



Sara Seager

Exoplanet Mass, Radius, and the Search for Habitable Worlds

Our sun is one amongst hundreds of billions of stars in our galaxy. Based on the number of times the planetary dice must have been thrown, all kinds of imaginable (and even planets far beyond our imagination) must be out there. This is a very exciting time for extrasolar planets (“exoplanets”): almost 300 are known to orbit nearby stars and their diversity is enormous.

THE KNOWN EXOPLANETS ARE SHOWN in *Figure 1*, in terms of the planet mass vs. planet-star separation. In this figure, we can see that exoplanets exist with all masses and planet-star separations that are accessible using current technology. Exoplanet formation appears to be a random process, and, together with “planetary migration” gives rise to such a wide range of exoplanets.

In this article, I will describe the methods used to determine planet composition, the types of exoplanets found so far, and the ongoing search for habitable worlds.

Transiting Exoplanets

How can we characterize the composition of exoplanets? The answer lies with transiting exoplanets. Transiting planets are those that pass in front of their parent star as seen from Earth. The starlight dims by an amount equal to the planet-to-star area ratio. If we know the size of the star, we can infer the size of the exoplanet. From a different detection technique—radial velocity measurements—astronomers can determine the exoplanet mass. Mass and size (or volume) give density. Finally, from the average density and planet mass we can infer the planet’s bulk composition. The transit technique is the only way we can study the mass, radius and average density of exoplanets. Over fifty transiting planets are known, and more are being found monthly.

How to Infer an Exoplanet’s Bulk Composition

To study an exoplanet’s interior composition, we use the planet’s mass and radius. Indeed, these are often the only two observations available to us. Next, we use models of the planet interior that match the known planet mass and radius. The basic picture behind the models is the idea that pressure from solid or gaseous material inside the planet prevents the planet from collapsing under its own gravity. To model this so-called hydrostatic equilibrium, we must know how the density of a given material behaves under the pressure of the overlying shells of material in a planet. For example, a planet 10 times the mass of Earth made of the same material as Earth does not have the same average density as Earth. Instead, such a

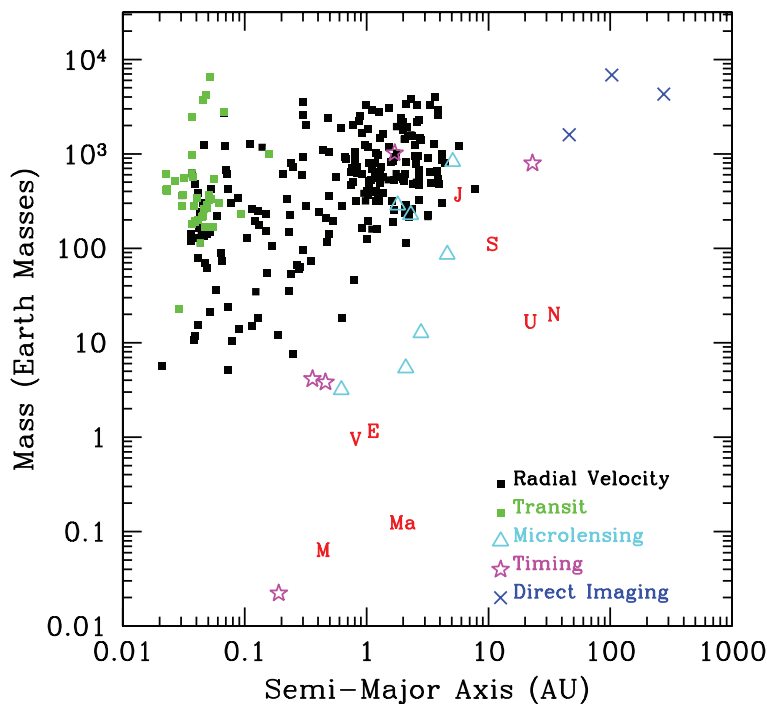
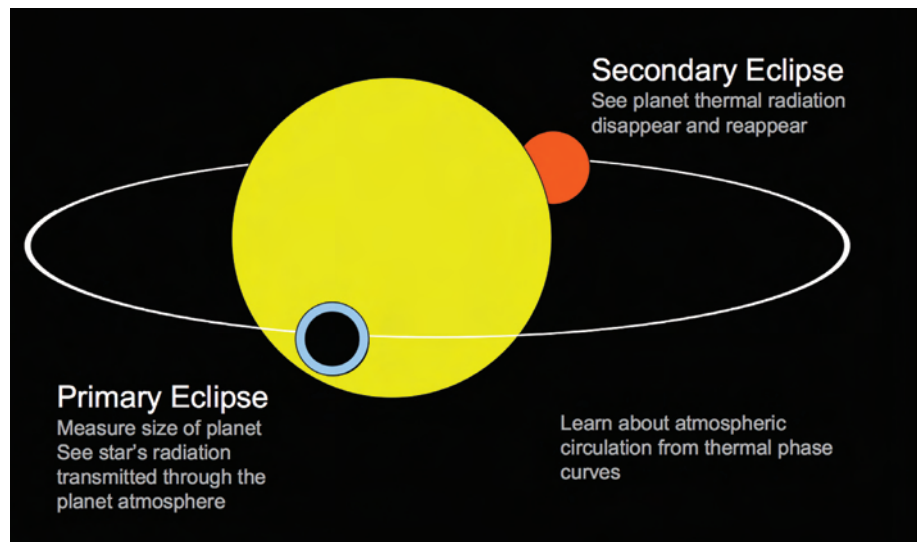


