Chapter One

Introduction

1.1 EXOPLANETS FROM AFAR

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 such questions as, “Do other Earths exist?,” “Are they common?,” and “Do they harbor life?” Critical to inferring whether or not a planet is habitable or inhabited is an understanding of the exoplanetary atmosphere. Indeed, almost all of our information about temperatures and chemical abundances in planets comes from atmospheric photometry or spectroscopy.

Ultimately we would like an image of an Earth twin as beautiful as the Apollo images of Earth (Figure 1.1). For our generation we are instead limited to observing exoplanets as spatially unresolved, i.e., as point sources. The *Voyager I* spacecraft viewed Earth in such a way from a distance of more than four billion miles (Figure 1.1). The Earth’s features are hidden in a pale blue dot’s tiny speck of light.

For exoplanets, we can potentially measure brightnesses, brightness temperatures, and spectra. Earth itself has been observed “as an exoplanet.” We show Earth’s visible- and mid-infrared wavelength spectrum in Figure 1.2. As we shall

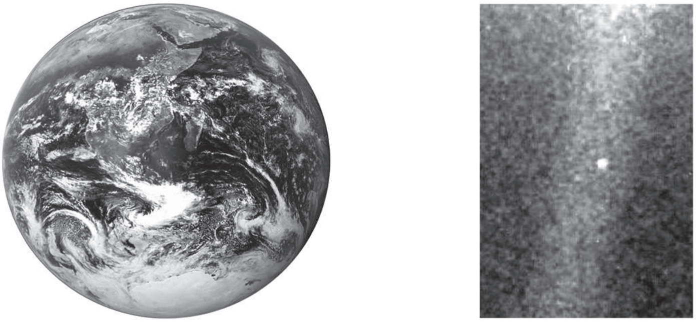

Figure 1.1 Earth as viewed from space. Left: image from NASA’s *Apollo 17* spacecraft in 1972. Right: image from *Voyager I* at a distance of more than four billion miles. The Earth lies in the center of a band caused by scattered light in the camera optics.

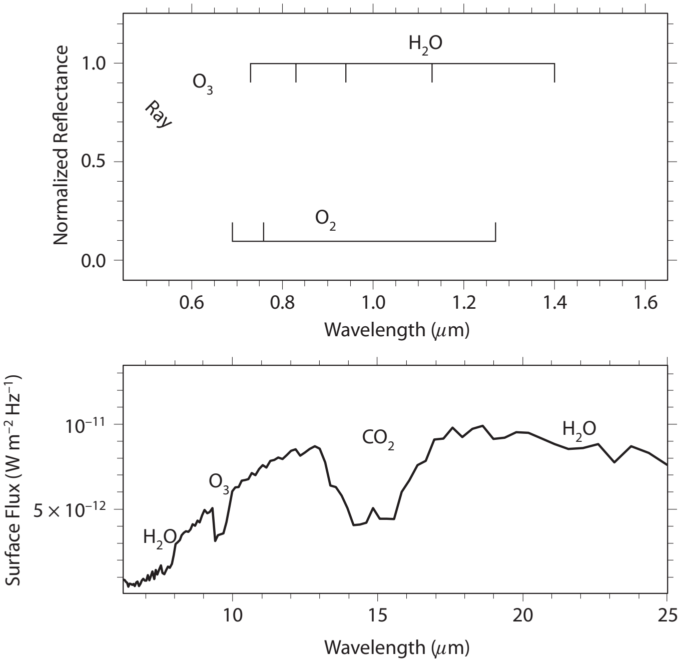

Figure 1.2 Earth's hemispherically averaged spectrum. Top: Earth's visible wavelength spectrum from Earthshine measurements [1]. Bottom: Earth's mid-infrared spectrum as observed by Mars Global Surveyor enroute to Mars [2]. Major molecular absorption features are noted; Ray means Rayleigh Scattering.

see in later chapters of this book, a spectrum contains information about a planet atmosphere's temperature and composition.

