Chapter 15: Exoplanets: Planets of Other Stars

"The curtain is going up on countless new worlds with stories to tell." – Timothy Ferris

"Our Solar System is a marvel filled with magnificent specimens of planets. Yet for all its beauty, we now know that it is a poor showcase for the remarkable diversity of known planetary systems." – Jonathan Fortney

Exoplanets are extrasolar planets are planets of other stars (not the Sun).

Astronomers became able to detect planets around other stars in 1991. Thousands are now known, with more being rapidly discovered. There are probably billions to be discovered, since nearly all stars appear to have planets. (See Figures 15-01 and 15-02.)

So far, this has been mostly indirect detection. Only a few exoplanets have been seen in direct images. (See Figure 15-01.) There are several indirect detection methods. Over 400 of the first 500 known exoplanets were discovered with the Doppler effect. As an exoplanet orbits its parent star, its gravity pulls the star around. (See Figure 11-14.) The Doppler effect makes lines in the star's spectrum move, and telescopes equipped with spectrographs can detect this. Most of the next 3,000 exoplanets to be discovered were found by observing transits. In a transit, exoplanets pass between their parent star and Earth. (See Figures 15-03 and 15-04.)

What have astronomers found?

(1) **Pulsar planets:** Pulsars are dead cinders of stars that blew up in supernova explosions. Finding exoplanets around pulsars was surprising, since the last place anyone expected to find exoplanets was around the remnants of stars that have exploded. These exoplanets probably formed after the explosion, from material falling back. If exoplanets can form under such extreme conditions, this suggests that exoplanets may be just about everywhere.

(2) **Hot Jupiters:** These are as massive as Jupiter, but are closer to their parent stars than Mercury is to the Sun. They were also a surprise. Astronomers used to think we knew that Jupiter, Saturn, Uranus, and Neptune are all more massive than Earth because the giant planets are farther from the Sun. The thinking was that giant planets could only form far from the Sun, since giant planets are made mostly of gas and ice, which can clump together by gravity only where it's cold. Hot Jupiters show that giant exoplanets *can* exist close to their parent stars. Do hot Jupiters form far from their parent stars, and then migrate inward?

(3) **Eccentric Jupiters:** These are also as massive as Jupiter, but their orbits are highly eccentric (or in other words, long and thin). These orbits are unlike those of any of the planets in the Solar System: they are like the orbits of comets. Astronomers therefore realized that the orbits of eccentric Jupiters cannot be stable, since the gravity of other planets would throw them out of orbit, the way that Jupiter's gravity does with comets. Eccentric Jupiters are therefore hot Jupiters caught in the act of migrating.

(4) **Classical Jupiters:** These are similar to Jupiter, in both mass and distance from their parent stars. (See Figure 15-05.)

(5) **Gas dwarfs (formerly hot or warm Neptunes):** No known planets in the Solar System have masses between 1 and 15 Earths. Around other stars, these are the most common exoplanets known. Observations show that 30-40% of stars like the Sun have gas dwarfs, or super Earths.

(6) **Super Earths:** Many exoplanets with masses of 1-2 Earths are rocky, like Earth. That these are rocky is known because transits show their radii. Apparently, there is a transition at masses above 2 Earths, with most exoplanets more massive than this being gas dwarfs with thick, gaseous envelopes. No one knows why. (See Figure 15-06.)

At least 26 super Earths are in their parent stars' habitable zones (abbreviated HZ). A star's habitable zone is the region around the star with temperatures between 0 and 100° C, so that liquid water can exist. Liquid water is the one requirement for life-as-we-know-it on Earth. (It's hard to say much that makes sense about life-as-we-don't-know it, because we don't know it.) That's right: these 26 exoplanets *might be able to support life*—although we *still don't know* whether any of them *do* have life. (See Figure 15-07.)