FIGURE I
Known planets as of June 2008. The symbols indicate the discovery technique. Technological limitations prevent planets from being discovered in most of the blank regions in this diagram.

FIGURE 2

Schematic illustration of a transiting exoplanet. Not to scale.



super Earth has a higher density, because the outer layers of the planets crush the inner layers and make the planet more compact.

Exactly how much the material in the inner planetary layers can be crushed is a critical input to the model. Indeed, many researchers spend entire careers on experiments to understand planetary materials at high pressure; we use this data as input to models. Some exoplanet interiors are expected to reach high pressures (millions of times higher than atmospheric pressure), beyond the reach of laboratory experiments. In this case, we use calculations from quantum mechanics that describe how nuclei and electrons interact at very high pressures, when some of the electrons have been “popped off” the atoms due to the high pressures, thus creating an electron degenerate gas. Stated another way, my models solve two equations (the mass of a spherical shell and hydrostatic equilibrium) together with a third equation, the “equation of state” or relationship between pressure and density (and temperature) of a given material.

Types of Known Exoplanets

Let us start the discussion of planet types with the planets in the top right corner of the mass-radius diagram. These are massive giant planets, about 300 times the mass of the Earth, and composed mostly of hydrogen and helium. Here we can see the diversity of exoplanets in terms of their masses and radii. Some of the most extreme exoplanets are very near the top of the diagram. These planets are too big for their mass and age. Planets are born big and hot, and contract and cool as they age. Something is preventing the largest hot Jupiters from contracting and cooling. While researchers do not agree upon what, everyone agrees that an extra source of energy must exist in the planet interior. The source of this interior energy is one of the most interesting, outstanding questions in exoplanet research.

The exoplanet second closest to the right edge of *Figure 4* is also an intriguing planet. This planet is eight times the mass of Jupiter—an additional 2,500 Earth masses! Yet, the planet is the same size as Jupiter. Let’s imagine starting with a

