Thermal Radiation of Worlds beyond Our Solar System

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Let's begin simply: what is an exoplanet? The term is short for extrasolar planet, which is any planet that is orbiting a star that is not our sun. There are also rogue planets, which are not associated with any star and are extremely difficult to find. We're going to focus on exoplanets, which do orbit a host star. Before we talk about thermal radiation or how we look for exoplanets, however, let's start off by talking about why exoplanets matter. The most compelling reason is the search for life, particularly beyond our own solar system. Within our solar system, we know there is life on Earth, and there may also have been, or could currently be, life elsewhere in the solar system, including on the two moons Titan and Europa or on the planet Mars.

How might we approach looking for life beyond the solar system? The strategy is to search for water. As far as we understand it, life requires water, specifically liquid water; therefore, we want to find planets that have the potential to have liquid water on their surface. How far away does the planet have to be from its host star for liquid water to exist? There's a sweet spot called the habitable zone, and it mostly depends on the size of the host star because larger stars are generally hotter. For such stars, planets have to be farther away from the star to avoid the water boiling away. For low-mass, cooler stars, planets must be a lot closer to the star to avoid the water freezing. Let's look at our own system. At the bottom of Figure 1 below is the inner solar system, with the planets Mercury, Venus, Earth, and Mars. The green band indicates the habitable zone around the sun. Shown at the top is another star system, Trappist-1, with six exoplanets shown, three of which are within its habitable zone. This depiction of Trappist-1 is enlarged twenty-five times. This entire system could fit within the orbit of Mercury in our own solar system with room to spare because Trappist-1 is a small, red dwarf star. Planets must be closer to it for a chance at liquid water. Exoplanet researchers have found that many star systems are very compressed systems.

Trappist-1 is not the only system with potentially habitable exoplanets. Depending on your definition (there is some debate as to just how close or far the habitable zone extends), there may be as many as sixty currently confirmed, potentially habitable exoplanets. Some of them are shown in Figure 2

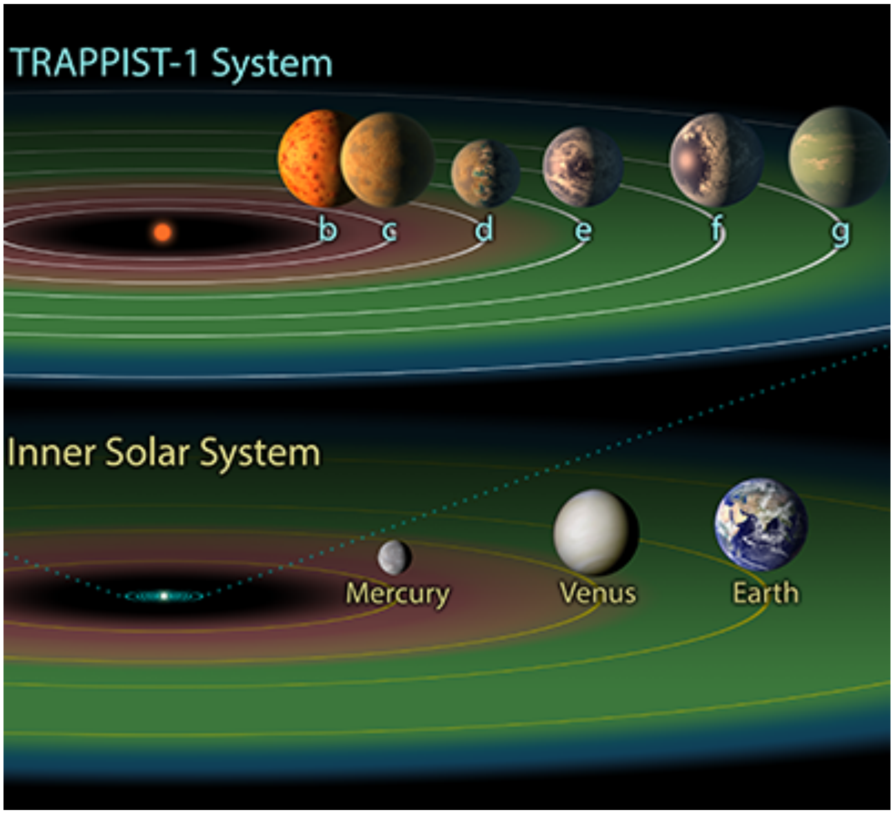

Figure 1. Illustration of the TRAPPIST-1 exoplanet system with the inner solar system for comparison. Image credit: NASA/JPL-Caltech.[1]

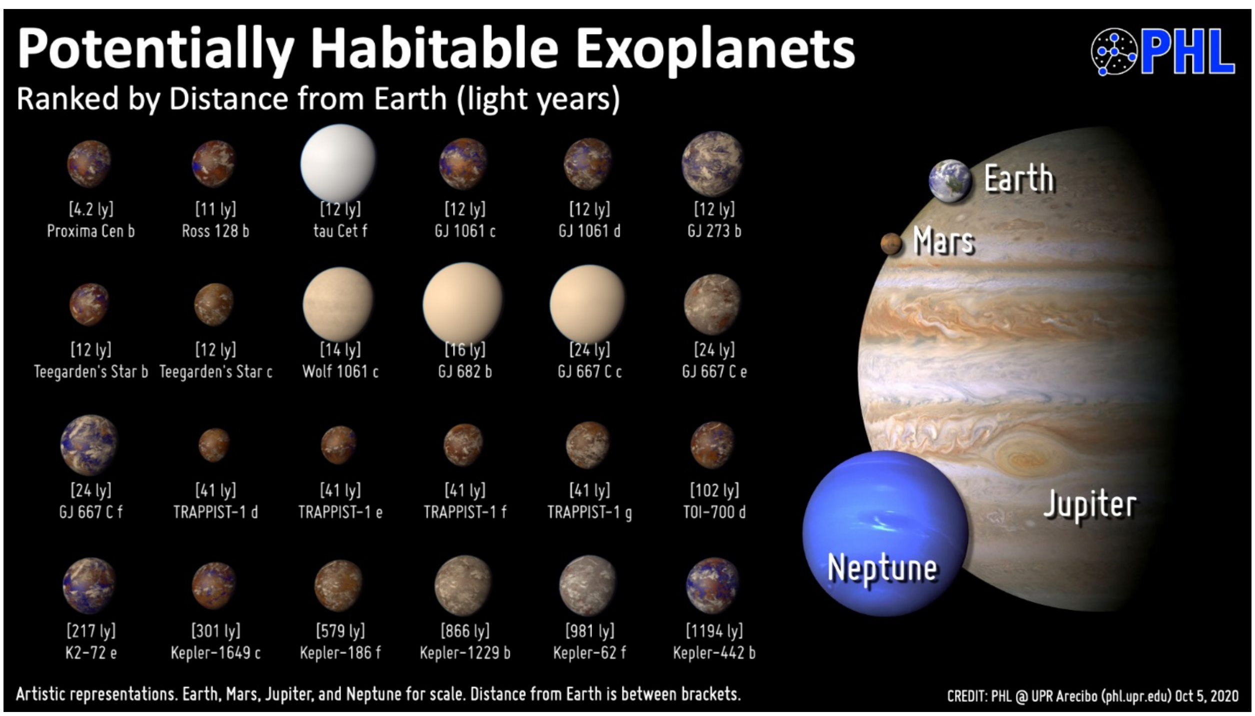

Figure 2. Artistic illustrations of potentially habitable planets with Earth, Mars, Jupiter, and Neptune shown to scale. Image credit: PHL @ UPR Arecibo.[2]

as artistic impressions, where Earth is to scale. They are ranked according to their distance from Earth, starting in the upper left. The planet on the top left is Proxima Centauri b, which is orbiting the star Proxima Centauri. Note the naming convention: “star name” followed by a lowercase letter, where “b” indicates the first exoplanet discovered around the star, “c” the second, and so on. Proxima Centauri is the star that is closest to the sun at only 4.2 light years away. Given our current understanding and our current dataset, it is believed that nearly every star has at least one exoplanet and that about one in five sun-like stars has one exoplanet in its habitable zone. Thus, potentially habitable planets might be fairly common.