(7) **Orphan (or rogue) planets:** These are planets that wander freely in space, and do not orbit any star. They may be as common as the planets that do orbit stars. Orphan planets were probably formed around stars, but were kicked out of their planetary systems by the gravity of other planets. (See Figure 15-08.)

(8) **Terrestrial planets:** Terra means "Earth" in Latin. NASA's *Kepler Observatory* spacecraft has found that *at least 1 out of 5 Sun-like stars have Earth-sized exoplanets in their habitable zones*. (As many as 1 in 2 of them might.) We still don't know whether any of these exoplanets have life. New observations, particularly of spectra, are needed for this.

Astronomers have also found:

• There are many known cases of multiple exoplanets orbiting their parent star. Some people call these "other solar systems." I disagree: I think the term "Solar System" should be reserved for the Sun and its system of 8 planets. Other stars and their planets should be called "exoplanetary systems," or better, just "planetary systems."

• Nearly all stars have planets. However, only 3% of planetary systems are similar to the Solar System, with at least one Classical Jupiter outside the star's habitable zone, and with at least one terrestrial planet in the habitable zone.

• Most planetary systems are unlike the Solar System. Hot Jupiters orbit 10% of stars like the Sun. Gas dwarfs, also called hot or warm Neptunes, orbit 30-40% of stars like the Sun.

• Most planetary systems have planets closer to their parent stars than Mercury is to the Sun. No one knows why.

• Most stars like the Sun have companion stars that orbit them, much like planets do. Binary stars, also called double star systems, can have planets. (See Figure 15-09.)

• The first three types of exoplanets discovered were pulsar planets, hot Jupiters, and eccentric Jupiters. All these are all unlike anything previously seen in the Solar System, or even imagined by science-fiction writers. Only the fourth type of exoplanets discovered (namely, Classical Jupiters) are similar to anything anyone did expect (namely, Jupiter). When the time comes for astronomers to discover life from Outer Space, therefore, don't be surprised if the first several kinds found are quite unlike anything from Earth.

• Before 1991, astronomers often assumed that nearly all stars like the Sun had planets. This turned out to be right. Also before 1991, astronomers often assumed that all planetary systems had to be copies of the Solar System. We now know this is quite wrong.

• Astronomers also used to assume that Earth is the best possible environment for life, and that nearly all life had to be on planets just like Earth. This may not be true. Super Earths appear to be more common than terrestrial planets. Many super Earths orbit stars less massive than the Sun, which last longer. (See Chapter 25.) If bacteria existed on super Earths, the stronger gravity would make little difference to them. Still, there has not yet been any definite discovery of life anywhere other than Earth, despite whatever UFO enthusiasts might claim. (See Chapter 31.)

