Writing 4: Astrobites II
Due Friday, November 13th 5pm

Read the Astrobites article "WASP-47b: A Hot Jupiter With Friends"(http://astrobites.org/2015/10/20/wasp-47-a-hot-jupiter-with-friends/) on the recently submitted paper "WASP-47: A Hot Jupiter with Two Additional Planets Discovered by K2" and then read the paper itself. The paper has many technical details and will be a challenging read. It is okay if you do not understand all the methods employed. Do your best to answer the following questions.

1) Background: Answer the following questions to gain a better understanding of what hot Jupiters are and why they are interesting. Follow the first link in the astrobites article to read more on hot Jupiters.

a. A hot Jupiter is defined as a planet with characteristics similar to Jupiter (gas giant of approximately Jupiter mass), but that is extremely hot due to its small semi-major axis around its host star. *According to this article hot Jupiters have semi-major axes that are similar to what planet in our own solar system? How many **times** smaller is this than Jupiter's actual semi-major axis in our solar system?*

b. It is believed that a Jupiter size planet must form outside the frost line (or snow line). This line is defined as the boundary beyond which volatile materials (ammonia, water, methane, carbon dioxide, etc.) can condense into solids. The snow line in our solar system is at about 5 AU. Beyond the snow line are Jupiter, Saturn, Uranus and Neptune—the gas and ice giants. Within the snow line are Mercury, Venus, Earth and Mars—the terrestrial planets. *What is the main difference between planets in our solar system that formed within the snow line (terrestrial planets) versus planets that formed beyond the snow line (giants)?*

c. *Given your answer to the previous question, why do you think it is unlikely that a hot Jupiter could form so close to its parent star (i.e. at distances much smaller the snow line)? Hint: think about the kinds of material available for forming planets within the snow line versus beyond the snow line, and the relative amounts of these materials.*

d. There is clearly nothing like a hot Jupiter in our own solar system, so the existence of this class of extrasolar planets challenges our previously held theories of planet formation. *If hot Jupiters cannot form within the snow line, how do they eventually get to such small distances from their host stars? Hint: the answer to this is in the sentence that talks about hot Jupiters being "bullies."*

e. The opening paragraph states that of all the hot Jupiters found only a small percentage have companions, and furthermore all of these companions are far from the host star. In other words, hot Jupiters are "lonely." *Why might we expect hot Jupiters to be "lonely" given their formation mechanism?*

2) Analyzing Figure 1: Figure 1 (not from the paper described here) is a log-log plot showing the semi-major axis (orbital distance from host star) on the x-axis in units of AU, and the mass of the exoplanet in Jupiter masses on the y-axis. Jupiter is roughly 320x more massive than Earth. All 9 hot

Jupiters with known companions are represented on this plot. Planets in the same system are plotted in the same color and connected by a dotted line.

a. *According to this plot (which does NOT include the newly discovered companions to WASP-47b), what is the orbital distance (in AU) of the closest companion to a hot Jupiter?*

b. WASP-47b is the hot Jupiter that this paper discusses. This plot shows that it already has one further out companion. *At what distance is WASP-47b's far-out companion? Assuming it orbits a star of 1 solar mass, use Kepler's Third Law to find the* ***period*** *of its orbit.*

3) Analyzing Figure 2: Figure 2 shows the light-curves from K2 (Kepler's new operating mode). The light curves depict the transits of the newly discovered WASP-47e (super-Earth sized), and WASP-47d (Neptune-sized) in addition to WASP-47b (the hot Jupiter). The x-axis is a proxy for time, while the y-axis depicts how much starlight a planet blocks during transit. The y-axis is normalized so one represents all the starlight, and anything less than one means some starlight is blocked. By measuring the time between successive transits one can get the orbital period of the planet. If the size of the star is known, then the depth of the transit can be used to infer the planet's size (radius). A larger planet will block more light than a smaller planet (have a deeper transit). From this plot it is also evident that in a given system planets that are further out from the star have a longer duration transit than planets that are closer in; this figure is ordered from closest in (top panel) to further out (bottom panel).