There is another reason to study exoplanet science: to learn a bit more about what is out there and about the formation of star systems and planets. Up until only a few years ago, we only had one system, one test case, to use to understand star system formation: ours. Now, we have a number of other star systems we can study, and we have started discovering new things. There are types of planets out there that do not exist in the solar system. The first are hot Jupiters, which are planets about the mass of Jupiter that orbit very close to their host star. Many of these have orbits of less than ten days. Compare that to Mercury, which has an orbital period of eighty-eight days. As a result of the close orbit, these planets can be very hot.

With more data, we now have a different picture of the size distribution of planets. A histogram from 2016 shows the number of planets by size, with the largest on the right (see Figure 3). Again,

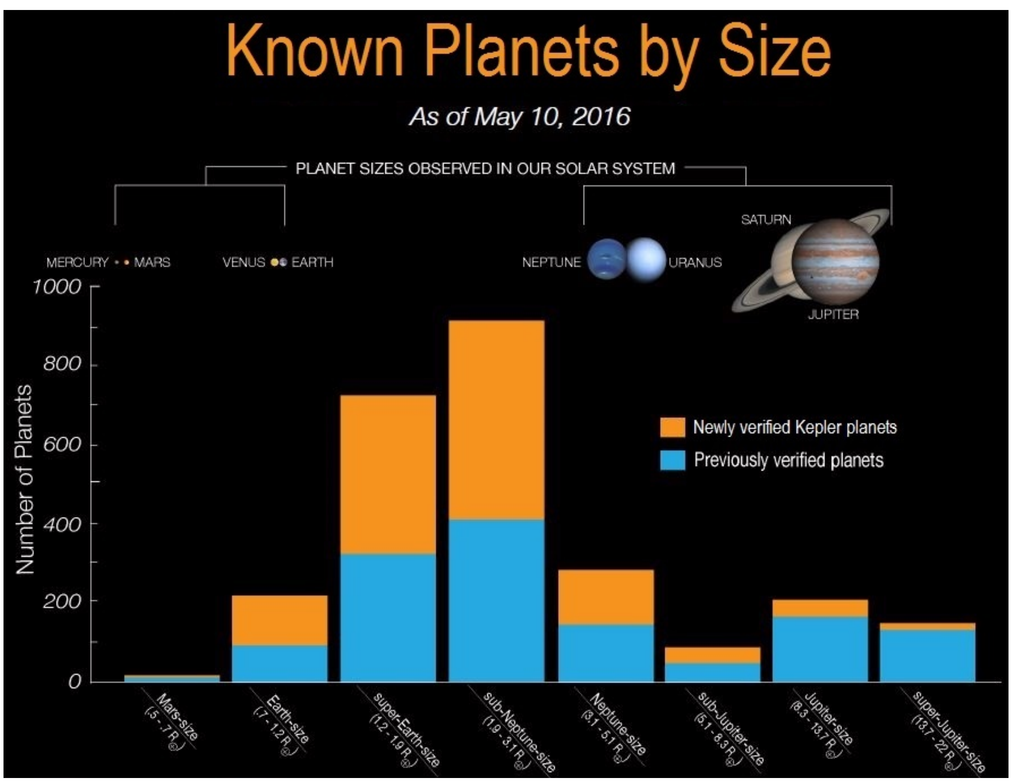

Figure 3. Histogram of known exoplanets by size from May 10, 2016. Image credit: NASA Ames/W. Stenzel.[3]

we have discovered something new. We now know there are super-Earths, which are a bit bigger than Earth, and sub-Neptunes, planets a bit smaller than Neptune. These do not exist in our own solar system although they are some of the most common exoplanets discovered so far. There's ongoing debate as to what exactly they are like. Are super-Earths rocky like Earth is, or are they a bit more gaseous? Are they like gas dwarfs? What about mini-Neptunes? Are these icy, like Neptune, or are they something we would call gas dwarfs? We're not sure yet. With more data and more researchers, we are going to start to be able to answer these questions. A plot of data from February 2021 confirms the pattern from 2016 (see Figure 4). We find that super-Earths and sub-Neptunes are still the most common, but we're also starting to get more objects like Mars. Mars is a bit smaller than Earth, so the size makes it difficult to find similar planets. There is also a large number of Jupiter-sized objects. The question remains: is the frequency of Jupiter-sized planets because there are a lot of them out there or because they are easy to find?

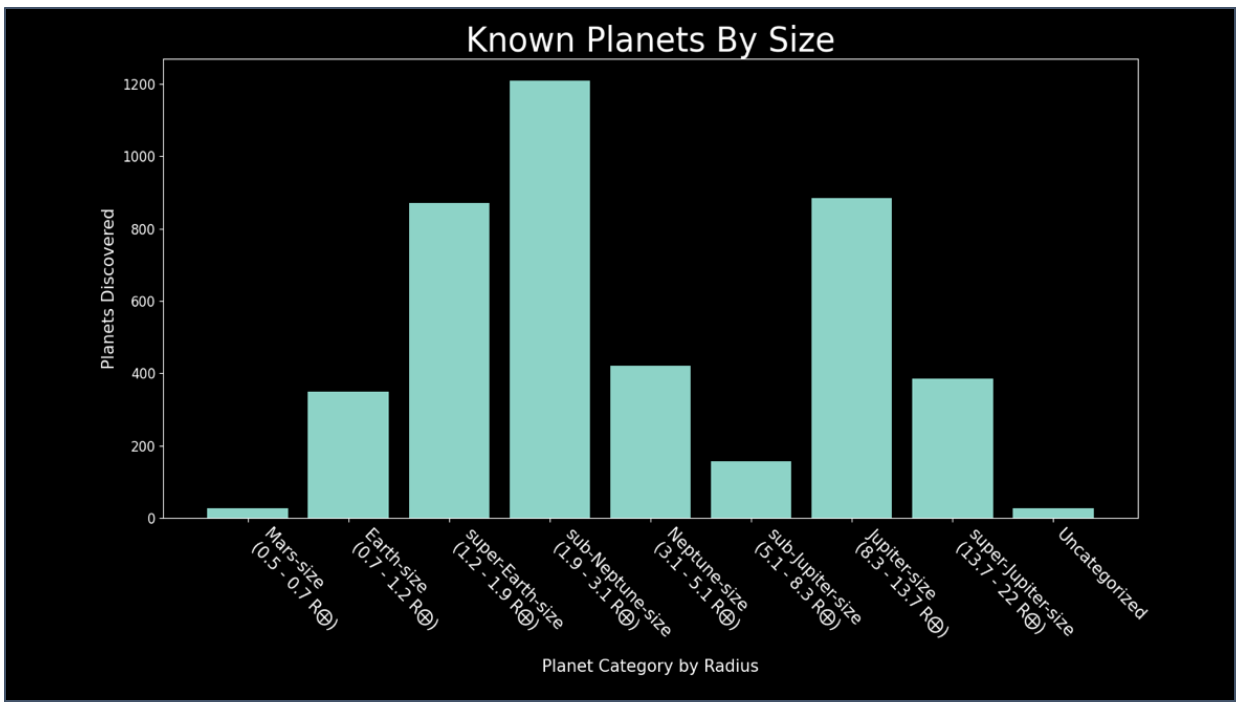

Figure 4. Histogram of exoplanets by size as of March 2021. Image credit: Kurt Beecher; used by permission.[4]

Now that we have taken a brief look at why we should study exoplanet science, let's talk a bit about how we have been studying exoplanets thus far. We are going to start with a history lesson (see Figure 5 below). Our timeline of modern exoplanet science starts in 1952 with a paper by Otto Struve.[5] He researched binary stars, which are stars that are orbiting each other. In such research, one detects the presence of another star that cannot be viewed with an optical telescope by using the radial velocity, or RV, method, which takes advantage of the fact that the stars will be moving back and forth along the line of sight. This back-and-forth motion, caused by the gravitational force of the stars, is detectable. Struve proposed using this method to detect planets. It works for stars, so why not also for planets? The technology to do this hadn't quite caught up yet, though, and it was not until 1988 that the first detection using the radial velocity method was achieved. However, this detection was not confirmed until 2002.[6] In 1992, using a method called pulsar timing, the first confirmed exoplanets were found orbiting a pulsar. A pulsar is the remains of a star that has gone supernova, meaning these planets actually survived a supernova explosion. We were able to detect them by looking for the changes they induced in the timing of this pulsar. In 1995, there was a major discovery: we actually found an exoplanet orbiting a main sequence star, which is a star a lot more like our sun. It has not exploded, so this is a much friendlier place to be.

