Law of Gravity Blurred by Perturbed Planetary Orbits for Alien Observers

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Abstract. The Fermi paradox is the contradiction between the high probability for aliens and its lack of evidence. This is perhaps the most significant of all questions in astronomy. Nowadays, thousands of exoplanets have been detected, providing us more information directly from alien planets to revisit Fermi paradox. Over recent years, the detection of habitable exoplanets has grown rapidly, and most of them in multi-planet system with fairly compact structures, which is partly due to our observational techniques. In such systems, planets’ orbits are significantly perturbed by gravitational interactions from each other. To travel within or out of a planetary system, one must understand the law governing planetary motion, but can extraterrestrials deduce the universal law of gravitation by observing planets in their system, as Johannes Kepler and Isaac Newton had done? Here we show that due to the close planetary orbits in systems hosting habitable exoplanets, planetary orbits significantly deviate from the Keplerian orbit. In our N-body simulation over a period of 300 days, out of the ten planetary systems which all include habitable exoplanets in our sample, the mean anomaly deviates from a Keplerian orbit by more than 5 degrees while the system remains stable as the semi-major axis remains relatively constant. This would significantly complicate what the observers on those planets observe as the motion in the system would not appear to have a pattern periodically. Although planets indeed affect each other in all systems, the compact nature of these systems have magnified the effect and provide no way for the extraterrestrials inhabiting those planets to discover the universal law of gravitation. Extraterrestrials lacking the law of gravity definitely cannot facilitate traveling beyond their planets. That could be one possible resolution of Fermi paradox, reducing the population of high-developed civilization in Universe.

1. Introduction

1.1. Fermi paradox

The Fermi paradox explores the contradiction of the age of the universe, thus the large possibility of extraterrestrials’ existence, with the lack of evidence we have collected exhibiting that. With billions of stars in the milky way similar to the sun, there are many exoplanets which are similar to Earth and it is likely intelligent life have developed elsewhere, it is also likely they can facilitate interstellar travel. The age of the universe is 13.8 billion years, which provides plenty of time for Earth-like planets to form and Earth itself formed only just 4.5 billion years ago [1]. From the large amounts of Earth-like planets that should have been produced over billions of years, there must be some which have developed into civilizations capable of interstellar travel [2]. If they have the ability to travel to earth, why is there no evidence of its occurrence? Possible explanations, first analyzed by Michael Hart, can be seen from several perspectives [3].
1.2. Discovery of exoplanets

The idea of exoplanets, planets orbiting stars other than the sun, was theorized decades ago, however it was not until 1995 that an exoplanet orbiting a solar-type star was discovered. This discovery of 51 Peg b was awarded the Nobel Prize in Physics 2019 as it contributed to our understanding of the evolution and origin of life in the universe. Ever since then, rapid progress has been made in enhancing the detection of extrasolar planetary systems. As of 2021, the known number of exoplanets exceeds 4000 (Fig 1). The two main methods of detecting exoplanets are radial velocity and transit[4].

The diverse nature of exoplanets was revealed with the discovery of 51 Peg b, as although the 51 peg star was a solar-type star, the planet had a semi major axis of only 0.05 au, an orbital period of about four days and a radius twice of Jupiter’s. Prior to the discovery, the perceptions of extrasolar planetary systems were based on the solar system, and it was believed a planet with mass similar to Jupiter’s would have a large orbital period as that is the case for planets in the solar system. Although there can be observational bias as the methods of detection favor those with planets closer to the host star, it can be seen the structure of the solar system is not at all a model for extrasolar planetary systems. Through the characterization of exoplanets, the understanding of the perspective of an extraterrestrial civilization can now be furthered, as the diversity of the orbital elements of exoplanets can possibly provide context for the lack of evidence of extraterrestrials in the solar system [5].

![Cumulative Detections Per Year](image)

Figure 1. This figure presents the number of detection of exoplanets up until February of 2021, with each color indicating the method used. It can be seen that Transits and Radial Velocity have been used for the majority of the detections and the number of detections has greatly increased in recent years.

1.3. Habitable exoplanets

Out of the over 4000 exoplanets discovered so far, the ones considered habitable only just exceed 60. The habitability of an exoplanet is impacted by factors including the star-planet separation, its atmosphere and its planetary orbit.

