how the equations are used in models, including a description of boundary conditions, are given in the chapters by Fortney et al. and Sotin et al.

Deducing exoplanet interior composition constraints is very difficult. Only two data points are available per planet: mass and radius. Even with perfect measurements there is simply not enough information to uniquely identify a planet's interior composition. Two exceptions are at the density extremes: Giant planets of low density must be composed almost entirely of hydrogen and helium, and any planet of extremely high density must be iron-dominated because iron is the densest cosmically abundant molecular substance.

There are two possible paths for moving forward beyond the limiting degeneracy of interior composition. One path involves observations and interpretation of an exoplanet atmosphere to help break the interior composition degeneracy for a specific exoplanet. Careful work must be done to understand which types of planet interiors can be constrained further with which kind of atmosphere measurements. A second path involves statistics. With enough planets with a measured mass and radius, the hope is that specific planet populations in the mass-radius diagram (Fig. 4) will emerge. With distinct planet populations, characteristics of terrestrial planets in general can be identified, even if the actual composition of individual planets cannot.

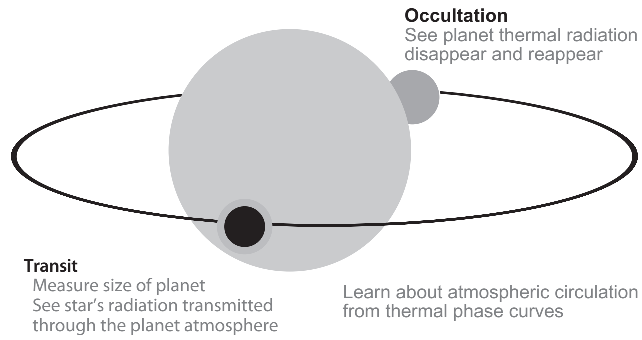

Fig. 5. Schematic of a transiting exoplanet and potential follow-up measurements. Note that the primary eclipse is usually called a transit, and the secondary eclipse is most accurately referred to as an occultation. In this illustration the planet orbit is viewed "edge-on," i.e., sin i = 90°. This figure was adapted from Fig. 5 of *Seager and Deming* (2010).

6.2. Atmospheres

Planetary atmospheres originate either from direct capture of gas from the protoplanetary disk (for massive planets) or from outgassing during planetary accretion (for low-mass planets). The former mechanism is accepted for giant planets like Jupiter and Saturn and the latter is expected for terrestrial planets like Earth and Venus. The final atmospheric mass and composition depends on the net of atmospheric sources vs. atmospheric sinks. The sources, both from direct capture and from outgassing, depend on the planet's location in the protoplanetary disk during formation, due to the compositional gradients in the disk. The atmospheric sinks include atmospheric escape, gas-surface reactions, and sequestering of gases in oceans.

Two ways are available for observing exoplanet atmospheres. Direct imaging is the most natural way to think of observing exoplanet atmospheres (see the chapter by Traub and Oppenheimer). At present, direct imaging is limited to big, bright, young, or massive planets located relatively far from their stars (see Fig. 1).

The second way to observe exoplanet atmospheres is via a collection of techniques used for transiting planets. Transiting planets are observed in the combined light of the planet and star (Fig. 5). The planet and star are not spatially separated as in the direct imaging technique. Instead, the precise on/off nature of the transit and secondary eclipse events provide an intrinsic calibration reference. For more details, see the chapter by Winn.

Over three dozen exoplanet atmospheres have been observed to date, dominated by Spitzer Space Telescope broadband infrared photometric observations of secondary eclipse. A handful of exoplanet atmospheres have been observed by the Hubble Space Telescope and a growing number of hot exoplanets observed with groundbased telescopes. Highlights of exoplanet atmosphere studies include identification of molecules and atoms, constraints on vertical temperature structure (such as the possible identification of thermal inversions), and day-night temperature gradients for the tidally locked hot Jupiters. For a very detailed review of exoplanet atmospheres, see *Seager and Deming* (2010).

The range of possible exoplanet atmospheric mass and composition has yet to be uncovered theoretically and observationally. As such, there is not yet a definitive categorization of atmosphere types (but see *Seager and Deming,* 2010). We do, however, expect atmospheres on different exoplanets to show a wide diversity, just as the orbits, masses, and radii of known exoplanets do. Jupiter (and presumably other massive planets) has retained the gases it formed with, and these gases approximately represent the composition of the Sun. The super Earth atmospheres, on the other hand, could have evolved substantially. In particular, there is an exciting sense of anticipation in observing and studying super Earth atmospheres, simply because we do not know quite what their diversity will be.

In order to interpret, predict, and generally understand exoplanet atmospheres, models are needed. In fact, a variety of different kinds of models are used for different aspects of the atmosphere. To understand the emergent spectrum and to interpret spectral data, radiative transfer codes are used (see the chapters by Burrows and Orton and by Meadows and Seager). But in order to theoretically understand the atmospheric composition for low-mass planets, atmospheric escape and photochemistry models are also needed. Atmospheric circulation describes the hydrodynamic flow in atmospheres and is essential for understanding the three-dimensional temperature structure of tidally locked planets, as well as for getting a handle on surface temperatures for any kind of terrestrial planet (see the chapter by Showman et al.)