We cannot detect and study an Earth twin with current telescopes and instrumentation. Earth's pale blue dot is adjacent to our Sun, a star that is many orders of magnitude brighter than Earth. To be precise, the planet-star visible wavelength contrast for an Earth-Sun twin is 2.1×10^{-10} and for a Jupiter-Sun twin is 1.4×10^{-9}. The fundamental difficulty in observing exoplanet atmospheres is not their intrinsic faintness—indeed they are no fainter than the faintest galaxies observed by the *Hubble Space Telescope*. Instead, the enormous planet-star contrast is the major impediment to the direct observation of exoplanets.

1.2 TWO PATHS TO OBSERVING EXOPLANET ATMOSPHERES

The most natural way for us to think of observing exoplanets—albeit as point sources—is by taking an image of the exoplanet. This would be akin to taking a photograph of the stars with a digital camera, although using a very expensive, high-quality detector. This so-called direct imaging of planets is currently limited

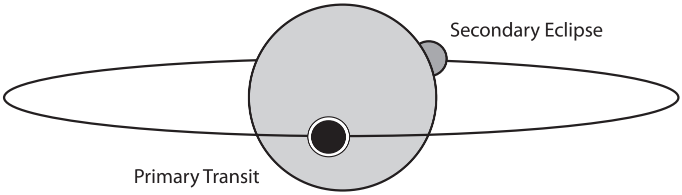

Figure 1.3 Diagram of a transiting exoplanet going in front of and behind its parent star.

to big, bright, young, or massive substellar objects located far from their stars [e.g., 3, 4]. Direct imaging of substellar objects is currently possible from space or with large ground-based telescopes and adaptive optics to cancel the atmosphere's blurring effects. For current technology, direct imaging of an Earth twin or Jupiter twin is out of the question. The high planet-star contrasts are prohibitive. Fortunately, much research and technology development is ongoing for space-based direct imaging to enable direct imaging of solar-sytem-aged Earths and Jupiters in the future.

For the present time, two fortuitous, related events have enabled observations of exoplanet atmospheres in a manner very different from direct imaging. The first event is the existence and discovery of a large population of planets orbiting very close to their host stars. These so-called hot Jupiters, hot Neptunes, and hot super Earths have less than four-day orbits and semimajor axes smaller than 0.05 AU. The hot Jupiters are heated by their parent stars to temperatures of 1000–2500 K, making their infrared brightnesss only $\sim$1/1000 that of their parent stars. While it is by no means an easy task to observe a 1:1000 planet-star contrast, this situation is unequivocally more favorable than the 10^{-10} visible-wavelength planet-star contrast for an Earth twin orbiting a sunlike star.

The second favorable occurrence is that of transiting exoplanets—planets that go in front of their star as seen from Earth. The closer the planet is to the parent star, the higher its probability to transit. Hence the existence of short-period planets has ensured that there are many transiting planets. It is this special transit configuration that allows us to observe the planet atmosphere without direct imaging (Figure 1.3).

Transiting planets are observed in the combined light of the planet and star (Figure 1.4.) As the planet goes in front of the star, the starlight drops by the amount of the planet-to-star area ratio. If the size of the star is known, the planet size can be determined. During transit, some of the starlight passes through the optically thin part of the planet atmosphere (depicted by the transparent annulus in Figure 1.3), picking up some of the spectral features in the planet atmosphere. By comparison of observations of the superimposed planet atmosphere taken during transit with observations of the star alone (outside of transit), the planet's transmission spectrum can in principle be measured.

Planets in circular orbits that go in front of the star also go behind the star. Just before the planet goes behind the star, the planet and star can be observed together. When the planet goes behind the star only the starlight is observed. These two observations may be differenced to reveal emission from the planet alone.

