Calculating Detection Signal of Different Methods for a Jupiter-like Planet around a Sun-like Star.

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**1. Introduction/Motivation**

The search for exoplanets is a direct extension of humankind’s longest-lasting question, *what else is out there?* In this paper, we analyze the ability of state-of-the-art technology to answer this question based on the current limitations of our instruments. In Section 2, we examine three primary detection methods, radial velocity (2.1), transit photometry (2.2), and direct imaging (2.3), and calculate the sensitivity of their detection capabilities. We then compare these limits on plots depicting various planet properties, which exhibit how our current technological capacities influence the known planet population in our galaxy. In Section 3, we apply these calculations to test the potential of discovering a Jupiter-like planet around a Sun-like star. However, it is important to recognize that different detection methods survey different planet parameters; therefore, a detection alone does not convey much information and must be followed up using other methods. Finally, we conclude that we are able to detect a Jupiter-like planet around a Sun-like star in exosolar systems using the radial velocity method.

**2. Methods**

In this section, we examine the limitations on our ability to detect exoplanets using three methods: radial velocity, transit photometry, and direct imaging. We use established mathematical relationships to solve for planet parameters (planetary mass or radius), which we compare to that of our Jupiter to determine whether detections of similar planets are possible.

2.1 Radial Velocity

The radial velocity detection method records light emitted from stars to calculate the “wobble” which a star experiences from the gravitational effects of the star-planet system using the Doppler effect. The R.V. amplitude, K, is the limitation which determines whether a planet is detected. Current technology can detect an R.V. amplitude of about *K*=0.5 m/s, where

Here, we use values from our solar system including Jupiter’s mass ( kg) for , our Sun’s mass ( kg) for , and Jupiter’s semi-major axis (778.479 km). Furthermore, G is the gravitational constant, and we assume an inclination of 90° so that sin(*i*)=1 to maximize this value.

2.2 Transit Photometry

The transit photometry method involves surveying the light from stars to analyze when part of the light is blocked by an orbiting planet passing between its parent star and Earth. This method requires a near edge-on inclination to capture a transit. Here, we calculate the probability of detecting a planet , where

In this calculation, we used the radius of Jupiter (69911.5 km) and the Sun (696347 km) for and , respectively, and we assume a semi-major axis equal to our Jupiter’s. In this case, the fraction of light blocked is given by

2.3 Direct Imaging

This detection method is—as its name suggests—the most direct, as it is like taking a snapshot in time of the exoplanet. However, many challenges arise in observing the planet’s presence, as planets orbit relatively close to their parent star, which is much brighter and can overpower the planet’s signal. Therefore, this light must be blocked, and the planet’s reflection and thermal emission must be large enough that we can differentiate the planet from the star. The light measured, *f*, is found by combining the black body emission of the planet and the reflected starlight, where

The term is given by

We assume an albedo value of 1 to maximize this term. Furthermore, the term is found from the Planck function:

which describes the specific intensity of the parent star. From this, we can solve for the star-planet contrast, where

The total light is the sum of these terms, where

Once again, we use the planetary and stellar masses from our solar system. Additionally, is the temperature of the sun (5772 K), is the temperature of Jupiter (130 K), and is the Boltzmann constant. We replace v with *hc*/, as we will use the Rayleigh limit as a basis for differentiating between stellar and planetary emission. This allows us to calculate the minimum angular separation, , where

In this equation, is the observation wavelength and D is the diameter of the telescope. To successfully determine the minimum angular separation for a Jupiter-like planet, the peak wavelength is calculated, where

and 2900 K\*μm is a constant. Due to this involving a Jupiter-like planet, the temperature of Jupiter is used again to determine this peak wavelength. In this case, will be used for the star-planet contrast and minimum angular separation equations.

**3. Results**

For the radial velocity method, we calculated a K value of 12.46 m/s, which is about 25 times larger than the lower limit of the detection signal. This means we are likely to find a planet as massive as Jupiter from its gravitational effect on the star. Additionally, the minimum mass of a planet which we could detect assuming a K value of 0.5 m/s is about 76 kg, or about 4% of our Jupiter’s mass.

When calculating the probability of detecting a transiting Jupiter-like planet, we found a very low chance at about a .01%. This means it is about 5 times more likely to find an Earth-like planet transiting. This is due to the planet’s semi-major axis, for which Jupiter’s is about 5 times larger than Earth’s.

For direct imaging, we first calculated an appropriate observable wavelength of 22.31 𝜇m

for an exoplanet that features a Jupiter-like temperature. For our computation, we chose the JWST (James Webb Space Telescope) which has an optimal wavelength range from 5-27 𝜇m

with a diameter of 6.5 m (Seager, Direct Imaging of Exoplanets, Section 5, Table 9), resulting in a minimum angular separation of 0.8637’’ or 1.157 parsec. When determining the star-planet contrast, we calculated a value of 8.367. Contrast limits at 1’’ for the MIRI instrument in JWST, which operates between 5-28 𝜇m, is predicted to approach (Beichman et al., 2020). Since our calculated star-planet contrast is less than the MIRI limit, we can establish that direct imaging would not be able to detect a Jupiter-like planet around a Sun-like star.

\*\* discuss graphs here

**4. Conclusions**

It is possible to detect a Jupiter-size planet around a Sun-like star using the radial velocity method. The large planetary mass ensures a wobble which we can measure using current technology. However, due to Jupiter’s distance from the sun, it is difficult to detect similar planets using the transit method or the direct imaging method. The planet’s semi-major axis is too large for our instruments to effectively detect a transit, even with Jupiter’s large radius which would block 1% of the light. Furthermore, the semi-major axis provides for a cool planet, which is difficult to detect using direct imaging; even though the parent starlight would not block the planet’s signal, there is not enough black body emission for the planet to be detected in the first place.

\*\* sum up graphs here

**5. Contributions**

Yuanhao and Missy wrote the necessary code and produced the plots with their detection limits. Alex researched the state-of-the-art technology and calculated the detection limits for our scenario. Ashley wrote the written report. Mariana created the presentation slides.

**References**

<https://nssdc.gsfc.nasa.gov/planetary/planetfact.html>

<https://github.com/bleichm/Project-1.git>

<https://www.stsci.edu/files/live/sites/www/files/home/jwst/about/history/white-papers/_documents/Astro2020-white-paper-BeichmanC.pdf>