Literature Review on Exomoons

HOW EXOMOONS COULD BE DETECTED AND WHY THIS SHOULD BE DONE IN THE FIRST PLACE

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Literature Review

A Brief History of Astronomy (Introduction)

Ever since antiquity, humankind has looked to the stars for inspiration and the answer to the burning question of "Are we alone?" As the field of astronomy has progressed, this question has been in its center.

Some of the earliest foundations for the field of astronomy can be traced back to the ancient Greeks. The most influential Greek astronomer, Ptolemy, wrote the *Almagest* in the 2nd century CE. Establishing a geocentric system, this text dominated astronomy for 1400 years after its writing (Evans, 2019). In 1547, Copernicus published his own book, *De revolutionibus orbium coelestium libri VI*, in which he proposed a heliocentric system instead (Evans, 2019). However, because astronomers were so obsessed with the idea of perfection in the celestial sphere, even when they came to accept Copernicus' model, they based their models on perfect circles. However, as planets actually orbit in slightly ovaloid circles called ellipses, astronomer had to add miniature circles to the outsides of these circles called epicycles in order to better approximate the future positions of the planets. Then, in 1609 Johannes Kepler published *Astronomia Nova*, outlining his infamous three laws of planetary motion (Evans, 2019). Kepler was able to find that planets orbit in ellipses by using the data of possibly the greatest observational astronomer of all time, Tycho Brahe. Galileo Galilei then further proved that the celestial sphere wasn't perfect by observing the rugged topography of the Moon, and finding that not everything orbits around the Sun or Earth. Instead, Galileo observed the four largest moons of Jupiter, Io, Europa, Ganymede, and Callisto, now called the Galilean moons in his honor. Then Newton published his *Principia Mathematica*, which helped explain why Kepler's models of planetary motion were correct and created Newtonian mechanics. This would later be overturned during the 20th century, where the discoveries of general and special relativity as well as quantum mechanics provided a whole new way of looking at astronomical phenomena.

Additional advancements such as being able to detect elements using spectroscopy and understanding more about how our solar system was formed have created a basis for the current study of exoplanets, planets that orbit stars other than our own, the focus of modern astrobiology. However, exoplanets should not be the end-all be-all in the search for extraterrestrial life. Exomoons, or rather, moons that orbit exoplanets, are also viable places to look, as seen with the numerous moons in our own solar system that are potentially habitable. By using a model system and extrapolating various relationships between given orbital parameters and changes in transiting, transit curves could technically help find exomoons.

The Search for Exoplanets

Exoplanetary science has evolved under the assumption that Earth and the solar system are not special. It is assumed that there exist other planets around stars that could potentially be habitable by life. There are various methods for detecting exoplanets that have been proposed over the years. The most popular is the transiting method, where the light of a star is observed continually over the course of many years. If an exoplanet has an orbit that brings it in between the line of sight of an observer on Earth and the face of its sun, periodic dips in the brightness of the star occur. These periodic dips in brightness can be indicative of an exoplanet, and the radius, semi-major axis, and period of the exoplanet can then be extrapolated (NASA, 2019). Another method that is used, though less frequently, is that of radial velocity. If an exoplanet were to be orbiting a star, it would exert the same force on the star that the star exerts on it, resulting in a periodic "wobble" of the star. This "wobble" can then sometimes be detected, and the mass of the exoplanet, as well as its semi-major axis and period, can be found (NASA, 2019). Spectroscopy can also be used to find exoplanets; if the exoplanet has a different composition than its star, the atoms in its atmosphere will absorb some of the light being emitted from the star, and absorption lines will appear in its spectra. If these changes in a star's spectra are periodic, it can indicate an exoplanet. This method can be used to find the overall composition of the planet's atmosphere, which is important when considering a planet's habitability. Yet another method is direct imaging, through which an exoplanet is found by taking a picture of the star and finding the exoplanet visually. This method can only be used for a very select group of exoplanets, and is not applicable for most, as direct imaging cannot be used for exoplanets that are too small or too far away from their planet star. Multiple methods of exoplanetary detection are usually used concurrently, in order to complement each other and find various different characteristics about the exoplanet.

