Reading a Science Paper II: Detection of Planetary Transits Across a Sun-Like Star

Background:

The detection and characterization of exoplanets (i.e. extra-solar planets, or planets orbiting other stars) is a major area of current astronomical research. Planets have been detected around other stars with six different methods, but two of them stand out as producing the most discoveries to date: *the transit method* and the *radial velocity* (or Doppler) method. Being able to detect exoplanets is very important because they give us insight into how planetary systems form by providing a large statistical sample. The science of planet finding goes far behind mere detection. We don't only want to be able to say "here is a planet!", but we also want to be able to determine the properties of the planet and its orbit, such as the planet's mass, radius, orbital period, orbital eccentricity, orbital inclination, etc. If we have particularly good data, we can even say something about the composition of the planet's atmosphere! The more we know and the more planets we can detect, the better we will be able to constrain our models of planet formation and dynamics and the physics that govern their atmospheres.

Perhaps the most interesting goal of planet finding missions (at least to the public at large) is to be able to find and characterize *habitable planets*. Now, this term might make you think of science fiction. It is important to understand that we are not specifically looking for intelligent aliens or for new homes to colonize. Current technology is not nearly good enough to get human beings to even the closest exoplanet (which exists several light years away from us!). However, it is still interesting to look for planets like our own. Developing the tools to find and confirm Earth-like planets will pave the way for more detailed studies of the environments and possible biology on other planets. It's important to understand that this "astrobiology" angle on exoplanet research is actually just one small part of the scientific motivation. *Planet research done today is done mostly for the purpose of better understanding planets in general.* How do they form? What are their physical characteristics as a population? How are they affected by their host stars? What are their atmosphere's made of, and how do they compare to the planets we know of in our solar system?

After reading this paper, answer the following questions:

1) Summarize the introduction. What are the goal(s) that the author(s) are trying to accomplish with this work? What are the "big" and "small" questions addressed?
2) Be able to explain what all the plots show and what their purposes are. What is "relative flux" in figures 1 and 2? Explain in your own words the purpose of Figure 3.
3) In Section 3.1, the authors explain how they determine the period of the orbit and the center of the transit. Summarize how they do this.

   Hint: to *interpolate* here refers to essentially copying and pasting the first data set into the future based on assuming a certain period. For a given period T, if you see a dip at time t, you would expect it to appear again in time t+T.

   Hint2: to *fold* a curve is to reflect part of it across a certain point. Think of it as folding the paper along some vertical line on the plot.

4) After reading this paper, explain the advantages of having both transit and radial velocity measurements for a planet. What information does this get you? What is(are) the advantage(s) of the transit method over radial velocity?
5) Do you think all planets transit their stars? Explain why or why not. You might want to try a cartoon to explain. Hint: Think in three dimensions.

Glossary:

AU (“Astronomical Unit”): This is a unit of measurement in astronomy, defined as the distance between the Sun and the Earth. So, a planet that is 0.1 AU from its host star is *one tenth* the distance that the Earth is to the Sun.

Albedo: a measurement of how reflective an object or surface is.

Atmospheric Absorption: Molecules in the atmosphere can absorb and scatter photons, causing you to see dips in the spectrum of your object. It can also cause you to loose a lot of light when calculating fluxes.

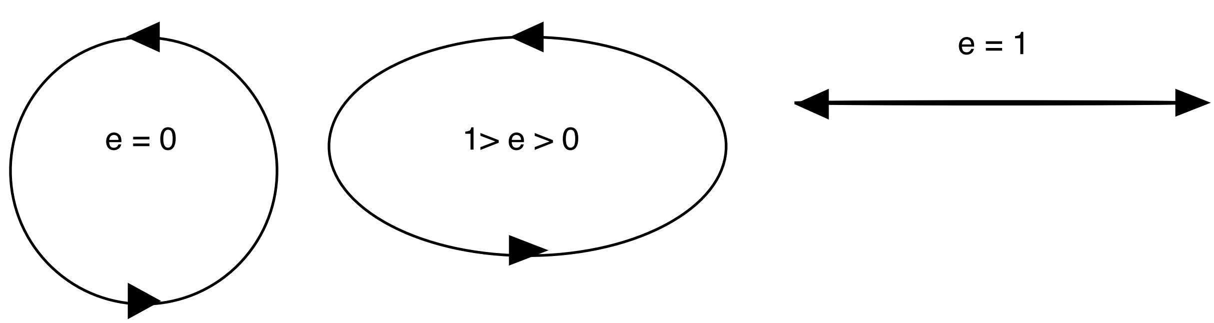
Atmospheric Scintillation: the “twinkling” of stars due to the light passing through the atmosphere.

Bias: this is essentially a measurement of the instrumental noise of a telescope

Colors: In astronomy, the “color” of an object just refers to the difference in *magnitudes* (and therefore a ratio of fluxes -- see below for *flux* and *magnitude* definition) of light emitted from an object and within a “red” filter and a “blue” filter (see below for *filter* definition).

Dwarf Stars: Another term for main sequence stars. The main sequence is where a star spends most of its lifetime. The sun is a main sequence star. These stars usually tend to just sit there and don’t change much until it is time to evolve away and become, e.g., a red giant. The classification of these stars is: OBAFGKM (“oh be a fine girl/guy, kiss me” is a nice way to remember the order). O stars are the brightest, biggest, and hottest stars. M stars are the smallest, dimmest, and coolest. The Sun is a G-type star.