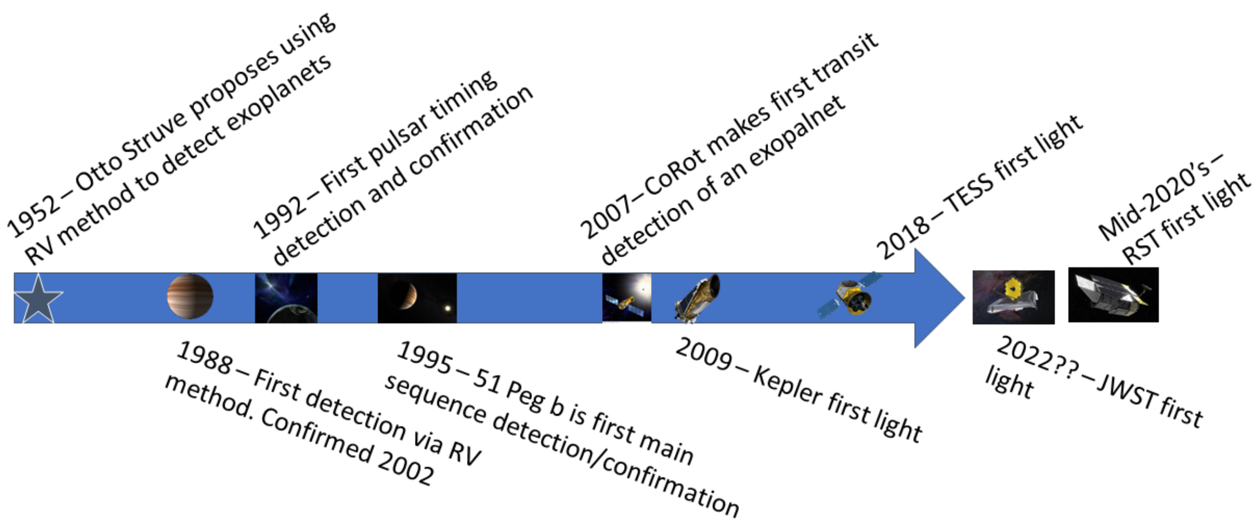

Figure 5. Timeline of modern exoplanet science. Graphic credit: Jennifer L. Carter. Image credits: NASA.

Now we're going to jump ahead to the transit method, which I use in my own research. Some of the first detections were made using the Convection, Rotation, and Planetary Transits (CoRot) space telescope in 2007. In a transit, a planet passes in front of the host star, causing a loss of light as that planet blocks some of the light of the star. Those occur in our own solar system as well: both Mercury and Venus can transit the sun. It is a lot like a solar eclipse, when the moon passes in front of the sun and blocks its light. For the most part, I use data from the Kepler Space Telescope, which first started sending data in 2009. There is a much more recent transit project, the Transiting Exoplanet Survey Satellite, or TESS. It started sending data back in 2018 and is still doing so. Looking to the future, we have the James Webb Space Telescope, or JWST, which has seen a number of delays, but it should start sending data back sometime in 2022. This telescope is going to do a lot more than just exoplanet science. Looking even further ahead, into the mid-2020s, we're looking at the Roman Space Telescope (RST) launching and continuing the search for exoplanets. We see that the field of exoplanet science is very new and growing. It's very exciting.

If exoplanets are so common, why did it take so long to find them? Remember that nearly every star has at least one exoplanet. Stars are very, very big and very, very bright; much bigger and brighter than planets. This is illustrated in Figure 6; on the left is a picture of HR 8799 taken in infrared. In the center of that, the little cyan dot represents the size of Pluto's orbit. Our entire solar system would fit comfortably within that dot. No planets are visible in this image, but we can use a coronagraph to block out some of the light of that host star. Doing so allows researchers to directly image exoplanets. Each one of the dots b, c, d, and e is an exoplanet orbiting HR 8799.

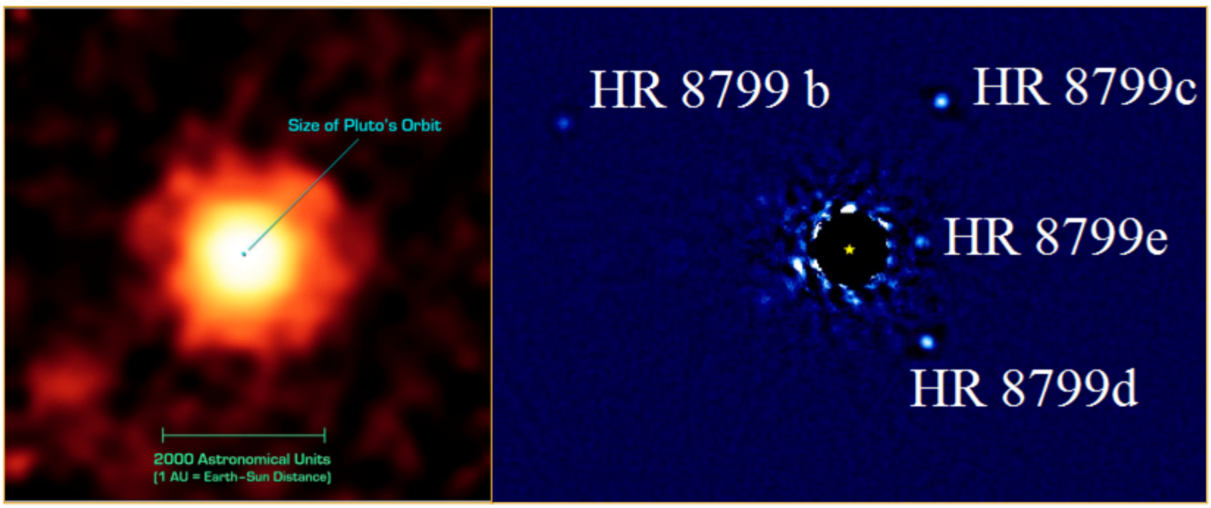

Figure 6. Images of the HR 8799 system. Left: Spitzer image of the debris disk. Credit: NASA/JPL-Caltech/K. Su (University of Arizona). Right: Image from the W. M. Keck Observatory in Hawaii taken using MOSFIRE, the multi-object spectrometer for infra-red exploration. Modified with added planet names. Image credit: Jason Wang/Christian Marois.[7]

So far, we have discussed four methods to detect exoplanets, but there are others. Shown in Figure 7 below are the number of detections per year, using a variety of different methods. You can see some of the first detections on the plot if you look very, very carefully. A lot more exoplanets are detected once radio velocity becomes popular; that's the method that looks at the back-and-forth movement of a star. In 2014-2016, we have some big jumps. These are planets discovered by studying transits, mostly using the Kepler Space Telescope.

As of March 5, 2021, according to the Exoplanet Catalog, there were nearly 4,700 confirmed exoplanets and 771 multi-planet systems.[8] Let's focus on data from just Kepler and TESS. From these two missions alone, Kepler and K2 found 2,820 confirmed exoplanets, with another 3,255 candidates; TESS has 120 confirmed exoplanets and 2,542 more candidates.[9] You might wonder why there are so