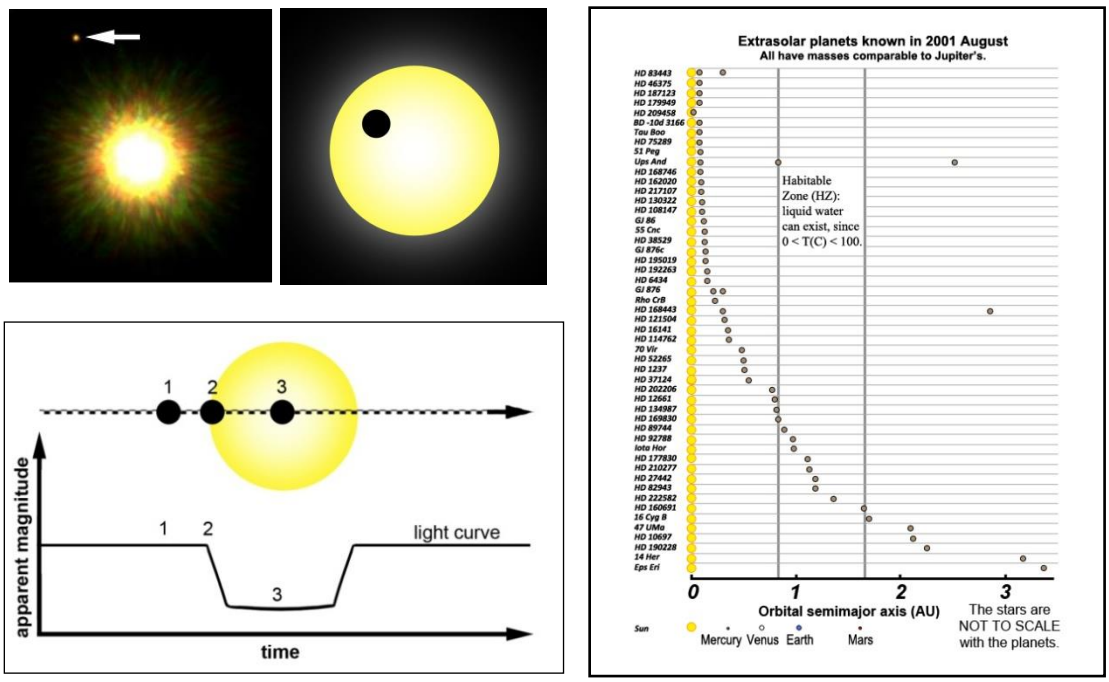

Figure 15-01: Exoplanets are planets that orbit other stars. They were first discovered in 1991. Thousands are now known. Many were discovered indirectly, from the Doppler effect in spectra (see Chapter 11). Many more are being discovered from *transits*.

Left top left: A few exoplanets have been found directly, in images. This is difficult because the parent stars are so much brighter than the exoplanets. The Sun, for example, is 270 million times brighter than Jupiter. It's like trying to see a firefly next to a searchlight. (Gemini Observatory/AURA)

Right top left: A transit happens when an exoplanet passes in front of its parent star. (Image by the author)

Bottom left: When an exoplanet transits its parent star, it causes the parent star's brightness to fade by as much as a few percent. Modern digital cameras are precise enough to detect this. (Image by the author)

Right: This is a plot of the exoplanets known in 2001 August. Why use a plot this old? It's because so many exoplanets have been found since then, an up-to-date plot would be so crowded it would be impossible to read if jammed into one page.

Notice that exoplanets have been found inside, in, and outside the habitable zones (HZ) of stars like the Sun (shown here). The habitable zone (HZ) is the region around a star where liquid water can exist, because temperatures are between 0 and 100° C. This is sometimes also called "the Goldilocks zone." (Image by the author, from an image by the California Carnegie Planet Search)

