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On the Detection, Frequency, and Habitability Free-Floating Exoplanets

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1. INTRODUCTION

Free-floating, unbound, or rogue exoplanets are those which have been separated from their parent star and are thus no longer gravitationally bound within a planetary system. Such planets symbolize a significant departure from usual understandings about the environment and evolution of exoplanets in our Universe. While we often consider planetary systems to be largely self-contained and self-influencing, free-floating planets lead us to understand that planetary systems participate in active exchanges with their surrounding environment. Thus, the study of unbound planets helps us to understand not only their own intrinsic properties, but also the dynamical circumstances that lead to planetary unbinding.

Free-floating planets are typically thought to have formed in protoplanetary disks, alongside their bound counterparts (Mroz et al. 2019). Following formation, disruptive events destabilize the orbits of free-floating planets, ejecting them from their parent stars and giving them their name. Such disruptions may originate both within the planetary system and from the surrounding environment. For example, dynamical interactions between planets or post-main-sequence evolution of a parent star may sufficiently destabilize the orbit of a free-floating planet to launch its separation. Similarly, stellar flybys or dynamical interactions within a star cluster may disrupt an entire planetary system, thus initiating a subsequent planetary ejection (Mroz et al. 2019).

Planet formation theory predicts that the majority of free-floating planets to have relatively low masses, on the order of Earth's (Ma et al. 2016). Intuitively, a lower-mass planet would have a relatively small escape velocity, and thus separate more readily from the gravitational potential of its host star. However, due to the detection limit of our observations, the majority of observed free-floating planets to have masses on the order of a couple Jupiter masses.

What about their composition, velocity dispersion, etc.? How many free-floating planets have been detected so far?

In Section 2, I will introduce the methodology by which we detect free-floating planets. Section 3 will discuss the wide-ranging results regarding the frequency of free-floating planets as compared to main-sequence stars. I will explore speculations regarding the habitability of unbound planets in Section 4. Finally, in Section 5 I will offer conclusions from all of these topics, as well as a road forward for free-floating exoplanet research.

2. DETECTION

When it comes to observing free-floating planets, the large majority of historically-successful methods of planet detection fall short. Methods such as planet transit measurement, stellar radial velocity measurement, stellar astrometric displacement, and direct imaging have catapulted exoplanet detection over the past decades (Perryman 2000). All of these methods, however, rely on either the presence of a host star — transit, radial velocity, astrometry — or an intrinsic planet luminosity — direct imaging — on which to based their observations. Free-floating planets lack both of these vital characteristics. By definition, they are unbound from a host star and typically too dim for direct detection. Therefore, to observe free-floating planets we require a method which relies on alternative planet characteristics (Han et. al. 2004).

With microlensing, successful detection depends only on an object's mass. As an object - in this case a free-floating planet - passes through our line of sight to a bright background source, the light from the source temporarily magnifies around the planetary lens. We indirectly observe the planetary lens based on the observable characteristics of this magnified light, and the degree to which the light fluctuates only depends on the lens mass. Therefore, microlensing enables us to detect free-floating planets as they intermittently intercept our line of sight toward various background sources throughout their trajectory.

As with all detection methods, microlensing introduces challenges that influence our detection capability. Furthermore, free-floating planets are particularly difficult to observe. The source of this difficulty is four-fold: a) free-floating planet detections are unpredictable, b) the observable characteristics directly related to free-floating planet physical properties are wrought with degeneracies, c) detection events are fleeting, and d) follow-up observations are effectively impossible (Han et. al. 2004).

As described above, our only possibility for observing free-floating exoplanets occurs when they happen to pass between us and a background source. Therefore, we may estimate that such events occur regularly, but we are nonetheless powerless to predict their exact timing and location. To alleviate this challenge, we rely on high-cadence wide-field surveys to optimize our potential for catching unpredictable microlensing events. Within the past decade, observations of free-floating planets have been lead by the Optical Gravitational Lensing Experiment (OGLE), Korea Microlensing Telescope Network (KMTNet), and the Microlensing Observations in Astrophysics (MOA) group with the Mt. John University Observatory. **What properties of these telescopes have lead them to champion exoplanet microlensing detections? What are their cadences, field sizes, detection limits, etc.?**

The primary physical property that confirms observation of a free-floating planet is its mass. More specifically, the mass of a lens differentiates the signal produced by a free-floating planet from that of a brown dwarf or a low-mass star. To determine the mass of a lensing object, we require three observable characteristics: the Einstein timescale (t_E) defining the duration of the microlensing event, the angular Einstein ring radius (θ_E) characterizing the size of the microlensing signal, and the projected Einstein radius onto the plane of the observer ($\tilde{r}_E$) (Figure 1). These observables are explicitly related to mass in Equations 1 and 2 (Han et. al. 2004), where μ_{rel} defines the relative proper motion between lens and source and π_{rel} defines their relative parallax.

$$t_E = \frac{\theta_E}{\mu_{rel}}, \quad \theta_E = \sqrt{\frac{4GM\pi_{rel}}{c^2\text{AU}}}, \quad \tilde{r}_E = \sqrt{\frac{4GM\ \text{AU}}{c^2\pi_{rel}}} \quad (1)$$

$$M = \frac{c^2}{4G}\theta_E\tilde{r}_E \quad (2)$$

From among the given equations, t_E is the most simplistic property to measure; however, t_E includes a degeneracy between the lens mass, relative lens-source proper motion, and relative lens-source parallax (otherwise parameterized as lens mass, lens-source distance, and lens-source relative velocity). In other words, when we observe a short-duration microlensing event, we cannot initially determine whether the signal comes from a free-floating planet or a more massive object with either an exceptionally small Einstein radius or exceptionally high relative proper motion. To make this determination, we must further observe θ_E and $\tilde{r}_E$, both of which are quite challenging to obtain (Han et. al. 2004).