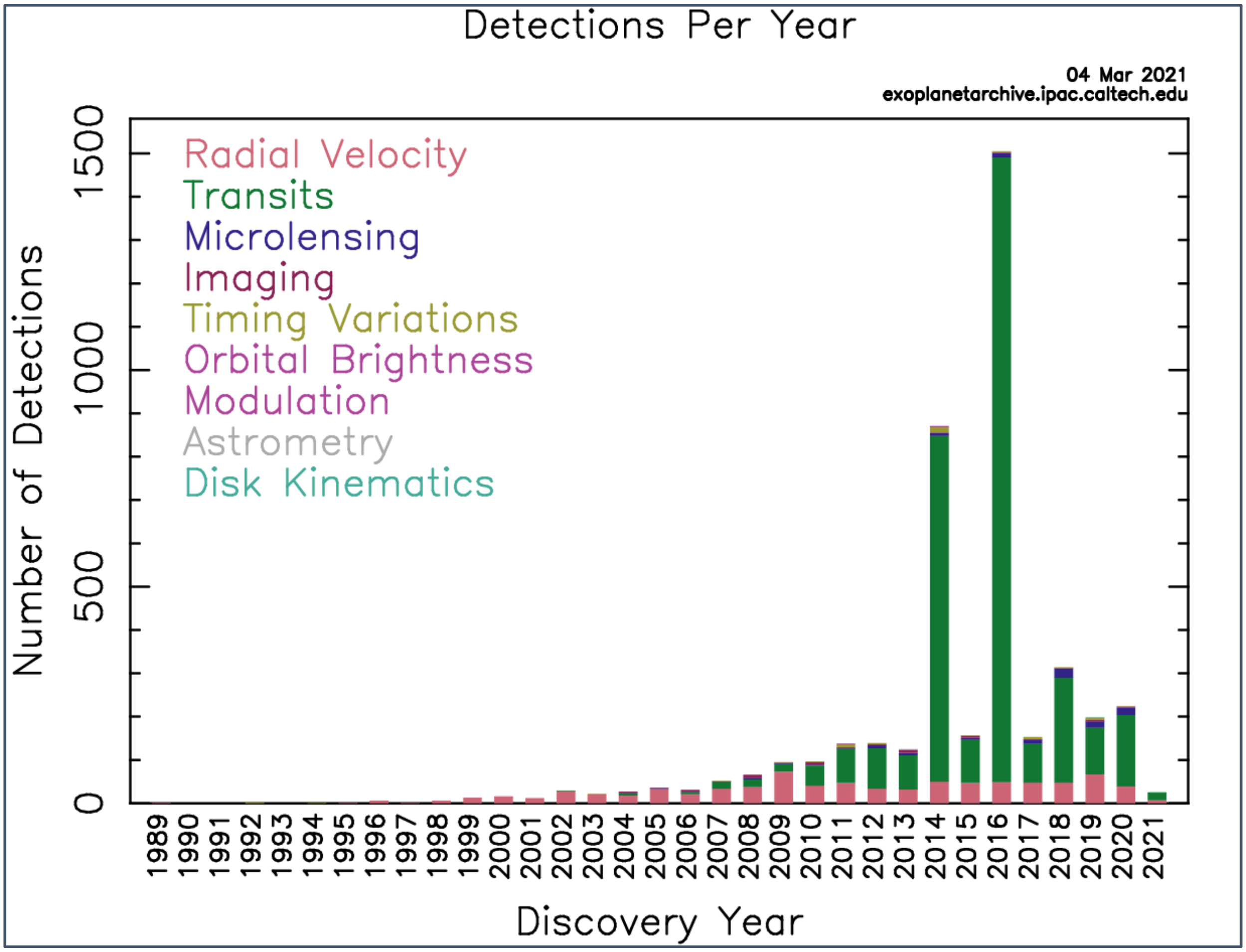

Figure 7. Number of exoplanet detections each year, color coded by detection method as of March 4, 2021. Image credit: NASA/Caltech.[10]

many fewer confirmations for TESS than Kepler. TESS was designed a bit differently and requires more follow-up than the discoveries made using the Kepler Space Telescope.

My own research focuses on transits and what is called a light curve. A light curve measures the amount of light along the vertical axis versus time along the horizontal. When a planet orbits a host star, as it passes in front of the host star, there's a loss of light, and the apparent brightness of the system decreases. Figure 8 below shows exoplanet transit data with an orbital period of 2.2 days for HAT-p-7b, which is a hot Jupiter. We know its period is 2.2 days because we have a transit at day zero and then about 2.2 days later, we have another transit. That is part of how we confirm exoplanets using the transit method: we want to see transits at regular intervals that don't change, that are the same depth, that are the same height, that are in the same length of time.

There is more of interest here than just that transit within a light curve. In particular, a secondary eclipse occurs when an exoplanet passes in back of its host star and we have stopped seeing the light that it emits. Figure 9 below shows another light curve. Flux, or amount of light, is on the vertical, and we've

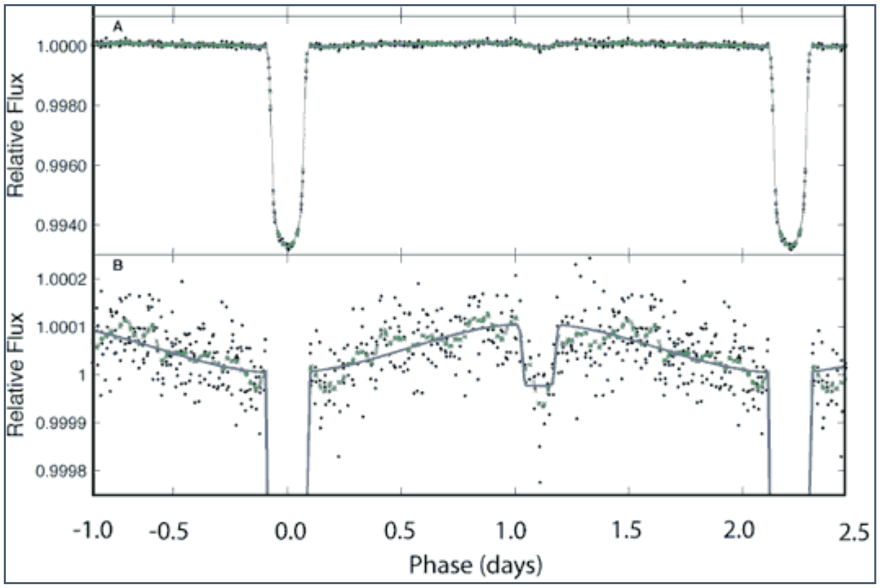

Figure 8. Light curve data for the hot Jupiter HAT-P-7b. This planet's mass is about 1.8 times that of Jupiter, and its orbital period is only 2.2 days. Image credit: Borucki et al.[11]

wrapped time around itself here on the horizontal. The transit depth is the ratio of the planet's cross-sectional area, πR_p^2, to that of the host star, πR_s^2, where R_p indicates the radius of the exoplanet and R_s indicates the radius of the star. In other words, the transit depth, symbolized as ΔF, is given in this equation:

$$\Delta F = \frac{R_p^2}{R_s^2}$$

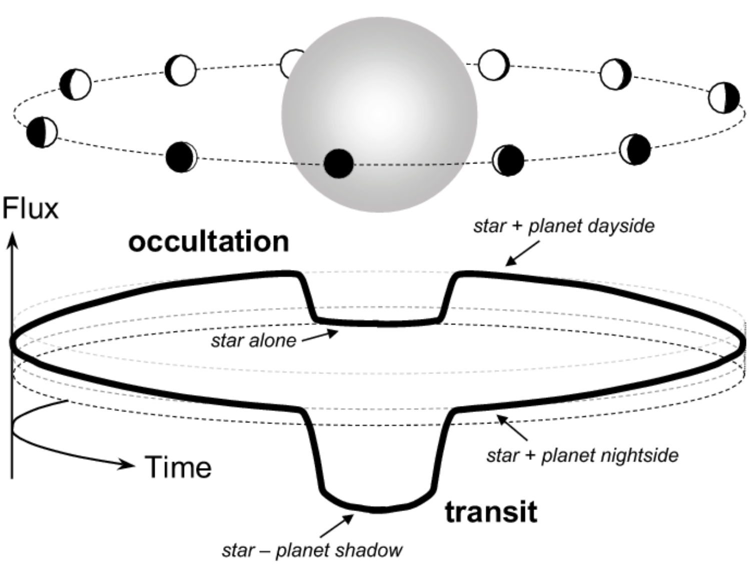

Figure 9. Depiction of a transit light curve on the bottom with a model of planet position about the host star on top. Credit: Joshua Winn.[12]

Let's look at that secondary transit. What happens when the planet passes in back of its host star, and what governs how deep the loss of light is? That loss of light depends on two main things: the light the planet reflects and the thermal radiation of the exoplanet, as represented in this equation:

$$\Delta F_s = A_g \left(\frac{R_p}{r}\right)^2 + \frac{F_{day}}{F_s}\left(\frac{R_p}{R_s}\right)^2$$

The first term in the equation is related to the light the planet reflects. Just as we see the moon because it reflects the light of the sun toward us, we can see the loss of light from the lack of reflected light from the exoplanet, which depends on a few things. First, A_g basically tells us how shiny the planet is, and the number is larger for more reflective planets. R_p is, again, the radius of the planet. Larger planets will reflect more light. The second term in the equation is the contribution from the thermal radiation of the exoplanet. These planets are sometimes so hot that, like a hot iron or glowing coals, we can see them. The amount of light due to thermal radiation depends on a few things. Again we see that the size of the planet is important: larger planets will appear brighter. The term F_{day} divided by F_s describes the amount of thermal light that is coming from the dayside of the exoplanet and is dependent upon temperature. All the information regarding temperature is hidden in the variables F_{day} and F_s. The secondary eclipse only depends on the dayside portion because that is the side that would be facing us if the planet were not blocked by its host star. We never see the whole dayside of the exoplanet, but we see most of it to either side of the secondary transit.