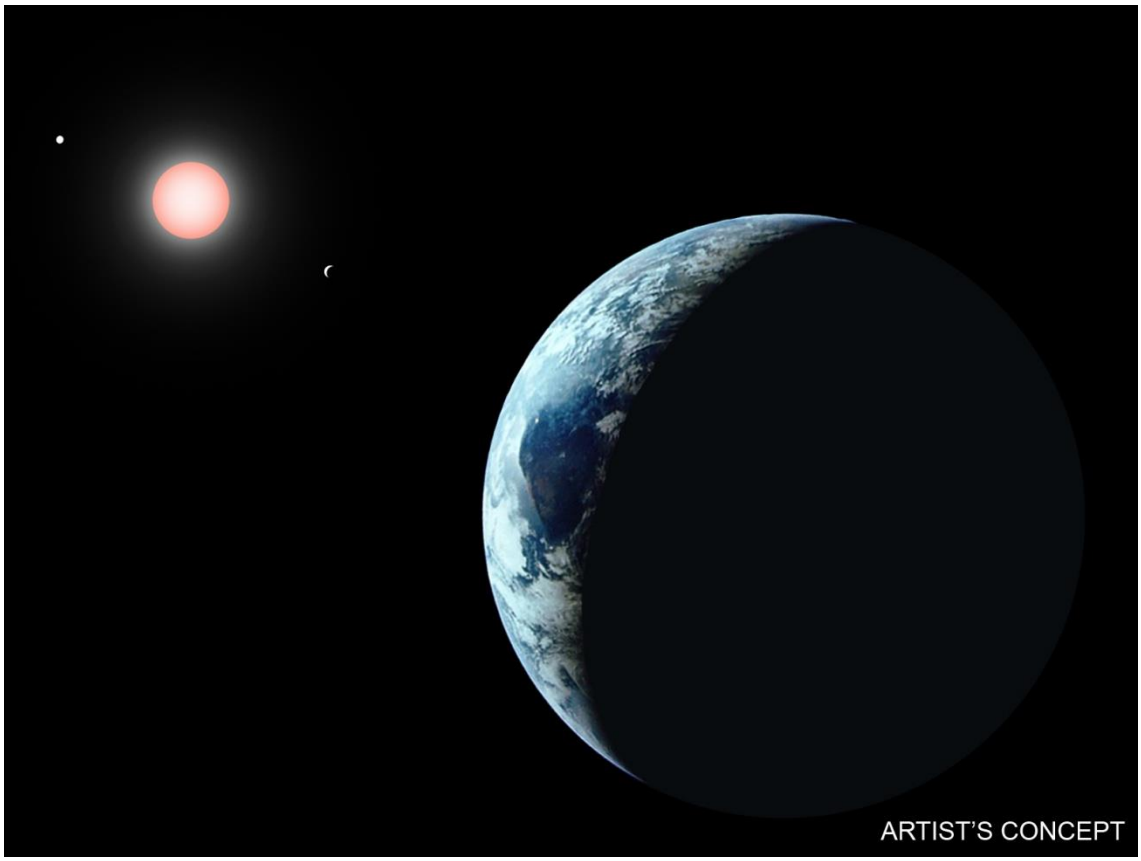

Figure 15-02: What everyone wants to find are truly *Earth-like* exoplanets. The first may be found at any time now: at least 26 exoplanets that are 1-2 times the size of Earth in the habitable zones of Sun-like stars are now known. Many more are expected to be found in the coming years. (Image by the author, using a NASA image taken on *Apollo 11*)

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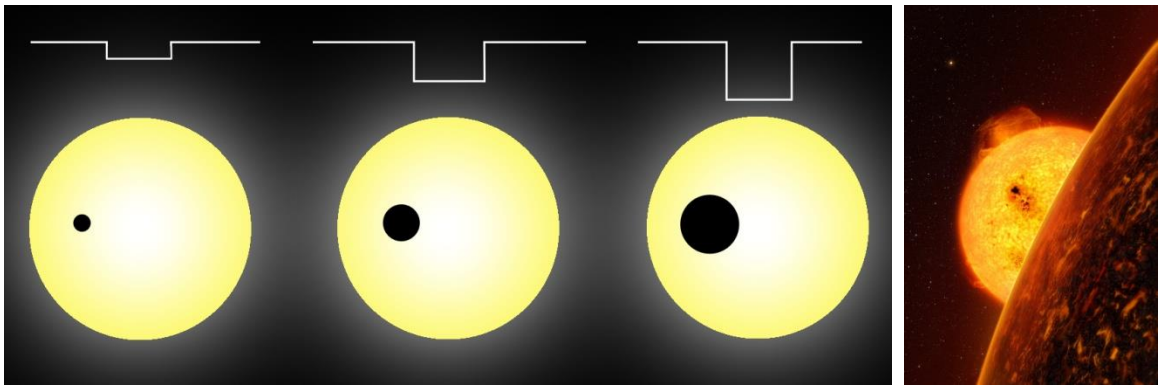

Figure 15-03: *Left:* Transits show an exoplanet's size. (Image by the author)

Right: A milestone made in 2009 was the discovery of CoRoT-7b, the first confirmed Earth-sized exoplanet. It was also the *first confirmed rocky exoplanet*.