Eccentricity: How “ellipse”-like an orbit is. A circle has an eccentricity of zero. The higher the eccentricity, the more “ovally” the orbit is. An eccentricity of one is either a totally radial orbit or a parabolic orbit (the star will either fly away or crash into the star!).



Escape Velocity: the velocity that an object must attain to escape the gravitational pull of another object (e.g. a planet). This only depends on the mass of the object you are "escaping" from and how close you are initially to that object.

Filter: This refers to a range of wavelengths. To make a measurement through a certain "filter" means to make a measurement using only photons within a certain wavelength range. A "red" filter refers to light of higher wavelengths and "blue" refers to lower wavelengths. *Note: "red" and "blue" filters do not necessarily have to be within the visible spectrum.*

Flat: a measurement taken such that all pixels of a CCD (the thing used to record data from telescopes... also used in your phone!) are given about the same amount of light. This is used to correct for the slight differences in pixel efficiencies within the CCD.

Flux: Amount of light per unit area. Essentially, this is a measurement of how bright something is. More flux = brighter. This value depends on distance. The farther away an object is, the less flux it will have to an observer.

HJD: "Heliocentric Julian Day". A unit of time used to give precise timing information.

Inclination: the orientation of an orbit with respect to our line of sight. An inclination of 90 degrees is "edge-on" and one of 0 degrees is "face-on".

Magnitude: This is an archaic, yet still widely used, unit to measure the brightness of objects. It is defined as $m = -2.5 \log_{10}(f/f_{ref})$, where f is the observed flux of the object and f_{ref} is the flux of some other reference object, for example a well known star like Vega. The ***apparent magnitude*** of an object is related to how bright it *looks*, i.e. how much flux we see here on Earth. How far away the object is matters here. The ***absolute magnitude*** of an object is how bright it *actually* is, or how much flux we would see standing on the surface of the object. The distance to the object doesn't matter for this value. If we know the apparent magnitude and distance from direct measurements, we can derive the absolute magnitude.

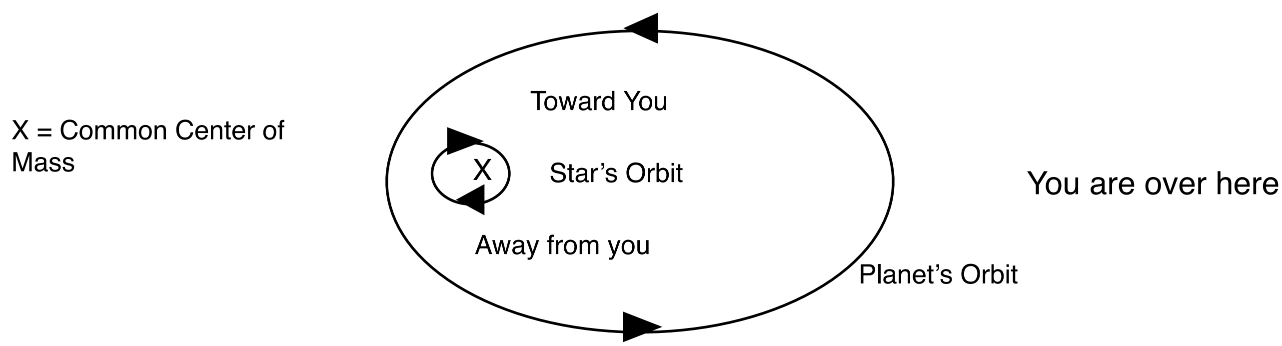
Period: The time it takes a planet to complete one full orbit around its host star.

Photometry: measuring the total amount of light emitted from an object. Sometimes limited to a specific *wavelength band*, or range of wavelengths. ***Aperture Photometry*** is when you define the total amount of light emitted from an object to be that which is emitted within a region (or "aperture") around the center of that object.

Point-Spread Function: Don't worry too much about this... essentially this is just referring to the blurring of an image. In this case, the image of the star the planet orbits.

Radial Velocity: This describes how fast an object is moving towards/away from us.

<u>Radial Velocity Method</u>: This is a technique used for discovering planets. The planet and host star *both orbit around their common center of mass*. Thus, if we look at an orbit of a planet/star edge on, we will be able to see the star move toward and away from us as it “wobbles” due to the planet’s orbit. We see this by utilizing the *doppler shift* of light. When a source of light (e.g. a star) moves toward you, the light you see get shifted to “bluer” (or lower) wavelengths. When it moves away, it gets shifted to “redder” (or higher) wavelengths. So, if we look at the *spectra* of these host stars for long enough we will see a periodic shift due to the existence of a planet.



<u>Semiamplitude</u>: Basically, this is just the same as “amplitude” of a sinusoidal curve. When applied to the radial velocity method, this corresponds to the maximum radial speed of the star-planet orbit. This value is directly related to the mass of the planet.

<u>Semimajor Axis</u>: One half of the length along the long axis of an ellipse. For an orbit, this is the *average distance* that the planet is from the host star. For a perfectly circular orbit, this value is equal to the radius of the orbit. (so, when we say that the Earth is 1 AU from the sun, we really mean that it is *on average* 1 AU from the sun)

<u>Transits</u>: a planet passing in front of its host star relative to us, the observer. Causes some of the light from the star to be blocked, which will make the star appear dimmer to observers.