Let's now consider the details of how we model the light of exoplanets, called photometric variations. *Photo* means light, and *metric* means measurement. Figure 10 plots the photometric

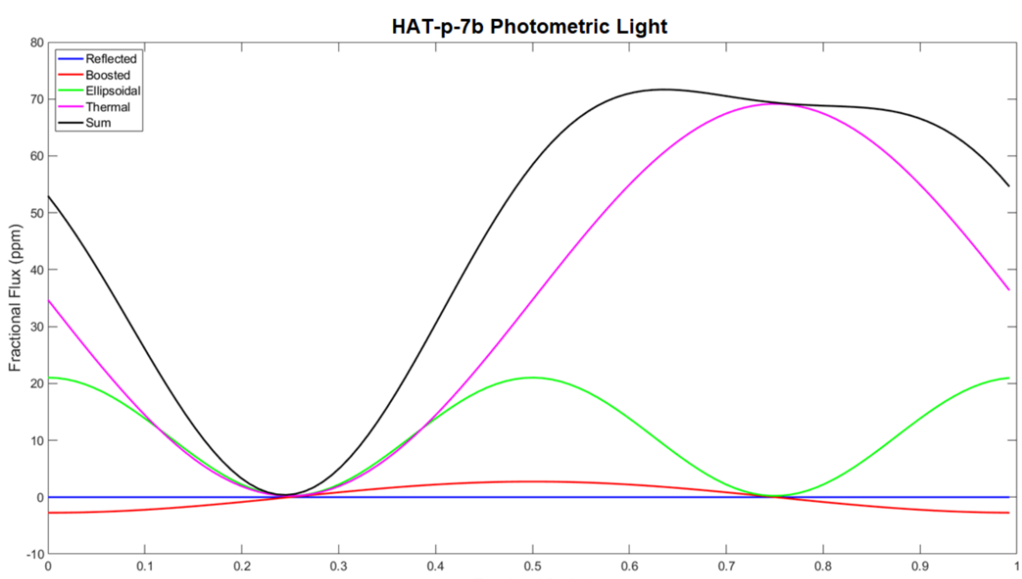

Figure 10. Model of photometric emissions from HAT-p-7b. Shown in blue is reflected light, in red is light from boosted variations, in green is light from ellipsoidal variations, and in magenta is thermal light. The black line is the sum of the other variations. Image credit: Jennifer L. Carter.

variations for the hot Jupiter HAT-p-7b and contains all of the information in the light curve that isn't the transits. The light curve is comprised of two main components: light from the exoplanet, or planetary emissions, and changes to the star's emissions, called stellar variations. Likewise, light from the exoplanet is comprised of two parts: thermal light and reflected light. The pink line in Figure 10 models just the thermal light from HAT-p-7b. The blue line captures the light the exoplanet reflects, and it's not very much.

To talk about reflected light, another topic I research, you first must consider the incoming light from the host star because that is what is reflected by the exoplanet. Typically, researchers make a lot of assumptions about this incoming light. First and foremost, we assume that incoming light is formed like a flat sheet, but this is not the case for extremely close-in exoplanets. Both for the flat-sheet assumption and for extremely close-in exoplanets, the amount of light received at the poles is very different from the amount received closer to the sub-stellar point. This is why the poles are colder: they get less direct light. Compared to assuming that the received light is a flat sheet, more careful modeling, which assumes that the received light is not a flat sheet, reduces the amount of light received on the dayside and increases it on the nightside. Questions then arise about how this would affect climate models of exoplanets. Unfortunately, using our current technology, the detection of reflected light from an Earth-like planet orbiting a sun-like star at an Earth-like distance isn't possible because the reflected light is too dim. We'd be able to detect the planet itself from its transit, but the reflected light portion of the photometric variations would be too small to rise above the noise.

Continuing our discussion of photometric variations, two curves constituting the stellar variations are shown in Figure 10. These occur because the presence of an exoplanet affects the light the host star emits. First are ellipsoidal variations, so named because, instead of having a spherical star, the gravitational influence of the exoplanet stretches the star out into an ellipsoid. The other piece is called boosted light or beaming, which occurs because the star is moving back and forth along our line of sight. As it moves toward us, some of the light is beamed towards us. As it moves away, it is beamed away from us. Beaming is a relativistic effect. The last curve in Figure 10 is present because we don't observe any of the foregoing variations alone. We always see their summation, as shown with the black curve. You can see that the thermal light and the ellipsoidal variations contribute the most to the total for HAT-p-7b.

There are a variety of methods used to model those thermal variations, some of which I will describe here. The first one involves treating the exoplanet as if it had one equilibrium temperature, meaning that the planet is at perfect equilibrium. For the planet to be in equilibrium, all the energy that comes into it is emitted outward as if it the planet were one temperature. A heat redistribution coefficient that governs how quickly heat is redistributed around the planet from the side that's facing the host star is sometimes included in such a model. Alternatively, you can model the planet as if it had two main sides: a dayside and a nightside, creating two main temperature zones, the dayside being hotter than the nightside. Instead, we could model the planet as if it looked like a beachball or orange slices, where each slice can be a different temperature. Some of our observations have shown that, instead of the hottest point on the exoplanet being directly aligned with the host star, it's offset a little bit, and these slices can help exoplanet researchers account for that offset. The slices can also account for large land masses and oceans.

For now, let's focus on the dayside-nightside model because it is most similar to the model I am developing. In this case, we would consider the thermal radiation as modeled in Figure 11, which shows a hot Jupiter, Kepler-91 b. The green curve shows the radiation due to the dayside of the planet. It's at a

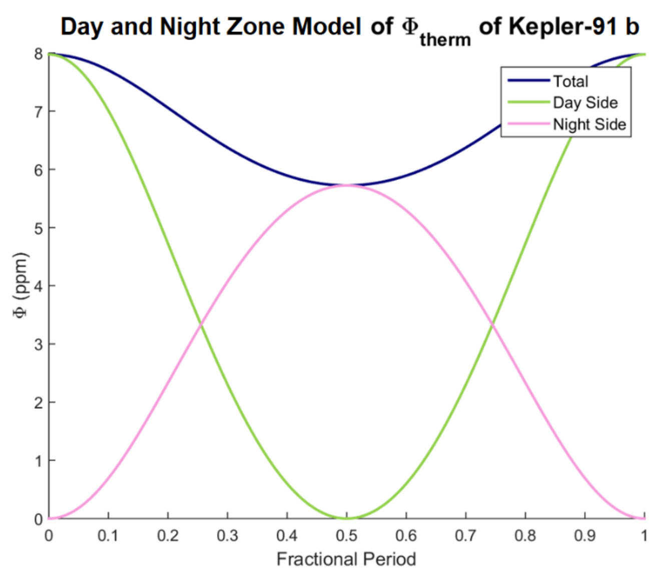

Figure 11. Thermal radiation fractional flux, Φ, vs. the fractional period curve based on parameters for Kepler-91 b. The green line represents the radiation from the dayside of the planet, the pink line represents radiation from the nightside, and the blue line is the total thermal radiation of the planet. The total thermal radiation is the sum of the day- and nightsides. Image credit: Jennifer L. Carter.

maximum on the far left of the figure when the planet is actually behind its host star during secondary eclipse. We wouldn't really see the full dayside of the planet, but we'd see most of it just before it goes in back of its host star at ingress and then just as it comes out at egress, which is the point on the left side of the occultation modeled in Figure 9. The curve shown in pink in Figure 11 applies to the thermal radiation of the nightside of the exoplanet. Its maximum occurs during the primary transit. Notice that the maximum for the dayside is higher than for the nightside because it is hotter. Note also that we don't see those two in isolation; we observe their sum, shown by the blue curve, which is never quite zero because the nightside does emit some thermal radiation.