CoRot-7b is a lava planet with a mass of 5 Earths. It is very hot because it orbits its parent star closer than Mercury is to the Sun. It's not very Earth-like, is it? (NEED PERMISSION from European Sothern Observatory/L. Calcada)

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Figure 15-04: NASA's *Kepler Observatory* spacecraft operated between 2009 and 2018. It observed exoplanet transits in Sun-like stars. It found 2,681 confirmed exoplanets. Of these, 290 are in their stars' habitable zones. Of these, 26-30 (and probably more) are Earth-sized. This implies that *at least 1 in 5 Sun-like stars have Earth-sized exoplanets in their habitable zones.* The habitable zones are where temperatures are between 0-100º C, allowing liquid water and possibly life. As many as 1 in 2 Sun-like stars may have planets that could support life. (NASA)

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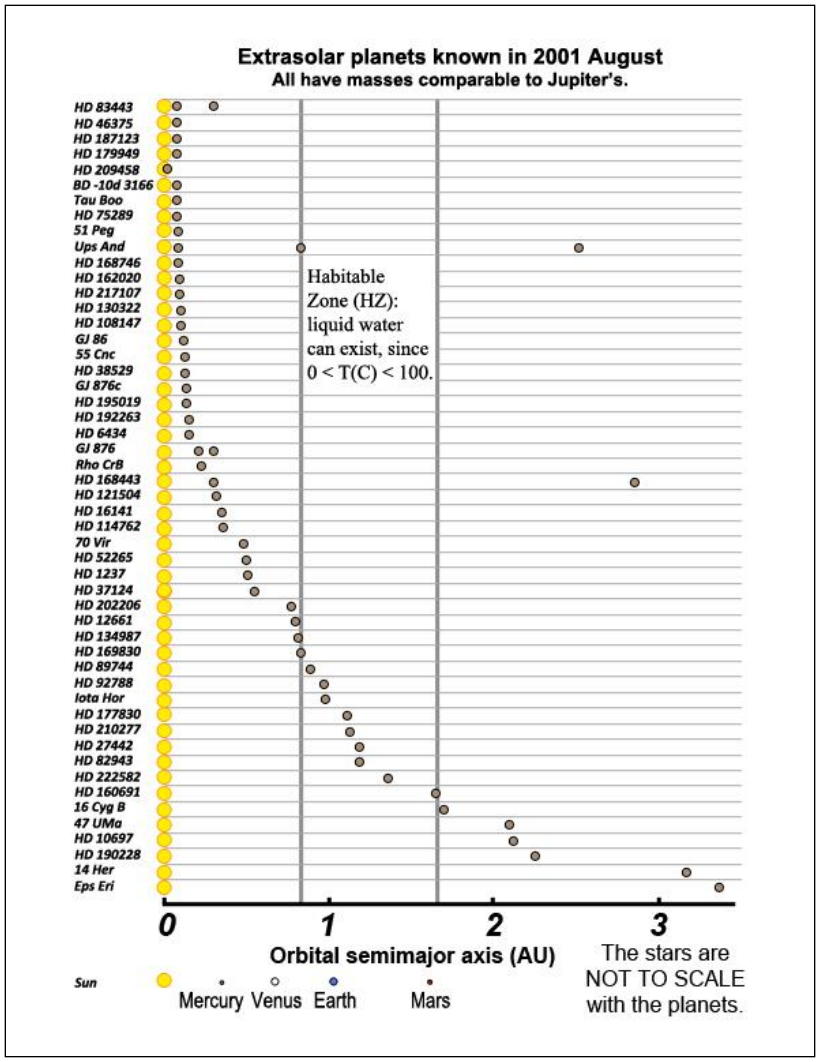

Figure 15-05: What have astronomers found, so far?