Arguably the most exciting investigations that planetary atmosphere observations can enable in the study of exoplanets is the potential to detect biosignatures produced by life. A biosignature gas is one produced by life that accumulates in an exoplanet atmosphere to detectable levels. A surface feature (such as the vegetation red edge) can also be a biosignature. Biosignatures are covered in the final chapter of this volume, by Seager and Meadows.

7. PROSPECTS FOR DETECTION AND CHARACTERIZATION OF HABITABLE PLANETS

We stand on a great divide in the detection and study of exoplanets. On one side of this divide are the hundreds of known massive exoplanets, with measured atmospheric temperatures for a handful of the hottest exoplanets. On the other side of the divide lies the possibility, as yet unrealized, of detecting and characterizing a true Earth analog — an Earth-like planet (a planet of ~1 $M_\oplus$ and 1 $R_\oplus$ orbiting a Sun-like star at a distance of roughly 1 AU).

NASA's Kepler space telescope, currently in an Earth-trailing heliocentric orbit, will determine the frequency of Earth-sized planets (*Borucki et al.,* 2010). Kepler is monitoring 150,000 stars for 3.5 years, seeking the characteristic signature of a transiting Earth and ruling out false positive signatures. Most Kepler stars are too far away and too faint for planet follow-up atmosphere studies, and many of them are out of reach for radial-velocity mass determination.

There is an exciting possibility of a fast track for finding and characterizing habitable exoplanets. This is the search for super Earths orbiting small, cool stars (M dwarfs). M dwarfs are much less luminous than the Sun, so the locations amenable to surface liquid water to support life as we know it are very close to the star, although questions remain regarding the accretion and retention of volatiles by such planets (*Lissauer,* 2007). The relative size and mass of the planet and star are much more favorable for planet detection than the Earth-Sun analog. Two different yet complementary planet-searching techniques (transits and radial velocities) are very sensitive to super Earths orbiting with close separations to M dwarfs. A set of transiting planets will enable average density measurements and hence identification of terrestrial-type planets. Suitable transiting planets can have their atmospheres characterized by the James Webb Space Telescope, now under development, building on the current Spitzer Space Telescope studies of hot Jupiters.

The quest for atmosphere studies for Earth analogs means there will always be a desire for direct imaging to find and characterize exoplanets. Direct imaging at the 10-billion planet-star contrast level needed for Earth analogs will require future spaceborne telescopes.

8. PERSPECTIVES

The field of exoplanet research has blossomed, with hundreds of planets found at very broad ranges of masses and semimajor axes. This points to the diversity of outcomes of planet formation combined with subsequent planet migration. Among the most unexpected discoveries are planets orbiting extremely close to their host stars with periods of only a few days, planets that orbit their star in a direction opposite to the star's rotation (see chapter by Winn), planets with high eccentricities, and (hot) jovian-mass planets with radii significantly larger than that of Jupiter. Regarding exoplanets, we now know that "anything is possible within the laws of physics and chemistry," and we should expect to continue to discover new classes of unpredicted planets.

We do not completely know where the field of exoplanets is heading, and what discoveries will be made. But among the most important results that are emerging, and will continue to emerge, is our sense of perspective: How normal or unusual is our own solar system? How common or how rare are planets analogous to the Earth? Will we find unequivocal biosignatures of life beyond Earth?

At a few special times in history, astronomy has changed the way we see the universe. Hundreds of years ago, humanity believed that Earth was the center of everything — that the known planets and stars all revolved around Earth. In 1453, the Polish astronomer Nicolaus Copernicus advocated the view of the solar system where the Sun was the center, and Earth and the other planets all revolved around it. Gradually, science adopted this "Copernican" theory, but this was only the beginning. Astronomers eventually recognized that our Sun is but one of hundreds of billions of stars in our galaxy, and, in the early twentieth century, that our galaxy is but one of upward of hundreds of billions of galaxies. If and when we find that Earth-like planets are common and see that some of them have signs of life, we will at last complete the Copernican Revolution — a final conceptual move of Earth, and humanity, away from the center of the universe. This is the promise and hope for exoplanets — the detection and characterization of habitable worlds. We are on the verge of, if not in the very midst of, the greatest change in perspective of our place in the universe since the time of Copernicus.

9. APPENDIX: PLANET DEFINITIONS

The word "planet" comes from the Greek word for "wanderer"; planets were originally defined as objects that moved in the night sky with respect to the background of fixed stars. There are no offical definitions for exoplanets or categories of exoplanets. For reference, we nevertheless present commonly accepted definitions here. Some of these definitions are taken from the 2006 *Terrestrial Planet Finder Science and Technology Definition Report* (*Levine et al.,* 2006).