It seems, however, a bit unreasonable to treat a planet like it has just two zones. Imagine if that happened on something a bit hotter than Earth, a hot Jupiter. You might have one side of the planet at 2,500 kelvin and the other side at 2000 kelvin, and the transition would occur at the terminator. However, that doesn't match our observations. Usually, we see gradual changes in temperature. We can model this temperature gradient using a series of concentric rings as shown in Figure 12, where the hottest ring, or cap, is pointed directly toward the host star. Then we're going to space the other zones evenly and assume that the temperature of each one decreases monotonically as you move away from the side facing the host star. This is just a starting point that would apply best to close-in exoplanets because they are tidally locked, which means that only one side of the planet is ever facing the host star. Earth is very different because, of course, it rotates. In ongoing work, I want to allow the spacing of the zones to be uneven and to allow the temperature of each zone to vary independently from the others because it may not be the case that the temperature of the zones decreases monotonically.

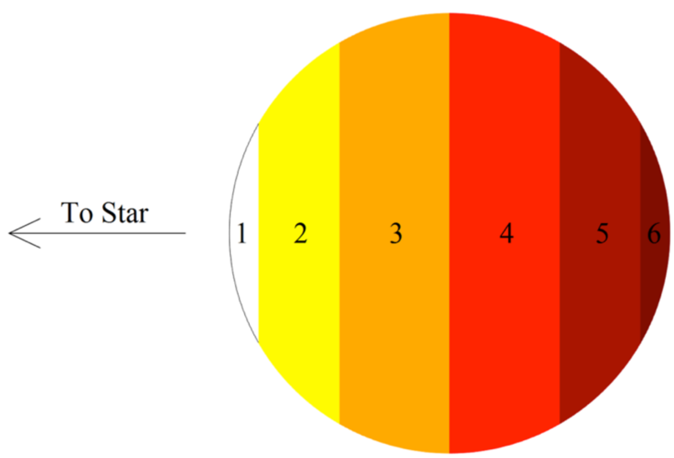

Figure 12. Image depicting the orientation of thermal radiation zones using N-concentric rings arranged axially about the line connecting the center of the planet to that of the host star. In this model, the hottest zone contains the substellar point (N = 1), and the temperature decreases monotonically. Image credit: Jennifer L. Carter.

Now let's consider this: what would the current, simpler, model for temperature zones look like as a 3-D object? It would look like a spherical exoplanet model with six zones, with the hottest zone opposite our coolest, as in Figure 12. Turning the sphere represents the orbit of the planet. The secondary eclipse is when the dayside (zones one through three) is facing you and there is the greatest amount of light. As the planet continues to orbit, we see more and more areas that are cooler and would emit less thermal light until we get to a minimum, when it's just the nightside (zones four through six) facing us. Then the light would start to increase until we reach that maximum again, and the cycle would repeat.

What are the results of modeling an exoplanet's temperature distribution in such a manner? In terms of the thermal variations, there are a lot of different questions we can ask. The first is this: what happens when the number of zones changes? Figure 13 shows four plots for the amount of light, Φ, along the vertical versus time along the horizontal. On the top left, there are four zones; on the top right, six zones; on the lower left, eight zones; and, on the lower right, ten zones. Included in each subplot is the amount of light from each zone. The total thermal light is shown in blue in each subplot. The blue curves in these four graphs don't look very different from one another.

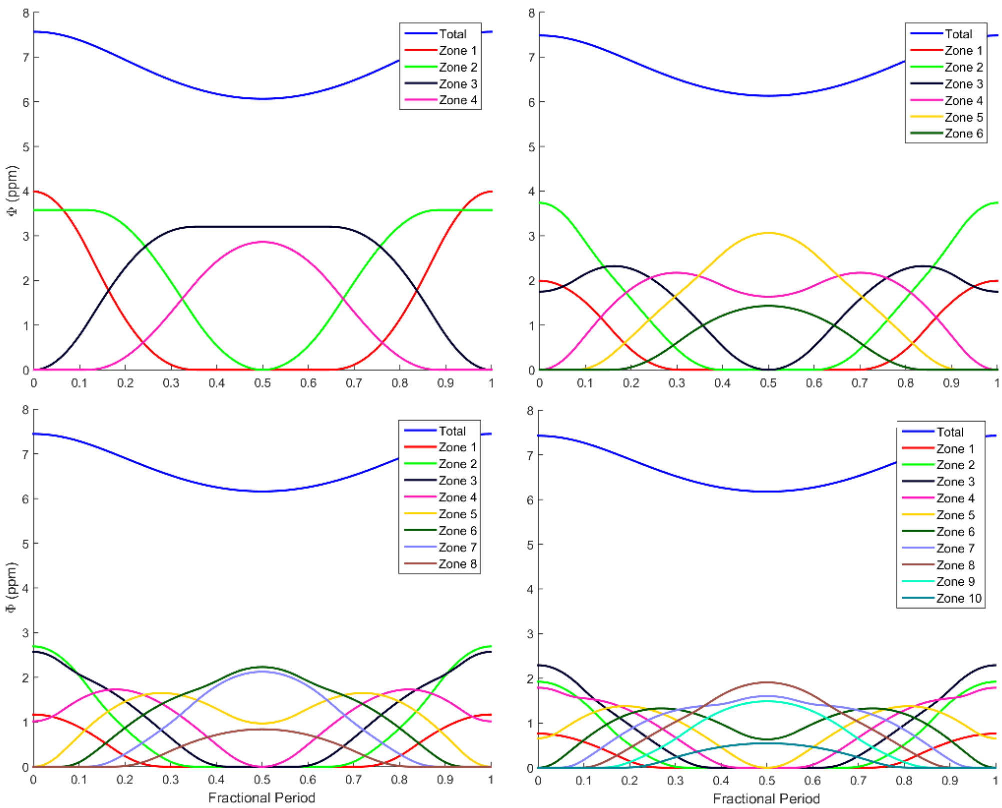

Figure 13. Plots of the thermal radiation from each zone and the total thermal radiation for different values of the number of zones, N. Moving left to right, starting at the top left, the number of zones increases from four to six to eight to ten. Image credit: Jennifer L. Carter.

To get a better sense of how the number of zones changes the thermal variations, we can compare each against the day-night model, which has just two zones. Figure 14 below shows, in yellow, the day-night model; blue indicates the N-zone model with four zones (where N is equal to four). On the top left, during that secondary eclipse when the dayside of the exoplanet is facing you, we find that the amount of light from the day-night model is larger. Now why is that? It is because in the day-night model, the whole dayside of the planet is at the same, dayside, temperature. In my model, however, a smaller area is at this temperature and more area is at lower temperatures. We see the opposite behavior during the primary transit, which would occur at the low point in the curve, shown in Figure 14 at the 0.5 fractional period. There's more light from the N-zone model during this part of the exoplanet's orbit because areas of the planet closer to the host star are hotter and would emit more light in total than in the day-night model. You can see that it is not very convenient to look at many of these at once. It's much easier to just do a subtraction between the day-night model and the N-zone model, $\Delta\Phi$, as shown in the curve at the bottom of Figure 14.

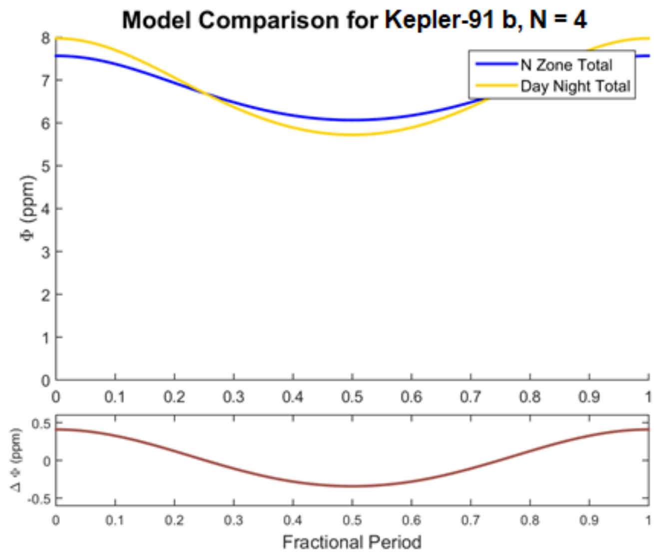

Figure 14. Comparison of the total thermal radiation versus fractional period for four zones (blue solid line) and the day/night model (yellow line). The bottom curve shows the difference between the two, $\Delta\Phi$. Image credit: Jennifer L. Carter.