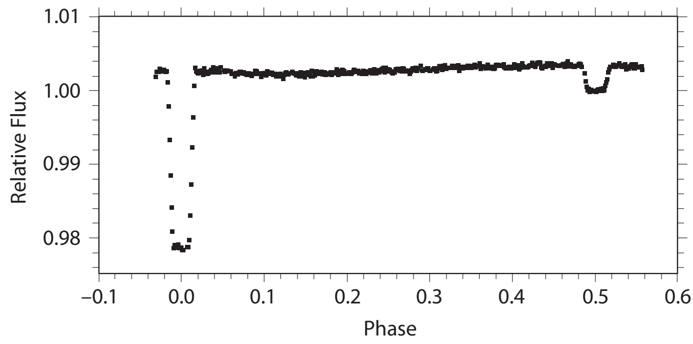

Figure 1.4 Infrared light curve of HD 189733A and b at 8 μm. The flux in this light curve is from the star and planet combined. The first dip (from left to right) is the transit and the second dip is the secondary eclipse. Error bars have been suppressed for clarity. See Figure 1.3. Data from [5].

The primary transit and secondary eclipse of the planet HD 189733b at 8 μm are shown in the combined light of the planet-star system in Figure 1.4. HD 189733 is a star slightly smaller than the Sun with a radius about 75% of the Sun's radius and the planet has an effective temperature of about 1200 K. At 8 μm we are seeing the thermal emission from the planet. As we will see in Chapter 3, the planetary brightness temperature can be measured by considering the depth of the secondary eclipse.

1.3 TYPES OF PLANETS

The most surprising aspect of the hundreds of known exoplanets is their broad diversity: a seemingly continuous range of masses and orbital parameters (Figure 1.5). Planet formation is a stochastic process, whereby the randomness likely 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. We expect to find a diversity in exoplanet atmospheres that rivals the diversity in exoplanet masses and orbital parameters.

The solar system itself contains an interesting menagerie of planets. Despite their very different visual appearances, the solar system planets are usually divided into two main categories: terrestrial planets and giant planets. The terrestrial planets include the four inner planets, Mercury, Venus, Earth, and Mars. The terrestrial planets are predominantly composed of rock and metals and have thin atmospheres. Atmospheric evolution, from both atmospheric escape of light gases and gas-surface reactions, has substantially changed each of the terrestrial planet atmospheres from their primitive state.

The giant planets include the four outer planets, Jupiter, Saturn, Uranus, and Neptune. These planets are vastly different from the terrestrial planets, with no rocky surfaces and masses up to hundreds of times those of the terrestrial planets.

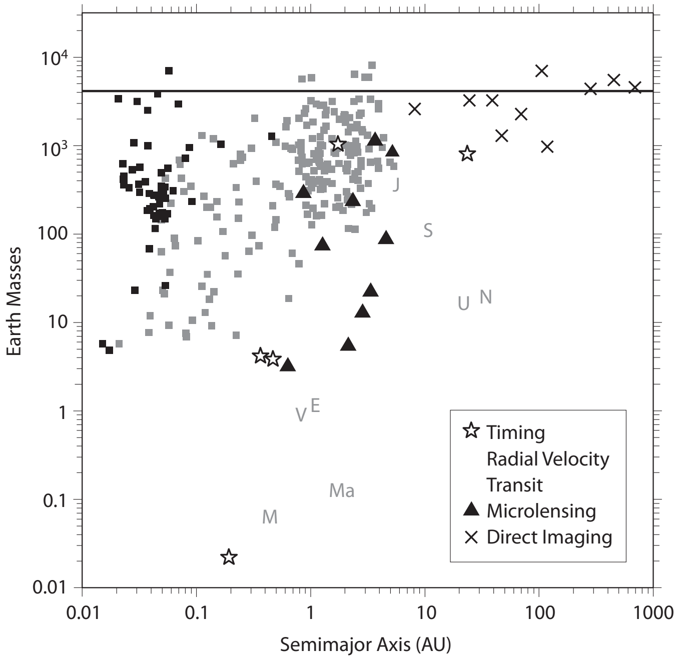

Figure 1.5 Known exoplanets as of January 2010. Exoplanets surprisingly are found at a nearly continuous range of masses and semimajor axes. Many different techniques are successful at discovering exoplanets, as indicated by the different symbols. The circles surround planets with an atmosphere measurement. The solar system planets are denoted by their first initial. The horizontal black line is the conventional upper limit to a planet mass, 13 Jupiter masses. The sloped, lower boundary to the collection of grey squares is due to a selection effect in the radial velocity technique. Data taken from [6].