(1) Pulsar planets, around dead stars

(2) Hot Jupiters, around normal stars

(3) Eccentric Jupiters

(4) Classical Jupiters, which are much like Jupiter

(5) Gas dwarfs (or hot/warm Neptunes), which are gaseous exoplanets with masses of 2-15 Earths

(6) Super-Earths, which are rocky exoplanets with masses as low as 1-2 Earths

(7) Terrestrial planets: "Terra" means "Earth" in Latin. NASA's *Kepler Observatory* spacecraft has shown that at least 1 in 5 Sun-like stars have Earth-size planets in their habitable zones. Astronomers still don't know whether they have water or life: we need spectra. Still, we may identify another Earth at any time now.

(Image by the author, inspired by an image by the California Carnegie Planet Search)

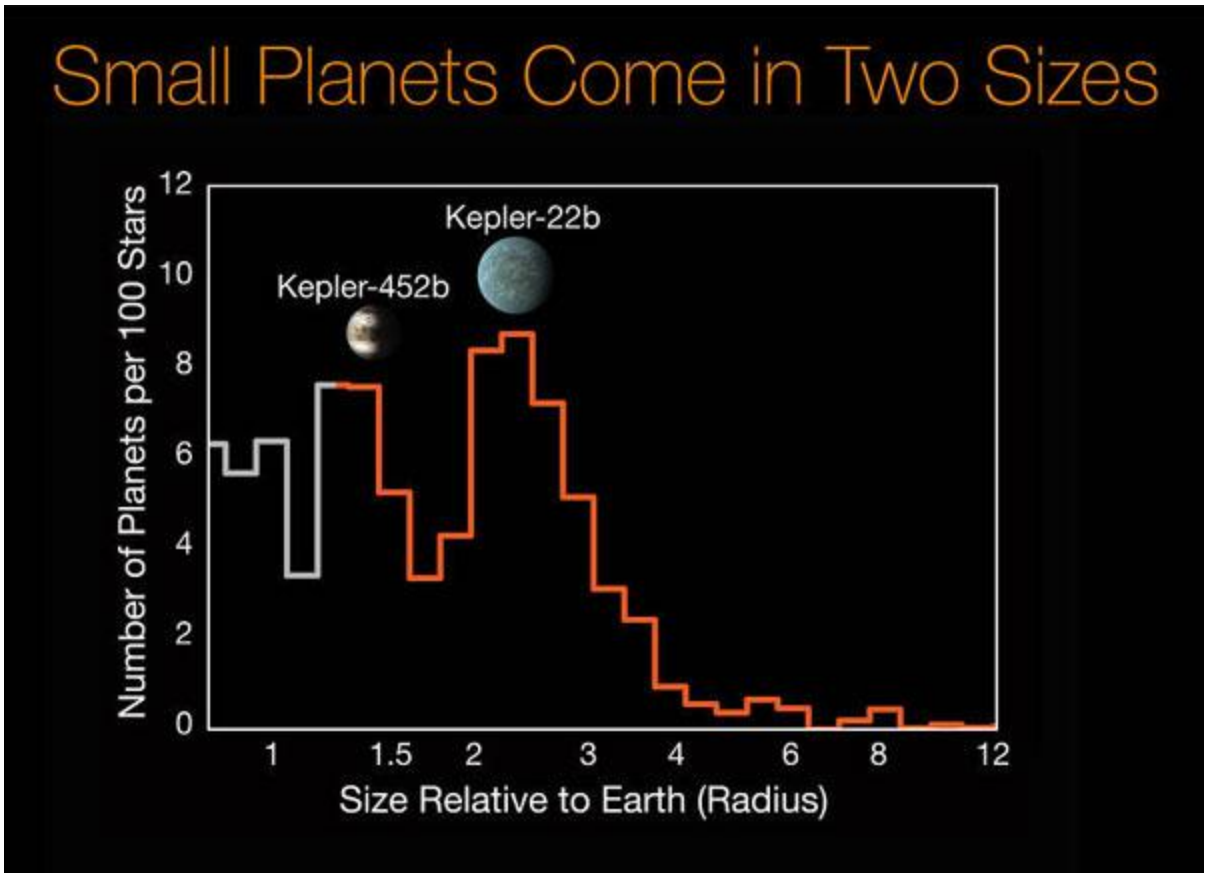

Figure 15-06: So far, observations suggest that the most common exoplanets have masses of 1-15 Earths. These appear to come in two distinctive types: (1) Super-Earths, which are rocky exoplanets with masses as low as 1-2 Earths, and (2) Gas dwarfs, which are gaseous and have masses of 2-15 Earths. (NASA)