An exoplanet’s earth similarity index (ESI) considers five parameters: mass, semi major axis, radius, stellar radius and stellar temperature. ESI only characterizes one type of a habitable environment; it ultimately does not determine a planet’s habitability as other factors like planetary tidal locking and magnetic field are not considered. The planetary habitability index however, measures habitability based on what requirements are essential to support life, in ways which can differ from Earth. It considers factors including the energy sources, the chemistry composition and the presence of liquids.

The habitable exoplanets that have been discovered so far primarily orbit around M-type stars, whose surface temperatures range from 2000 to 3700K. As a result, the circumstellar habitable zone is much closer to the star compared to the solar system, since the star’s radiation falls as the distance from it increases. \( L \propto 1/r^2 \)

From the plot (Fig 2) illustrating the mass and radius of those in planetary systems containing habitable exoplanets, it can be seen their size and mass vary but are generally larger than Earth. However, the graph of semi major axis (Fig 3) reflects how compact these systems are, as most measurements seem are only a fraction of Earth’s semi major axis, although that maybe a bias from our current detection techniques.
2. Theories

2.1 Orbital elements and planetary motions
A planetary body’s orbit can be found using Kepler’s laws and its motion can be summarized using six orbital elements. The six elements include: a, the semi major axis which is one half of the major axis; e, the eccentricity which is how elliptical the orbit is with 0 being a circle and 1 being a parabola and larger values belong to a hyperbola or straight line; I, the inclination angle of the orbit which is the angle between the orbital plane and the reference planet; the longitude of pericenter represents the longitude at the point where the body is closest to the star if the inclination angle was 0; Ω, the longitude of the ascending node, represents the angle from the location of the body at a specific time to the ascending node which is when the body crosses from below the reference plane to above it; ω, longitude of pericenter is the angle between the ascending node and the pericenter (Fig 4).

2.2 perturbed orbits in three body problem
A solution for the N-body problem has been long sought after and by using simulations, solutions can be found with the given parameters although these are only particular solutions that can not be applied
to more than one set of parameters. A system with two bodies interacting through gravity can construct a system with predictable orbits. More importantly, a stable orbit allows the planet’s climate and conditions to remain relatively consistent, and eliminates the possibility of collisions, making the planet more habitable.

With the law of universal gravitation, one can deduce the strength of a gravitational force decreases in proportion to the square of the separation. In the case of the solar system, the planet separation is large and as a result perturbations due to other planets is small; for example the force between just Earth and Jupiter, the most massive planet in the solar system, is less than 0.005 percent of the force between Earth and the Sun. However, in compact systems, the small separation and less massive stars produce more impactful perturbations on the planetary orbits as in the TRAPPIST-1 system, the force between b and c is more than 0.01 percent of the force between b and the star, and there are seven exoplanets in the system in total, each exerting a push on planet b. These perturbed orbits produce a more complex system; although the orbits can be predicted using simulations, it is only feasible with prior knowledge of the universal law of gravitation and the relationship it presents between the mass, separation and force between bodies, which has been made much less direct apparent in compact systems like TRAPPIST-1. A restricted three body system differs from others as it contains one body whose mass is too small to affect the motion of the others for example a satellite between Earth and the Sun. Lagrange points are points at which the third body is able to remain in equilibrium. The Sun-Earth Lagrange points are used for probes, telescopes and satellites although L3 cannot be used because of its placement behind the Sun. Natural objects at Lagrange points include the Trojans and Greeks asteroids which are at the Sun-Jupiter Lagrange points L4 and L5.

3. Simulation and analysis

3.1 Mercury

Mercury is a numerical integrator which was used to create a simulation of effects of the N-body movements which were present in all planetary systems, but especially significant in the compact systems used. The program is written in Fortran 77 by John E. Chambers [6]. Its function includes the ability to calculate the evolution of orbits for objects including comets moving in the gravitational field of a large central body (Fig 5). It allows for the inclusion of general relativity in its calculations although in the cases tested only the Newtonian gravitational forces were used. Mercury6_1.for is one of the drivers for this program and contains the basic integration program which carries out the necessary calculations and produces the desired outputs in a compressed file. Element6.for is used to convert the outputs into files in terms of the keplerian orbital elements for each object of integration, which better demonstrates how exactly the orbit evolves and can be used for the visualization of the simulation.