The "gas giant" planets Jupiter and Saturn are composed almost entirely of hydrogen and helium with massive atmospheres and liquid metal interiors. The "ice giant" planets Uranus and Neptune are composed of mostly water, methane, and ammonia ices, yet also have a 1–2 Earth-mass envelope of hydrogen and helium. In contrast to the terrestrial planets, the giant planet atmospheres are primitive—little atmospheric evolution has taken place so that they contain roughly the same atmospheric gases as at their formation.

We turn to a detailed definition of planet types, in part taken from [7]. 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. Reliance on theoretical models indicates that such objects are less massive than about 13 Jupiter masses. A lower mass limit to the class of objects called planets has not been convincingly determined. An exoplanet is a planet orbiting a star other than the sun. (We note the term exoplanet has been used to include "free floating" planets that lack a host star.)

A terrestrial planet is a planet which is primarily supported from gravitational collapse through Coulomb pressure, and which has a surface defined by the radial extent of the solid interior or liquid outer layer. Terrestrial planets are often referred to as "rocky planets". A thin gas atmosphere may exist above the surface.

A giant planet is a planet with a mass substantially greater than terrestrial planets but less than brown dwarfs, e.g., $0.03\ M_{\rm J} < M_{\rm p} < 13 M_{\rm J}$ ($\sim$10 $M_{\oplus} < M_{\rm p} \lesssim 4000\ M_{\oplus}$). Giant planet interiors are thought to contain a substantial fraction of metallic hydrogen surrounding a rocky core.

A potentially habitable planet is one whose orbit lies within the star's habitable zone. The habitable zone is the region around a star in which a planet may maintain liquid water on its surface. The habitable zone boundaries can be defined empirically based on the obervation that Venus appears to have lost its water some time ago and that Mars appears to have ahd surface water early in its history. The habitable zone can also be defined with models. A habitable planet is a terrestrial planet on whose surface liquid water can exist in steady state. 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.

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.

Beyond the above generally accepted definitions are terms for exoplanets with no solar system counterparts. Super Earths are loosely defined as planets with masses between 1–10 $M_{\oplus}$, intended to include predominantly rocky planets. Mini Neptunes might be used for planets between about 10 and 15 Earth masses that have gas envelopes. The term water worlds has been used for planets that have 25% or more water by mass. Carbon planets refer to planets that contain more carbon than silicon, planets expected to form in an environment where elemental carbon is equal to or more abundant than oxygen. At present, observations cannot always distinguish among the above planet types.

Apart from planet types, there is not yet a definitive definition of atmosphere types (but see [8]). We do, however, expect atmospheres on different exoplanets to show a wide diversity, just as the orbits, masses, and radii of known exoplanets do. 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 will depend on the net of atmospheric sources versus. 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 and sequestering of gases in oceans. The range of atmospheric composition has yet to be uncovered theoretically and observationally.

The formalism presented in this book is intended to give you, the reader, knowledge to understand and interpret observations of any kind of exoplanet atmosphere.

REFERENCES

For further reading

For a review article on exoplanet atmospheres that summarizes observational and theoretical advances as of 2010:

- Seager, S., and Deming. D. 2010. "Exoplanet Atmospheres." Ann. Rev. Astron. Astrophys. 48, 631–672.

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8. Seager, S., and Deming. D. 2010. "Exoplanet Atmospheres." Ann. Rev. Astron. Astrophys. 48, 631–672.