Let's now consider the difference for several different values of N. In Figure 15, for N equals two, there is no difference, which serves as our sanity check. We need to make sure that our model

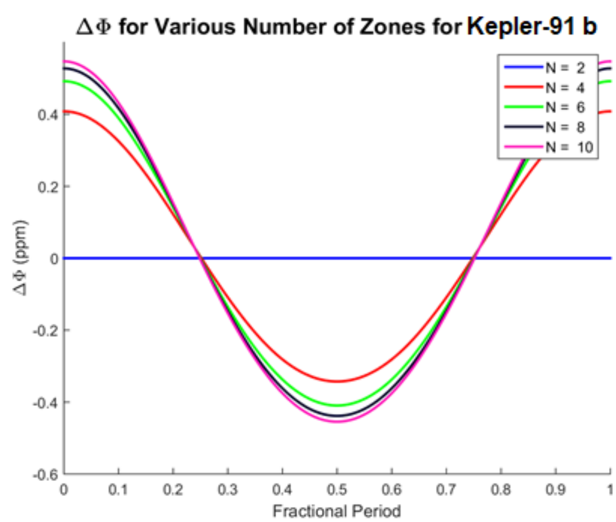

Figure 15. The difference between the day-night model and the N-zone model for different values of N, the number of zones. The blue line is for two zones, for which there is no difference, as expected. The red line is for four zones, green for six zones, black for eight zones, and pink for ten zones. Image credit: Jennifer L. Carter.

perfectly matches the case where N equals two to show consistency. As we increase the number of zones from two to four, six, eight, and ten, we see that the difference increases, but there are also diminishing returns. The difference between the eight- and ten-zone models is a lot smaller than the difference between the two- and the four-zone models. This implies something important: that there is probably an ideal number of zones required to describe the thermal emissions of an exoplanet. That's part of what I'm researching. How many zones do we actually need? Does it depend on the planet? If so, how much does it depend on the planet? That's ongoing research. The plot in Figure above looks at one set of temperatures for one planet throughout its orbit.

Let us now turn to considering the effect of temperature range on this model. Figure 16 shows two snapshots in time for different numbers of zones and temperature ranges. On the top row are the secondary eclipse snapshots when the dayside of the exoplanet would be visible. On the bottom row are

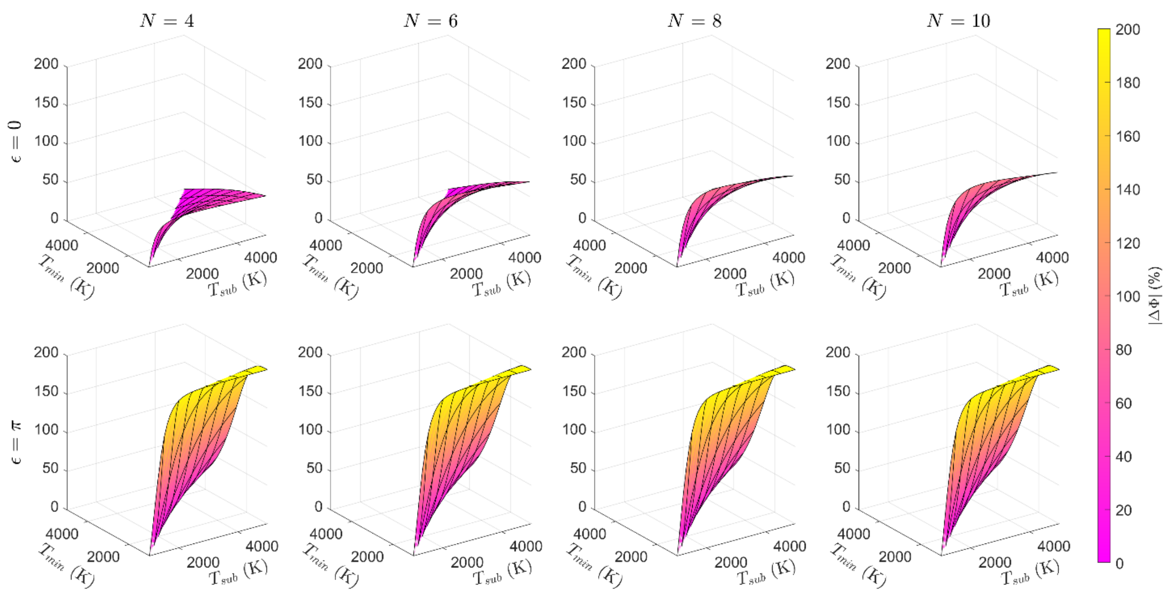

Figure 16. Surface plots of $|\Delta\Phi|$, the absolute value of the percent difference between the day-night model and the N-zone model as compared to their average. The top row shows the difference for $\epsilon = 0$, or the full phase of the exoplanet, and the bottom row shows the difference for $\epsilon = \pi$, or the new phase of the exoplanet. The horizontal axes are T_{sub}, the substellar point temperature, and T_{min}, the minimum temperature. Image credit: Jennifer L. Carter.

the primary transit snapshots when the nightside would be visible. On the axis labeled T_{sub}, we have the sub-stellar-point temperatures. The sub-stellar point is the point on the planet closest to the host star and is located in zone one in Figure 12, the hottest bit. On the other horizontal axis, we have the minimum temperature on the opposite side of the planet, T_{min}. On the vertical, I have plotted the magnitude of the percent difference between the N-zone model and the day-night model. We see that the percent difference between the N equals four model and the day-night model is greatest for the largest temperature gradient, when T_{sub}, the sub-stellar-point temperature, is 5,000 kelvin and the minimum temperature is 1000 kelvin.

This is also true during the primary transit; in other words, the magnitude of the percent difference is always greatest for that largest temperature difference.

You might notice something about the number at the top of the vertical axis for the percent difference, implying a difference of 200 percent. It is large because we are dividing by a small number; the amount of light from the nightside is not very great. This means that, although this is a large percentage difference, the difference still might not be detectable because the amount of light is just so small. As we go from N equals four to six to eight to ten, the percentage difference similarly becomes larger across the board but with not as big an increase as the number of zones increases.

I want to conclude with something very new. I'm going to attempt to use a method to fit real exoplanet data, data from Kepler-41 b, which is a low-mass, hot Jupiter. The goal is to use the planet's light curve, which is the amount of light versus time from the exoplanet system, to determine the model that best fits, or describes, that data. The model that does so is the "best fit" model and represents my best guess as to the correct way to describe the exoplanet. The cyan dots in Figure 17 are cleaned and folded-over data points for this exoplanet; this is called phase folding. In blue, we have binned the data. I've taken little bins and averaged the values within them to reduce the number of data points because that makes my fitting algorithm work better. I mentioned earlier that one of our big questions is this: how many zones do we need? According to these preliminary results, Kepler-41 b is best accounted for with six zones, where the red line in Figure 17 represents the best fit for this data.

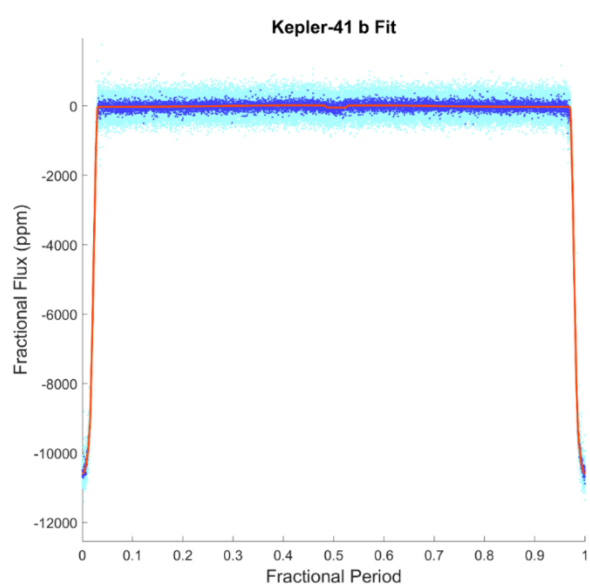

Figure 17. Fractional flux vs. fractional period light curve for Kepler-41 b. The cyan dots are phase-folded data, the blue dots are binned and averaged data, and the red line is the best fit model to the data. The model uses six temperature zones. Image credit: Jennifer L. Carter.