**Figure 5.** From left to right, the figures present the orbits of two masses over one year, whose mass and semi-major axis have been altered to exaggerate the effects of three body motion to better demonstrate it visually as with the deviations in a real system, although they do exist, are not visually apparent when plotted.

The program takes inputs, the initial data for necessary measurements, as input files like big.in and param.in. Big.in allows the user to enter in the orbital elements for each planetary body involved in the integration. Param.in includes several parameters including those which control how the integration is carried out, like time period and how often an output is recorded, and physical parameters of the central
body. The program produces output files with the orbital elements over the integration for each planet in the input file. For our ten systems, it was necessary for the perturbations to be visible, so two sets of data were taken for each planet in order to contrast its orbital evolution under only the gravitational influence of the central body with if all gravitational influence from other planets were included. The visualization of the integration was achieved using the two sets of data for each planet and the graphing features of python. We also plotted the difference between the two sets of data over the time period of 300 days to analyze these systems more closely.

The simulation used parameters found in the NASA exoplanet archive described in the previous section, and any unknowns were set to zero [7]. We consider the two separate cases of when the planet to planet interactions are included and excluded from the evolution of the orbit over 300 days. The simulation allowed us to consider the change of the mean anomaly over time as it demonstrates change of the planets’ orbit distinctly.

### 3.2 Trappist1

The Trappist-1 star, 12 parsecs away, is the host star to seven confirmed planets and has a surface temperature of 2550 K which defines it as an ultracool dwarf, along with its low temperature it also has the mass and radius of 8% and 11.5% those of the sun [8]. Trappist-1b and c were first detected using their transits, which had periods of 1.5 and 2.4 days. Trappist-1d, e, f, g and h were detected later using the 34 transits identified from the light curves constructed from the data collected by the Spitzer space telescope and had periods of 4.04, 6.06, 8.1, 12.3 and 18.9 days. The mass and size of the planets were determined through analyzing transit depths and Transit timing variations, which also reflected the significant planet on planet forces present, influencing their orbits and transit timings. Trappist-1b, c, e, f, g have been found to have sizes close to the Earth and all of them have an equilibrium temperature within the range at which liquid water can exist. The orbital periods of the planets demonstrate multiple examples of orbital resonance (1/2 for 4.04/8.1 and 6.06/12.3) which present the possibility of the planets initially forming further from each other and then migrating inwards (Fig 6).

![Figure 6](image)

**Figure 6.** This is a visualization of the simulation at the end of the 300 days, showing multiple aspects of the Trappist-1 planets’ orbit including their eccentricities, semi-major axis and positions throughout the simulation. It can be observed that the positions of the planets when gravitational influence from other planets is included, represented by the colored dots, deviate significantly from the positions of the planet if it was only engaged in a two-body relationship with the star, represented by the grey dots.
The simulation allowed us to visualize the evolution of the orbits in terms of their mean anomaly and eccentricity in some cases. For the Trappist-1 system, all seven of the planets exhibit visible change in their orbits. Figure 7 shows the difference in mean anomaly which essentially represents the planet’s angular position on its orbit, reflects the deviations from a Kepler orbit. Despite the deviations, the system is predicted to be able to remain stable for at least 0.5 million years, as when a simulation is carried out for 1000 years, the semi-major axis’s deviations in relation to the semi-major axis is negligible as seen in Figure 8. There are observable patterns in the differences between the mean anomalies, an example would be Trappist-1e, and g, which are due to the orbital resonance between the planets as the ratio between their periods are close to a whole number (Table 1). Although the resonance chains result in periodic gravitational influences as opposed to random pushes, the deviations from a Kepler orbit remains prominent and constructs a complex system that does not directly demonstrate the universal law of gravitation. The most apparent demonstration of the universal law of gravitation in a system would be the gravitational influence exerted by a star on the planet but in compact systems like Trappist-1, the complex planet to planet interactions, despite also being governed by the universal law of gravitation, blur the relationship between the star and the planet.

Figure 7. This shows the mean anomaly change of the Trappist-1 planets over the period of 300 days in degrees.