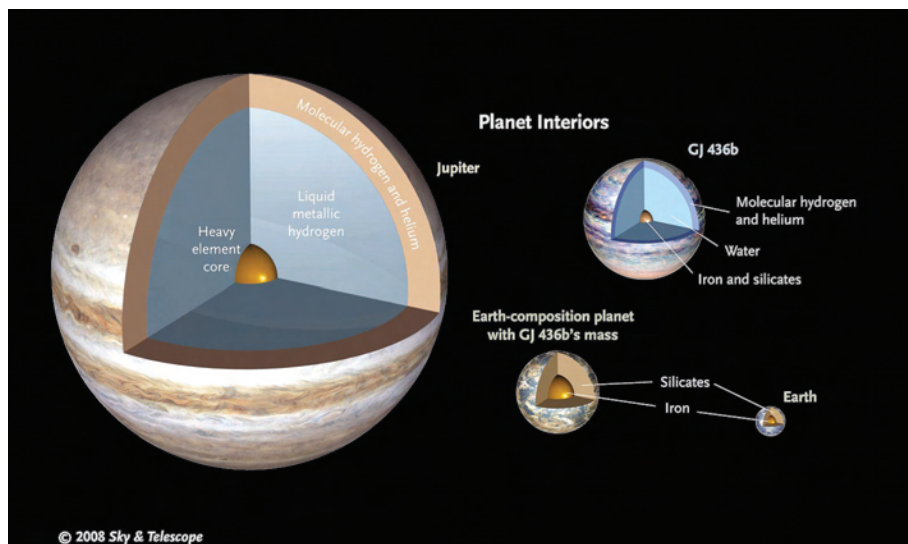


FIGURE 3
Illustration of planet interiors for several different exoplanets. (Figure by Casey Reid, courtesy Sky and Telescope.)

Jupiter-mass, Jupiter-size planet and adding 2,500 Earth masses-worth of hydrogen and helium. We expect the planet to get larger, and the outer layers of the planet indeed get larger. With increasing mass, however, the interior of the planet reaches a higher and higher pressure, so high that an increasing number of the electrons are stripped from the parent atoms, creating a sea of electrons called an “electron degenerate gas.” For objects we experience in everyday life, adding mass to an object makes it larger. For electron degenerate material, adding mass makes the material smaller because with some of the electron-electron repulsion removed by the stripped-off atoms, the atomic nuclei are able to get closer and closer together. The net effect is that the interior of the planet gets smaller with increasing mass. The canceling effects of the bigger exterior and smaller interior mean the planet remains the same size despite being so much more massive than Jupiter.

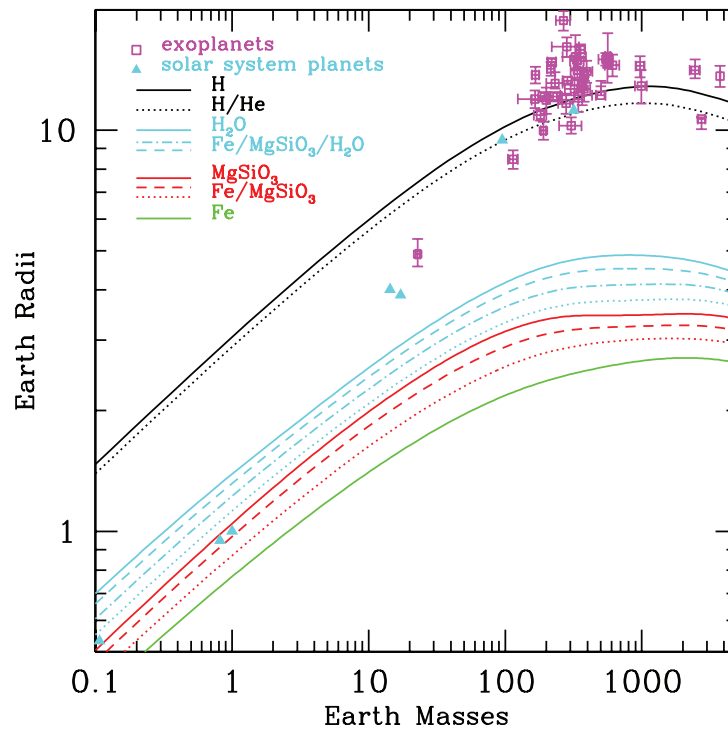
Moving down in planetary mass, the planet HD 149026 also has no solar system counterpart. This Saturn-mass planet is composed of an outer layer of about thirty Earth masses of hydrogen and helium. The planet’s interior is made up of about sixty Earth masses of rock and ice. This is equivalent to all of the rock and ice in the solar system combined, in one exoplanet! A Neptune-mass exoplanet has recently been discovered, and while its size is also the same as Neptune’s the details of the planet’s average composition is not known. We can think of both HD 149026 and the Neptune-mass transiting exoplanet as rock-gas hybrid planets.