***Planet* —** A planet is an object that is gravitationally bound and supported from gravitational collapse by either electron degeneracy pressure or Coulomb pressure, that is in orbit about a star, and that, during its entire history, never sustains any nuclear fusion reactions in its core (note that in practice the word "never" is too strong). Reliance on theoretical models indicates that such objects are less massive than approximately 13 times the mass of Jupiter (M_{Jup}) for objects with metallicities close to that of the Sun. Between 13 and 75 M_{Jup} objects (known as brown dwarfs) fuse deuterium for a portion of their youth (e.g., *Hubbard et al.,* 2002, and references therein). Objects above 75 M_{Jup} are known as stars. A lower-mass limit to the class of objects called planets has not convincingly been determined.

Solar system planet — The International Astronomical Union has given a specific definition for solar system planets. The exact wording of the official IAU definition is this: "A 'planet' is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighbourhood around its orbit." Based on this definition the solar system has eight planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. The IAU also has defined "dwarf planet," bodies such as Pluto that are round but may orbit in a zone that contains many other objects (such as the asteroid or Kuiper belts).

Exoplanet — An exoplanet is a planet orbiting a star other than the Sun. For the working definition of the IAU's Working Group on Extrasolar Planets, see section 2. Note that free-floating planets are not included in the working definition of exoplanets.

Giant planet — Giant planets are those with substantial H/He envelopes. Our solar system retains two types of giant planets ("gas" giants and "ice" giants); other types are likely to exist in exoplanetary systems. Such planets have no solid or liquid surfaces as terrestrial planets do, but their sizes are usually defined at a pressure of roughly 1 bar.

Terrestrial planet — A terrestrial planet, often referred to as a "rocky planet," is a planet that is primarily supported from gravitational collapse through Coulomb pressure, and that has a surface defined by the radial extent of the liquid or solid interior. A gaseous atmosphere may exist above the surface, but this is not a defining feature of a terrestrial planet. Theory suggests that most terrestrial planets will have masses less than about 5–10 $M_\oplus$, as planets larger than this are thought to be likely to capture gas during accretion and develop into giant planets.

Habitable planet — A habitable planet is a terrestrial planet that has surface liquid water. This definition presumes that extraterrestrial life, like Earth life, requires liquid water for its existence. Both the liquid water, and any life that depends on it, must be at the planet's surface in order to be detected remotely. This, in turn, requires the existence of an atmosphere with a surface pressure and temperature suitable for liquid water. (Moons of exoplanets might also be habitable.)

Potentially habitable planet — A potentially habitable planet is one whose orbit lies within the habitable zone, broadly construed, and has a solid or liquid surface. This includes planets that have high eccentricities, but whose semimajor axis is within the habitable zone. A definition for a potentially habitable implies that some planets within the habitable zone may not actually be habitable.

Earth-like Planet — An Earth-like planet or Earth analog is a habitable planet of approximately 1 $M_\oplus$ and 1 $R_\oplus$ in an Earth-like orbit about a Sun-like star. Earth-like planets are not necessarily habitable planets, nor vice-versa; it depends on the context of usage. While an Earth-like planet is used to describe a planet similar in mass, radius, and temperature to Earth, the term Earth twin is usually reserved for an Earth-like planet with liquid water oceans and continental land masses.

Habitable zone and continuously habitable zone — The habitable zone, or HZ, is the region around a star in which a planet may maintain liquid water on its surface, i.e., it is the zone in which Earth-like planets may exist. Its boundaries may be defined empirically (based on the observation that Venus appears to have lost its water some time ago and that Mars appears to have had surface water early in its history) or with models. The continuously habitable zone, or CHZ, is the region that remains habitable over some finite period of time (usually commencing when the star was young) as a star ages. All main-sequence stars brighten with time, and so the HZ moves outward with time.

Exoplanet subcategories — A growing list of terms are being used for exoplanets with no solar system counterparts. Although the following terms may not have long-term stability in the exoplanet community, they are included here for completeness. The term "hot Jupiter" refers to a planet with mass comparable to or greater than Jupiter (but less than the deuterium-burning limit of ~13 M_{Jup}) that is located close to its primary star (e.g., within 0.1 AU). "Super Earths" is a term that has been used to refer to primarily rock worlds (by volume, not just mass) that are significantly larger than our Earth, but is applied by some to other exoplanets with masses <10 $M_\oplus$ and/or radii ≤1.75 $R_\oplus$. Exo-Neptunes might be used for planets between about 10 and 25 $M_\oplus$ whose volume is dominated by a H/He envelope, but mass is dominated by heavier elements. The term "water worlds" has been used for planets that lack large gaseous envelopes and have ~25% or more water by mass. Carbon planets refer to planets that contain more carbon than oxygen, so that rocks are likely to be carbides rather than silicates. At present, observations cannot always distinguish among the above planet types.

Acknowledgments. We thank R. Binzel for very useful comments on this chapter.

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