**Modern Methods of Exoplanet Detection**

1. **Motivation**

Ever sinceWolszczan and Frai made the first definitive discovery of exoplanets in 1992, astronomers have been looking for ways to make other such discoveries. The primary reason being our solar system is just one of many such planetary systems that exist in the universe and analyzing these exoplanets in turn helps in understanding our solar system and its planets better. It enhances our understanding of the various trends in planet formation around different stars and make comparisons to our solar system in order to determine if the existence of a planet like Earth was just a fluke or are there other worlds where similar conditions can be achieved for life to prosper.

Over the years, the exoplanet detection methods have progressed leaps and bounds and today we have over 4000 confirmed detected exoplanets [NASA, 2022], all of which have enhanced our knowledge about the Universe as a whole. However, not all of these methods work all the time and sometimes require very specific conditions for orientation of planet’s orbit, planet’s distance from the star or even the thermal emission of the planet. Which is why it is important to understand the caveats associated with these detection methods to minimize selection bias.

1. **Methods**

In this report the physics behind the three main methods of exoplanet detection: (1) Radial Velocity, (2) Transits and (3) Direct Imaging are discussed in detail along with estimates about the limits of today’s cutting-edge technology and if it was our solar system being observed, would Jupiter be detected as an exoplanet around the Sun.

* 1. **Radial Velocity**

This technique involves finding the relation between the radial velocity of an object in orbit and its mass assuming 2-body Keplerian motion (Seager). The equations below explain said relation:

--- (1)

--- (2)

Here *P* refers to the planet’s period of revolution around the star, *a* is the semi-major axis of the orbit, *G* is the universal gravitation constant, *M\** is the mass of the star, *Mp* is the mass of the orbiting planet, *vp* the orbital speed of the planet and *i* is the angle of inclination of the orbit from our plane of view. Equation (1) is Kepler’s third law and can be used to derive Equation (2) which gives the value if the planet’s redial velocity signal, also called the RV semi-amplitude (*K*) (Seager). Usually, the angle of inclination is unknown and therefore a measurement of: *Mp sin (i)* is made and an estimate of the ‘minimum planet mass’ is made. The state-of-the-art detection is currently the most suitable for detecting planets around unevolved-G, late-K and M stars due to the smaller noise signal and low mass of these stars amplifying the RV signals of the orbiting planets. The current latest and greatest equipment is capable of measuring RV signals as low as 0.5 m/s.

* 1. **Transits**

This method of observation relies on the principle of eclipses that Dr. Joshua Winn defines as “the obscuration of one celestial body by another” (Seager). The most important requirement to effectively use this technique is that the inclination of the planet’s orbit around the star needs to be ‘near edge-on’. Below are some important equations needed to make calculations using this technique:

--- (3)

--- (4) --- (5)

In equation (3), *PTransit* represents the probability of a transit being detected, *Rp­*, *R\** and *a* once again represent the radii of the planet and star respectively and the semi-major axis of the orbit. The ratio of the cross-sectional areas of the planet and star are given in equation (4) with *f* being called the depth of transit. This depth of transit is the important quantity that must be significant enough for the state-of-the-art detectors to measure. It heavily favors large planets (comparable to Jupiter) with short revolution periods (of the order of a few days). Insert detection limit

* 1. **Direct Imaging**

This detection method involves directly observing the planet around a star by artificially suppressing the light from the central star using techniques such as a rectangular mask coronagraph or angular differential imaging. Direct Imaging heavily favors young, hot, self-luminous planets as their high temperature gives them a strong detectable flux and ‘Their large distances from their planet stars makes them easier to see in the halo of atmospherically or instrumentally scattered star light’ (Seager). Below are the important equations for this technique:

--- (6)

--- (7)

--- (8)

--- (9)

Here, *fR* is the starlight reflected by the planet and is directly related to the albedo (*A*). Equation (7) shows the Planck function which is a measure of the thermal emission of a body and depends on the Planck’s constant (*h*), speed of light (*c*), frequency (*v*), Boltzmann constant (*kB*) and temperature (*T*). Assuming that both the star and the planet emit thermal emission, equation (8) shows the Star-Planet contrast and its relation to *Tp* and *T\** which are the temperatures of the planet and the star respectively. Another criterion for using this technique is that the planet needs to be identified as a distinct source by the telescope and equation (9) shows the Rayleigh limit with *λ* acting as the wavelength over which the telescope operates, and *D* is the telescope’s diameter.

1. **Results**

The first set of results (Figures insert number) involves extracting exoplanet data from NASA’s Exoplanet Archive (NEA) and overplot the solar system planets on them to get a better understanding of how common it is to detect similar planets. It can be clearly seen that most of the detected planets are above the sensitivity lines for their respective detection methods and the few outliers can be explained by statistical uncertainties or, a different method was used to obtain that data.

Additionally, there is a considerable decrease in the planets discovered through RV signals in the plots featuring ‘Radius’ on one of the axes. This is because as seen from equations (1) and (2), there is no *Rp* term and hence it is difficult to derive it from the data. The majority of the Radius data as seen from the plots is obtained from the Transits technique which lets us directly get a measure of the planet’s radius as seen from equation (4). (more to add after final graphs)

For the purposes of this project, the special case of a Jupiter-like planet around a sun-like star was chosen to better understand the limitations and capabilities of the state-of-the-art detection equipment for the three methods discussed in the previous section. Jupiter has a semi-major axis of 5.2 AU, mass of 1.898 x 1027 kg and for an edge-on orbit (*i* = 90o) the derived *K* value for the RV signal would be 12.46 m/s, which is higher than the state-of-the-art detector limit of 0.5 m/s. This means that the current RV equipment is a very good way to detect Jupiter-like planets around Sun-like stars.

Transits

Direct Imaging is the third and final detection technique discussed in this report and

1. **Conclusion**
2. **Acknowledgements and Contributions**

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**References:**

**https://exoplanets.nasa.gov/faq/6/how-many-exoplanets-are-there/**