We are now anticipating the discovery of a number of transiting rocky exoplanets. These so-called “super Earths” are planets from one to upwards of ten Earth masses. Super Earths are expected to be predominantly rocky, with little hydrogen and helium, because of formation processes for low-mass planets. One dozen super Earths are already known, though none are transiting.

Why all the excitement about small planets? Giant planets, while interesting in their own right, are not at all suitable for life as we know it. The giant planets have a significant amount of hydrogen and helium, in the form of massive “envelopes”

FIGURE 4

Mass-radius relationships for solid planets. The solid lines are models of homogeneous planets and the non-solid lines are models of planets with internal materials separated by layers according to density. The magenta squares denote the transiting exoplanets. Note that electron degeneracy pressure becomes important at high mass, causing the planet radius to become constant and even decrease for increasing mass.



that surround the planet interior. These hot envelopes make the planets completely inhospitable to life, because they act like a blanket on the planet, trapping interior heat and making the surface temperatures far too high for life. Planets like the hot Jupiters have no surface to speak of, further complicating the origin and existence of life. Super Earths, in contrast to the giant planets, are anticipated to be almost entirely rocky, with thinner atmospheres that are conducive to life, provided that the planet is neither too hot nor too cold.

Why all the excitement about *transiting* small planets? Again, transiting planets are the only exoplanets whose physical properties can be studied with current technology. Beyond the planet mass and radius, the planet's atmosphere can be studied in search of molecules that are helpful for life or are actual signs of life.

In anticipation of the discovery of transiting super Earths, my students and I have been studying the interiors and atmospheres of exoplanets. Our aim is both a fundamental understanding of the planet masses and radii, as well as a complete picture of the range of planet compositions that are possible for a given mass and radius.

Researchers at MIT are developing a satellite to search for more transiting planets. The Transiting Exoplanet Survey Satellite (TESS), led by George Ricker, will survey two million stars to find over one thousand transiting exoplanets, a subset of them super Earths. I am leading the development of different project, a suite of nanosatellites to search individual bright sun-like stars for Earth analogs (Earth-size planets in Earth-like orbits).

In 2008, we are standing on a great divide in exoplanets. On the one side of this divide are the 300 giant exoplanets. Over fifty are transiting planets, and we have been able to measure their masses and radii and make models to understand the planetary composition. On the other side, we are developing technology to discover true Earth analogs to answer the ancient questions, “Do other Earths exist?”, “Are they common?” and “Do they have life?” In the meantime, the observational and theoretical techniques we are developing will enable us to interpret observations of transiting super Earths, as soon as they are discovered, including identification of potentially habitable worlds.

SARA SEAGER is the Ellen Swallow Richards Professor of Planetary Science, and Associate Professor of Physics at MIT. Her current research interests are focused upon extrasolar planet atmospheres and interiors. Seager and her group aim to understand the atmospheric composition and the interior structure of exoplanets, with a focus on the growing data set of transiting exoplanets.

Seager received her B.Sc. in mathematics and physics from the University of Toronto in 1994, and earned a Ph.D. in astronomy from Harvard University in 1999, where she investigated recombination in the early Universe before moving to the then brand-new field of exoplanets. She was a long-term member at the Institute for Advanced Study in Princeton, NJ, and a senior research staff member at the Carnegie Institution of Washington in Washington, D.C., before joining the MIT faculty in 2007. Seager was awarded the American Astronomical Society’s Helen B. Warner prize in 2007 for her pioneering work on extrasolar planet atmospheres.