In Figure 18 are the resulting photometric variations using the parameters, or the values, for things like the radius of the planet, temperature, and mass that the best fit model produced. We see there that most of the variations are coming from thermal light. The next biggest contribution is from the ellipsoidal variations. Part of the reason I am calling these results for Kepler-41 b preliminary is that the

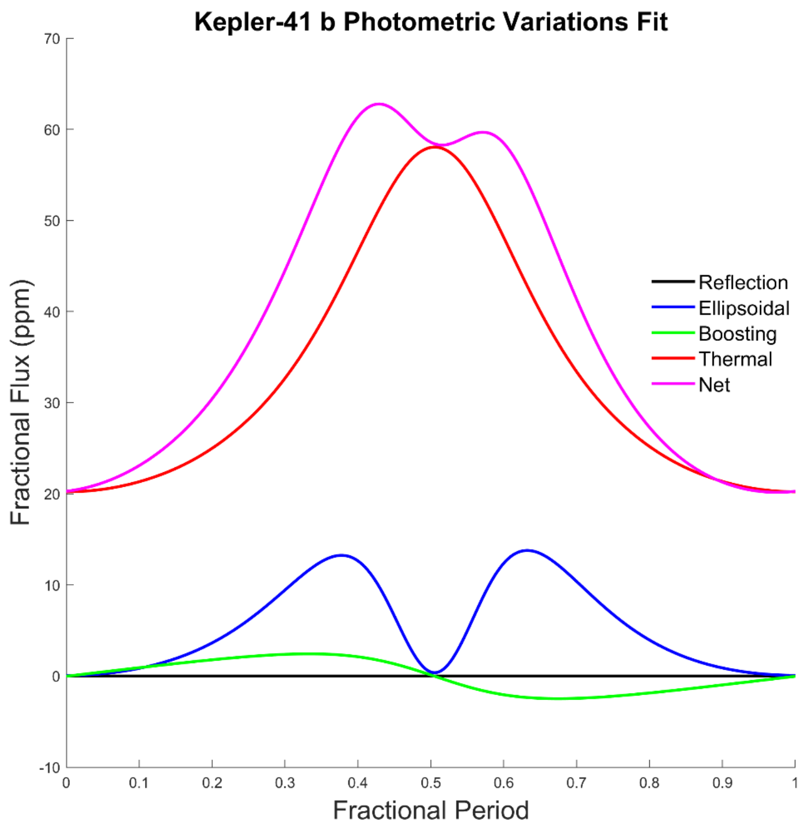

Figure 18. Fractional Flux vs. Fractional Period photometric variation curves for the best fitting model to Kepler-41 b's light curve. The black line represents reflected light, which has been set to zero for this test. The blue line is for ellipsoidal variations, the green line for boosted light, and the red line for the total thermal radiation. The magenta line is the sum of the other four lines. Here, a six-zone thermal model was used. Image credit: Jennifer L. Carter.

estimated mass of the exoplanet using this fit is about three times larger than the accepted value. There are at least two reasons this could be the case. First, it could actually be true; it could be that Kepler-41 b is more massive than previously thought. Second, it could be that I need to do a more precise fit. This fit was done using only about fifty samples. Ideally, I want to increase the number to 200 or more, which takes a very long time.

What have we learned so far about the difference between N-zones and two zones? The difference is greatest for hot, large planets with large temperature gradients, but, even with everything in your favor, it still might not be detectable using current-generation telescopes. The maximum difference observed for Kepler-91 b was only 0.5 parts per million, which is a measure of the amount of light. The

Kepler Space Telescope data can only detect differences down to 29 parts per million, which is much, much larger than 0.5 parts per million. TESS can detect only down to about 50 parts per million. Part of the ongoing research is to determine whether JWST will be able to detect the difference between a dayside-nightside model and this N-zone model. At the very least, it's going to be useful in climate modeling to help answer these all-important questions: what is the temperature of a particular planet, and can it have liquid water?

Finally, where do we go from here? First, I need to find more planets to test. For any planet tested, we need to know about the previous research done on it so we can compare our results to currently accepted values. Ideally, I want to test at least four planets because I am not satisfied with the fit to Kepler-41 b alone. The current results for Kepler-41 b are preliminary and their main purpose was to test whether the modeling code functions. In addition, scientists have observed hotspot offsets, in which the hottest spot on the exoplanet is not in line with the host star. I want to re-design my model to accommodate such an offset. Third, I want to finish implementation of the beachball model within my modeling code and test it against my model and the day-night model. It is possible that the model I am designing is not that effective; the beachball model or some other is better. To test this idea, the code must first be implemented. Finally, I want to return to a related, but different subject and revisit reflected light.[13] All these approaches provide valuable information about the universe and how it functions and help us in our search for life, particularly beyond our own solar system.

NOTES

1. All NASA-produced illustrations are generally not under copyright: **Error! Hyperlink reference not valid.**use-policy.

2. PHL @ UPR Arecibo, "Habitable Exoplanets Catalog," Planetary Habitability Laboratory, October 5, 2020, https://phl.upr.edu/projects/habitable-exoplanets-catalog. Used by permission.

3. W. Stenzel, *NASA Ames*, May 10, 2016, https://www.nasa.gov/sites/default/files/thumbnails/image/fig8-new-20use20this20one.jpg.

4. Kurt Beecher, personal communication, February 2021. The histogram was produced using data from IPAC at Caltech, "NASA Exoplanet Archive," 2021, https://exoplanetarchive.ipac.caltech.edu (accessed February 2021). Used by permission.

5. Otto Struve, "Proposal for a Project of High-precision Stellar Radial Velocity Work," *The Observatory*, (1952): 199-200.

6. How the existence of a planet is confirmed depends a little on the nature of the detection method. For the transit method, it can come in a variety of ways. Based on Kepler's precision, three transits in a row of the same period, same depth, and same length of transit (amount of time to go in front of that host star) were considered a confirmation and determined the mission length. The

mission was designed to look for Earth-like planets around sun-like stars. Because it would take about a year for the planet to go around the star once, the mission needed to be at least four years long to catch three transits. Researchers also confirm transiting-planet candidates using radial velocity follow-up because it is very precise. In fact, the use of radial velocity follow-up informed the design of TESS. TESS's job is to flag potential planets using the transit method, not necessarily to characterize them. Radial velocity data, which relies on ground-based telescopes, is then acquired to try to confirm flagged candidates.

7. Marc Kaufman, "A Four Planet System in Orbit, Directly Imaged and Remarkable," *Many Worlds,* January 24, 2017, https://manyworlds.space/2017/01/24/a-four-planet-system-in-orbit-directly-imaged-and-remarkable/.

8. NASA, "Exoplanet Catalog," *Exoplanet Exploration*, 2021, https://exoplanets.nasa.gov/discovery/exoplanet-catalog/ (accessed March 5, 2021).

9. This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program. IPAC at Caltech, "NASA Exoplanet Archive," 2021, https://exoplanetarchive.ipac.caltech.edu (accessed March 5, 2021).

10. Ibid. (accessed March 4, 2021).

11. William J. Borucki, D. Koch, J. Jenkins D. Sasselov, R. Gilliland, N. Batalha, D. W. Latham, et al. "Kepler's Optical Phase Curve of the Exoplanet HAT-P-7b," *Science* 325, (August 7, 2009): 709, https://doi.org/10.1126/science.1178312. Used by permission.

12. Joshua N. Winn, "Transits and Occultations," *eprint arXiv,* 2014. Used by permission.

13. This research was funded by a Research Publication Grant in Engineering, Medicine, and Science from AAUW. In addition, I want to thank my first two undergraduate research students who worked with me in summer 2020. Jocelyn McMahon helped work on the beachball model, which I'm also going to compare to my model as ongoing research. Amanda McLaughlin helped with retrieving data from the NASA exoplanet archive, which is publicly available through the website referenced in Notes 4, 9 and 10 above. You can get it, too, and do fun science with it.