Figure 8. The variations of planetary semi-major axis in a dynamical simulation with a long period of 1000 years are presented. The difference in their semi-major axis when only the gravitational relationship with the star’s mass is considered and when the gravitational influence from other planets are also considered, remains within a range of 0.0017 and 0.00033 of the planet’s measured semi-major axis. The trivial variations of this parameter demonstrates the stability of the system while they are also evident of deviations from a Keplerian orbit.
Table 1. Trappist1. Col 1: Planet, each planet in the Trappist-1 system from b to h; Col 2: a, semi-major axis in au; Col 3: e, eccentricity; Col 4: P, the orbital period in unit of day; Col 5: g, the argument of periapsis; Col 6: Inclination in unit of degrees; Col 7: ΔM, change of mean anomaly over 300 days; Col 8: Δa/a, change of semi-major axis over the measured semi-major axis.

| Planet | a   | e   | P   | g   | I     | ΔM   | Δa/a  |
|--------|-----|-----|-----|-----|-------|------|-------|
| b      | 0.01| 0   | 1.51| 0   | 89.65 | 3.011| 0.00045|
| c      | 0.015| 0  | 2.42| 0   | 89.67 | 5.580| 0.000328|
| d      | 0.0214| 0  | 4.049| 0 | 89.75 | 20.106| 0.00139|
| e      | 0.02817| 0  | 6.0996| 0 | 89.86 | 1.539 | 0.00177|
| f      | 0.0371| 0  | 9.206| 0 | 89.68 | 7.950 | 0.00229|
| g      | 0.0451| 0  | 12.35| 0 | 89.71 | 2.249 | 0.0111|
| h      | 0.03| 0   | 18.76| 0 | 89.76 | 3.334 | 0.000873|

3.3 Kepler186

The Kepler 186 system consists of five planets with one being inside the habitable zone of the star. Planet masses are not confirmed for any of the planets however estimates have been made based on their possible compositions. (The distance between the inner four planets (b, c, d, e) are much smaller compared to their distance to planet f whose semi-major axis is around 0.432 au, as shown in figure 9. Being the only known planet in the habitable zone of Kepler-186, planet f has been observed to have the qualities necessary to maintain liquid water. [9] The pattern in the change of mean anomaly, most obviously seen in planets b, c, and d can be attributed to their orbital periods whose ratios with each other are close to those between small integers (p_b:p_c is close to 3:4, p_c:p_d is close to 4:7). The ratios in their orbital periods reflect the periodic pushes to and from each planet, which stack up to produce the resonance pattern seen. Despite the large changes in mean anomaly seen in fig 10, when a simulation over the time period of 1000 years was done, shown in Figure 11, the Kepler 186 system demonstrated its stability over time through the minute changes in its semi-major axis in relation to its measured semi-major axis (Table 2).

Figure 9. visualization of the simulation of Kepler 186 at 100 days. Colored dots represent the planets’ orbit if the gravitational influence of other known planets were included. Grey dots represent the planets’ orbits if the only gravitational influence they experience is from the star.
Figure 10. The change in mean anomaly over the time period of three hundred days of Kepler 186 planets is shown in degrees.

Figure 11. The plots present the ratio between the change in Semi-major axis and the planet’s measured semi-major axis for each of the Kepler 186 planets.

Table 2. Kepler 186, see table 1.

| Planet | a  | e  | p   | g | I | ΔM     | Δa/a |
|--------|----|----|-----|---|---|--------|------|
| b      | 0.034 | 0  | 3.88 | 0 | 0 | 9.426  | 0    |
| c      | 0.045 | 0  | 7.26 | 0 | 0 | 22.432 | 0    |
| d      | 0.078 | 0  | 13.34 | 0 | 0 | 43.331 | 6.411*10^-9 |
| e      | 0.221 | 0  | 22.4 | 0 | 0 | 55.272 | 9.092*10^-9 |
| f      | 0.432 | 0  | 129.94 | 0 | 0 | 0.0614 | 0.000127 |