The very first exoplanet found orbiting around a sun-like star, 51 Pegasib, was discovered in 1997 (Marcy, 1997) by using the radial velocity method. Since then, more methods for finding exoplanets have been employed. The most successful, the transiting method, has found thousands of exoplanets, most notably through data collected by NASA's Kepler spacecraft. The transiting method measures the amount of light emitted from a star over a certain interval of time. This is then graphed onto a "transit curve". Researchers then look for periodic dips in the data, known as "transits", which could be caused by an exoplanet orbiting the star, and thus blocking part of its light as it crosses it. This method finds the period, radius, and semi-major axis of the exoplanet's orbit, but needs to be cross-referenced with another method of detection in order to suggest that at the exoplanet exists. There are major drawbacks to this method, such as its reliance on the orbital inclination of the planetary system being such that these "transits" actually appear from our field of view, and the inherent presence of noise in the observational data. However, this method has found many more exoplanets than any other method combined. Given that only a fraction of possible exoplanets can be found using the transiting method, this means that, statistically, many more exoplanets exist. This also supports the theory that our planetary system is not a unique one, and that life could exist outside of it.

Moons in the Solar System

Our only model for a planet that harbors life is our own, the Earth. As such, our definition for habitability is that it could host life as we know it, especially archaea or bacteria such as extremophiles. Mars, one of our closest planetary neighbors, could have potentially been habitable in its past. There are also multiple moons that could be habitable: Europa, Enceladus, Titan, Io, and possibly Ganymede. Enceladus, for instance, has a confirmed ocean under its icy surface and the Cassini spacecraft found organic particles were actively spewing out of the moon (Jet Propulsion Laboratory, 2019a). Europa is also thought to have an under-the-ice ocean (Jet Propulsion Laboratory, 2019b). Io has active volcanic activity (Jet Propulsion Laboratory, 2019c). A specific type of life on Earth, known as extremophiles, a specific set of archaea and bacteria, defined by being able to survive in extreme conditions, could survive on these three moons. Saturn's moon Titan has physical lakes and oceans of methane (Jet Propulsion Laboratory, 2019d). If a permutation of life that relied on methane like we rely on water existed, it could potentially survive on Titan as well.

Given how so many of the moons in our solar system could potentially be habitable, it makes sense that moons might be just as important as exoplanets in potentially finding life outside of our solar system. As such, in order to try to find a celestial body that could harbor life, it is important to try to find habitable moons as well, especially considering the vast numbers of moons seen in the solar system. The same methods to detect exoplanets could potentially be applied to the discovery of exomoons. However, though various methods have been suggested to detect them, no exomoon has ever been confirmed.

Exomoons

There are a few suggestions as to why exomoons haven't been confirmed yet. Some argue that exomoons do not exist, and that searching for them is a fruitless endeavor because there is nothing out there. However, because there are so many moons in our own solar system, and we've already found that exoplanets exist, it would be reasonable to assume that these exoplanet have moons as well. An alternate reason explaining why exomoons have not been detected yet is that they are too small to detect in a transit curve and their effects on their planetary system are too small to an effect that we could detect, given how the nearest star is 4 light years away.

Proposed methods for detecting exomoons revolve around two ways that the presence of an exomoon changes the transit curve of its exoplanet: Transit Timing Variation (TTV) and Transit Duration Variation (TDV) (Kipping, 2011). The first, TTV, focuses on how the time intervals between each transit could fluctuate based on how an exomoon would orbit the planet. However, there are other phenomena besides a moon that have been known to cause TTVs, such as trojans (very small bodies that orbit on a planet's outer Lagrangian points) and solar activity. An analysis of a system's TTVs can also lead to finding other exoplanets because of their gravitational effects on other planets (Nesvorný, 2013). The second way an exomoon could

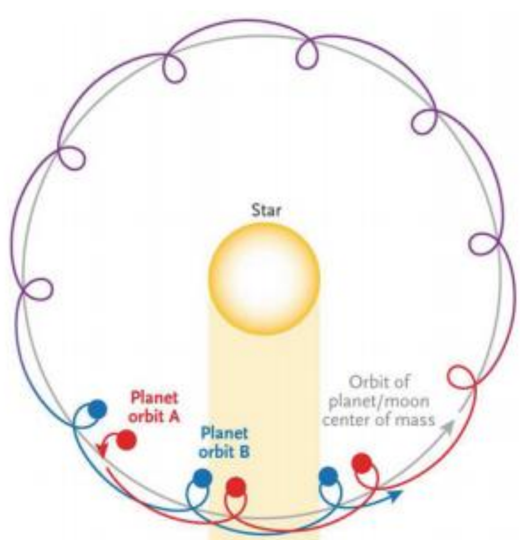

Figure 1. A visual explanation of what Transit Timing Variations look like in a sun-planet-moon system (Kipping, 2011). As you can see, the timing of the planet gets shifted due to the influence of the moon.

affect a transit curve, TDV, focuses on how an exomoon could change the length of transiting itself. When TTV and TDV effects agree with each other well, it is very possible that the exomoon could exist.