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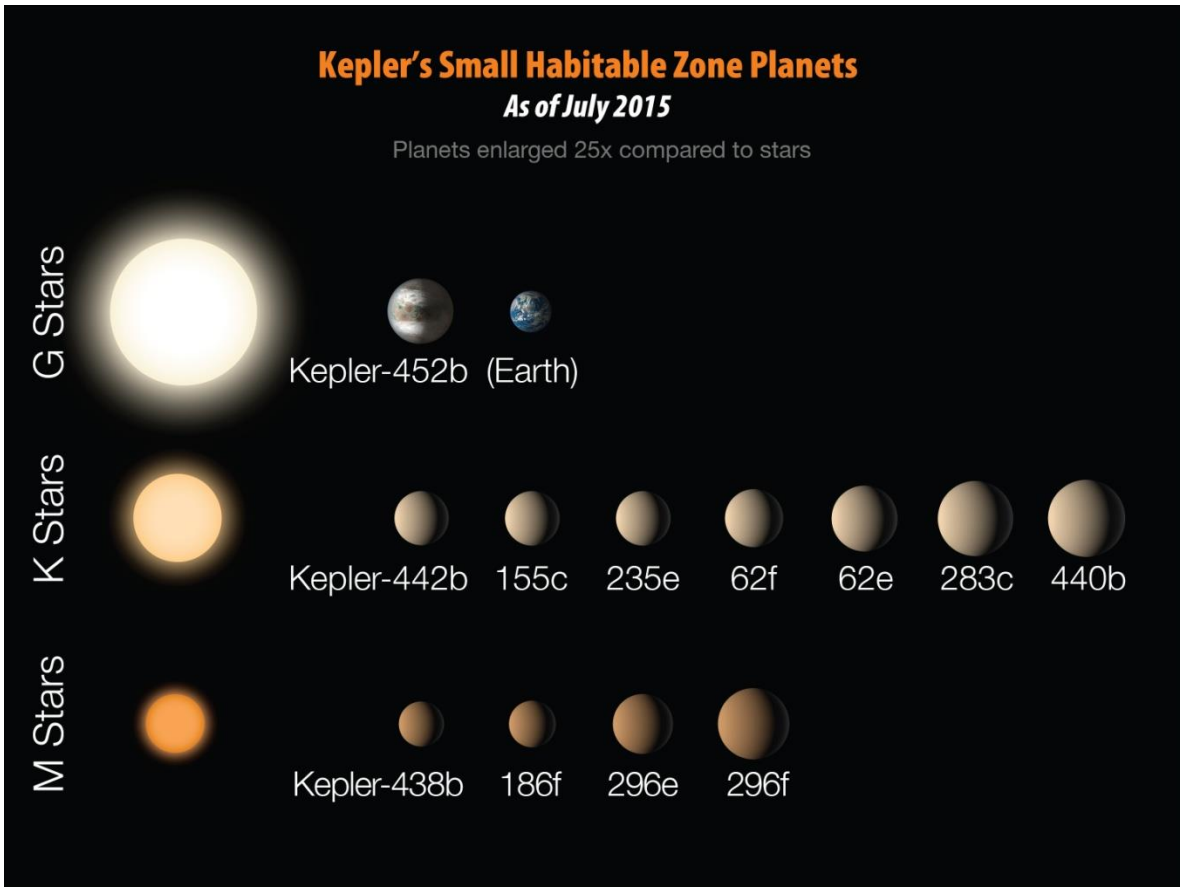