3.4 GJ 163
The three currently confirmed planets in the system GJ 163 were all found using radial velocity, 150 measurements of GJ 163 were taken by Bonfils et al. over eight years and five significant signals were found. Although two need further interpretation, the other three have been identified as exoplanets. GJ 163 b, c and d each have semi-major axes of 0.061, 0.13, and 1.03 au while the other two potential planets e and f would have the semi-major axis of 0.10 and 0.33 au. GJ 163 c, which receives more energy from its star than Earth has been found to potentially be habitable as its equilibrium temperature falls within the range in which liquid water may exist, however its habitable nature needs to be further analyzed [10]. Using our simulations of the mean anomaly of the planets over three hundred days shown in figure 12, we can see that although the ratio between the periods of GJ 163 b and c is 2.97, there is no evidence of resonance in its mean anomaly, which matches with the dynamical analysis performed by Bonfils et al.; also although the plot of GJ 163 d presents a pattern of how the mean anomaly changes, the ΔM over three hundred days is only about 0.043 degrees. When we performed a simulation of the system (specifically looking at the semi-major axis) over 1000 years, the system was able to remain stable as the largest change in a planet’s semi-major axis was only around 0.002% of the planet’s semi-major axis.
Figure 12. This shows the change in mean anomaly of GJ 163 over the period of 300 days in degrees.

The mean anomaly deviations demonstrated with our simulations are also found in transit timing variations, which have also been used to detect exoplanets (Table 3). In certain systems, the period of time between the occurrence of transits does not remain constant, which is observational evidence of the shift of the mean anomaly of a planet, one possible explanation of this may be the existence of an external force interfering with the planet’s orbit (Fig 13). This force may be from an unconfirmed planet however it likely needs to have other observational evidence for it to be confirmed.

Table 3. GJ 163. see table 1

| Planet | a  | e  | p  | g  | I  | ∆M          | ∆a/a          |
|--------|----|----|----|----|----|--------------|---------------|
|        |    |    |    |    |    |              |               |
| b      | 0.06 | 0.073 | 8.63 | 70.7 | 0 | 1.745 | 2.778*10^-5 |
| c      | 0.1254 | 0.099 | 25.63 | 227.1 | 0 | 0.0781 | 6.08*10^-4  |
| d      | 1.03 | 0.373 | 603.95 | 118.3 | 0 | 0.0437 | 1.394*10^-11|

Figure 13. Standard deviation for the mean anomaly for each planet in the ten systems. The color for each lettered planet is the same across all systems.

4. Conclusion

Using the simulations, we specifically examined how in compact planetary systems, the perturbed orbits of certain planets give rise to an unstable environment for their possible inhabitants. In Trappist-1 we found habitable planets d, e, f, and g to deviate by 20.106, 1.539, 7.950 and 2.249 degrees each in terms of their mean anomaly and although the most perturbed are not habitable as they cannot contain liquid water, inhabitants of the habitable planet can often observe those planets’ orbits as we observe the other planets in our solar system. In Kepler 186, we found the average of the deviations in terms of mean anomaly for all the known planets in the system was 26.09 degrees. The habitable planet Kepler 186 f, which has the largest orbital period in the system of 129.9 days, is minimally perturbed, partly because of its great distance to the other planets; however as observers view the other planets in the Kepler 186, they would be able to pick up on the irregular orbital periods of the other planets, such as Kepler 186d, which has a ∆M of around 43.33 degrees over 300 days, and to an observer on Kepler 186f, it would appear as a complicated system that doesn’t follow something like Newton’s universal law of gravity.
In GJ 163, we found the average of the deviations in terms of mean anomaly for the confirmed planets in the system was 0.622 degrees. Although in comparison to other systems, this value appears to be much smaller, the planets are in a compact system, especially GJ 163 b, which has a period of 8.6 days, the seemingly small deviations in mean anomaly will still lead to a change in its orbit. With the analysis of the three systems, out of the ten which we performed the simulation on, we found significant deviations in terms of their mean anomalies. Astronomers on Earth, like Kepler, used observations of other planet’s orbits in the solar system to make conclusions which then led Newton to the universal law of gravitation as he attempted to explain the observations; however for the compact systems like Trappist-1, observers from the habitable planets will only be able to record perturbed orbits of the other planets in the system, which do not directly demonstrate the relationship between mass and force as Newton’s law of universal gravitation does. An understanding of the law would be the basis of all space exploration attempts, as to launch an object out of Earth, the role played by Gravity must be understood; however in the compact systems seen above, it may be difficult to understand NLUG because of the naturally perturbed orbits, which would then slow the process of exploring the world outside of the planet, providing one of many possible explanations to the Fermi paradox. Further developments in detection of exoplanets can provide a new perspective and understanding of the fermi paradox as they will allow deeper interpretations of the possible habitats for extraterrestrials and whether their absence in the solar system can be attributed to their environment or other factors.

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