Habitability of Exomoons

Whether or not a planet could be habitable depends on multiple factors: the type of planet and whether it has the chemicals needed for life in an appropriate state. Likewise, whether or not an exomoon is potentially habitable relies on its initial composition. Additionally, the potential habitability of an exomoon depends on the distance from its star and planet and radius (Lammer, 2014), as well as the stability of its orbit and the maximum orbital separation (Kaltenegger, 2010). However, moons that would otherwise not be habitable could be rendered habitable if they exhibit special orbital characteristics, such as being tidally locked with their exoplanet or being in tidal resonance with another exomoon.

The Three Body Problem

A challenge in modelling the transit curve of an exomoon as opposed to that of an exoplanet is that there are more than two bodies acting upon each other, and the motions of all the bodies involved get much more complicated as you add different objects. When two bodies act upon each other, the resulting model is predictable. However, when more bodies act upon each other, the system is ever-changing and cannot be predicted. The “three body problem,” a case where three bodies act upon each other, has been especially researched. There are special cases for three body systems in which the model is periodic and solvable. In fact, 13 additional families of solutions (Šuvakov, 2013) to the three body problem were discovered in 2013, adding to the previous three that were already known.

In order to model three bodies, multiple methods can be used. One is to model the planet-moon system as a single body, and thus split the sun-planet-moon system into two separate two body systems (Kipping, 2011). Another is to evaluate the model in very small time intervals, and assume that the system will be close enough to its actual value that it won't affect the effectiveness of the model.

Orbital Resonance

In addition to all of these things surrounding exomoons, orbital resonance should also be mentioned. Orbital resonance is a phenomenon that occurs when multiple moons have periods that are fractions of each other. Though it is pretty rare, given that you need at least two moons and the right timing and initial conditions for it to happen, orbital resonance is nevertheless interesting enough to be looked into. It can render an otherwise barren exomoon habitable. This is because orbital resonance can cause periodic tidal energy to be released in exomoons through friction that gets dissipated through the moon. Orbital resonance is most evidenced by the Galilllean moons, Io, Europa, Ganymede, and Callisto, each of which are very intriguing (Yoder, 1979). In particular, Io is known to have volcanoes and Europa is thought to have an underground ocean. Both of these could render the moons hospitable to life. These phenomena are only able to happen because of the presence of the other Galilean moons though. If they weren't there, the moons as we know them today would not exist. Jupiter is simply too far away from the sun to have liquid water simply present on one of its moons. The only reason Europa's ocean is able to exist under its ice is because of the energy gained from tidal heating.

Tidal heating and how it can make an inhospitable moon inhabitable means that scientists should look for moons everywhere, because even a moon as far away as Jupiter or Saturn are from the

Sun could potentially be habitable. Even though these moons would need to have a very specific sets of conditions (multiple moons need to have orbital periods that are fractions of each other), the very possibility that this could occur increases the chances that moons might be habitable. Indeed, moons might be more habitable than planets for this reason. Though orbital resonance for planets could potentially exist, it is probably less common than orbital resonance for moons.

Conclusion

Due to the vast number and astonishing diversity of moons simply within our solar system, it is logical to try to find exomoons that mimic these same characteristics. The reason why exomoons are so fascinating, and why they could be so valuable when looking for potentially habitable bodies, is that there are many of them and they have a promising ability for habitability outside of the habitable zone due to phenomena such as tidal locking and tidal resonance. Even though the study of exoplanets has only been around for the past few decades, the search for exomoons is comparatively young and immature. However, the same principles techniques that are employed when searching for exoplanets could potentially be adapted to search for exomoons. There are many methods that could be used to look for exomoons, but one of the most promising is the transiting method. The three body problem could be circumvented by accepting a certain level of uncertainty and simply keeping the increment of time in a model to a minimum.

In order to attempt to find habitable moons, a sun-planet-moon system will be modelled, and the relationship between different orbital parameters and differences in the light curves of the star will be looked at. These relationships will then be used to analyze inconsistencies in available transit data for known exoplanets, which will hopefully result in possible traces of an exomoon.

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