a. The hot Jupiter (WASP-47b) has the deepest transit because it is the largest in size of these three exoplanets. Hot Jupiters are easy to detect in part because of their size—bigger planet, deeper transit. *What orbital property of hot Jupiters also makes them easier to detect?*

b. *If you know the orbital period of an exoplanet measured from its transit and the mass of the star what other orbital property can you get from Kepler's Third Law?*

4) Transit-Timing Variations (TTVs): TTVs can be used as a way to detect exoplanets while also yielding mass measurements for these planets. Remember, mass measurements do NOT come from transits; transits only measure size and orbital period. In closely packed exoplanet systems (such as the WASP-47 system) the planets in the system may exert gravitational tugs on one another. These gravitational perturbations by other planets in the system can cause a planet's orbital period to change slightly from one orbit to the next, meaning the planet will not transit at exactly the same time on each successive orbit. By measuring these "transit-timing variations" we can deduce the presence of another planet in the system and measure planet masses. In the case of the WASP-47 system, there are both transits and TTVs measured, meaning sizes, orbital periods AND masses are measured for all planets in the system.

a. *Give three reasons why the authors were able to find TTVs for the WASP-47 system.*

b. In Figure 3, the y-axis represents the transit timing, i.e. how early (negative numbers) or late (positive numbers) the transit is from what is expected. The x-axis is time in terms of the "barycentric Julian date." *Given that TTVs are due to gravitational tugs from other planets in the system, why does WASP-47e show the biggest transit timing variations compared to the other two planets?*

c. *Based on Figure 3, rank the masses of the planets in this system, from lowest to highest.*

5) Peaceful journey to WASP's doorstep: The final paragraph of this astrobites article summarizes why the WASP planetary system is so interesting—it is the first such system to show a hot Jupiter with close-in companions.

a. Think back to question 1d, which asked about how hot Jupiters might end up in such close-in orbits. *Copy the sentence in this paragraph that answers that question.*

b. *What does the discovery of this system tell us about the formation mechanisms for hot Jupiters?*

6) Read the paper "[WASP-47: A Hot Jupiter with Two Additional Planets Discovered by K2](http://arxiv.org/pdf/1508.02411.pdf)"(http://arxiv.org/pdf/1508.02411.pdf). Remember the strategies for reading a paper from the first assignment (i.e. start with the abstract, skip to the end for discussion/conclusions, then reread the whole paper). Look up terms that are unfamiliar to you. It's okay if you do not understand all the methods used in this analysis; try to get the "big picture" ideas from the paper and answer the following questions:

a. *From the introduction, what are two reasons that hot Jupiters are easier to detect?*

b. In Figure 1 the red lines are a model fit to the data. *According to the paper, what paramters go into the model fit? What is the name of the transit model used?*

c. *Are the sine curves overlaid on the middle and bottom panel of Figure 2 model fits?*

d. The authors devote a whole section to validating the planetary status of WASP-47d and WASP-47e both using other observational methods as well as statistical techniques. *Why are the transit signals not enough to prove that these objects are planets?*

e. *What are some potential astrophysical false positives for the transit signals they detect for these new planets (i..e. what are things that are not planets could mimic these signals)?*

f. *Looking at figure 3, what orbital parameter seems to affect the stability of the system the most? (For more fun with "simulating" the dynamics of a multi-planet system check out APOD's Super Planet Crash: http://apod.nasa.gov/apod/ap150112.html)*

g. **Big Picture:** *In your own words, why is this system referred to as a Rosetta stone for understanding TTVs? Hint: Your answer should reference the radial velocity method, which is another exoplanet detection method capable of measuring planet mass and is described below.*

h. **Big Picture:** *What does the discovery of this system imply about hot Jupiter formation mechanisms?*

i. **Big Picture:** The authors run not only dynamical simulations to test the stability of this system, but also come up with theoretical TTVs based on this configuration. *If the authors already have the observations, why do they bother with these theoretical calculations?*

Radial Velocity Method: 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.