Figure 15-07: To support life, exoplanets may *not* need to be exactly like Earth. Neither may their parent stars need to be exactly like the Sun. NASA's *Kepler Observatory* has found at least 12 exoplanets that are 1-2 times more massive than Earth, which are in the habitable zones of stars with masses of 0.1-1 Suns. Stars less massive than the Sun last longer than the Sun. (See Chapter 25.) It may therefore be possible that, while Earth is a good home for humans, it may *not* necessarily be the most likely environment for life. (NASA)

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Figure 15-08: “Orphan planets” are also called “rogue planets.” They do not orbit a parent star. They wander in the perpetual night of free space. They appear to be as common as exoplanets that do orbit stars. (NASA/JPL/Caltech)

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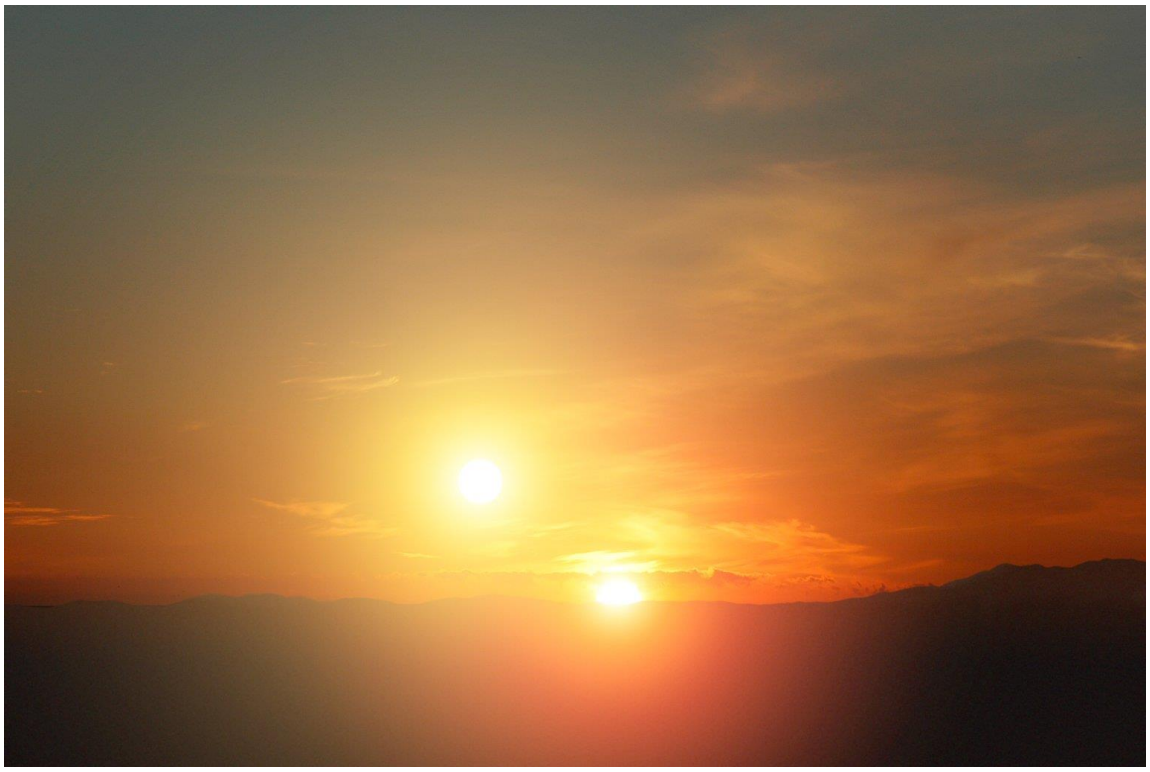

Figure 15-09: Exoplanets have been found orbiting binary, or double, stars, in which two stars orbit each other. This is an artist's conception of a double sunset. (NASA)

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