In brief, observations of θ_E and $\tilde{r}_E$ introduce both instrumental challenges and compounded degeneracies.

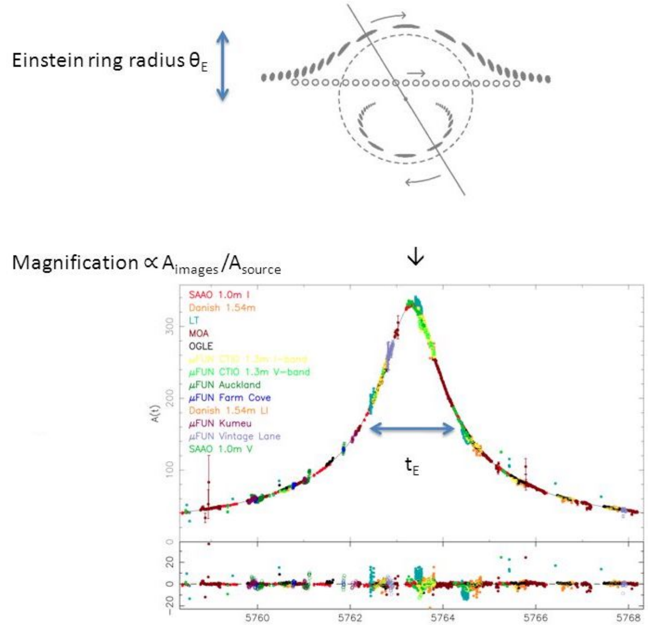

Figure 1. Top: Image illustrating the trajectory of light during a microlensing event. **Bottom:** Light curve relating the illustrated light trajectory to an observable time series.

To measure an object's parallax, an input values for θ_E, one must observe a celestial object from two different physical locations. Due to the brevity of microlensing events and the distance at which they occur, the required observation calls for synced space- and ground-based high-cadence wide-field surveys. Such an arrangement not only presents enormous technical challenges, but also introduces yet another degeneracy regarding the lens-source separation. The solution to the compounded degeneracy - introducing a second synced satellite - is prohibitively complex (Han et. al. 2004). Therefore, theoretical models of microlensing events have become crucial for determining lens properties.

By optimizing theoretical models over the observable parameters related to θ_E and $\tilde{r}_E$, we offer our best guess as to their physical values. Illustrated in Equation 3, the mathematics governing microlensing models are remarkably simple. They relate the Einstein timescale (t_E), the time of maximum lens magnification (t_0), and the impact parameter between lens and source (u_0) which directly relates to the lens magnification amplitude (A):

$$A = \frac{u^2+2}{u\sqrt{u^2+4}}, \quad u = u_0 + \frac{t-t_0}{t_E} \quad (3)$$

In the above equation, u represents the angular separation between lens and source, normalized by the Einstein radius (θ_E). MulensModel (Poleski & Yee 2019) is a Python package for modelling microlensing events. Figure 2 demonstrates MulensModel in action, modeling a microlensing event observed by OGLE in 2016 (Shvartzvald et. al. 2017).

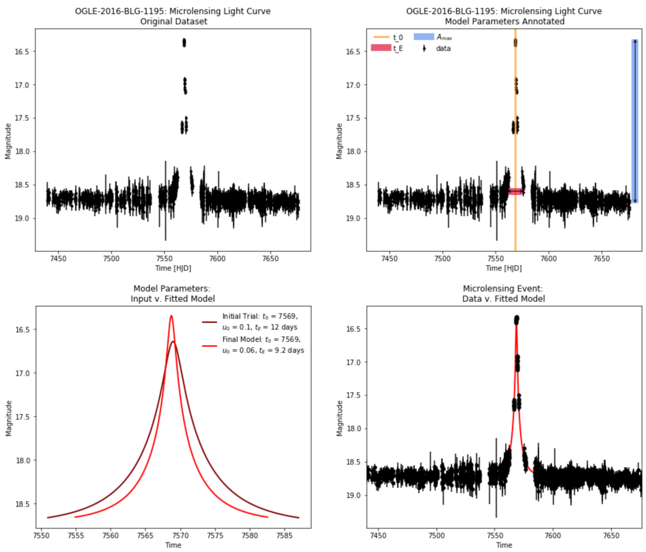

Figure 2. A demonstration of the microlensing modelling package MulensModel (Poleski & Yee 2019). **a.** Data for OGLE-2016-BLG-1195 microlensing event (Shvartzvald et. al. 2017). **b.** An illustration of the input parameters for microlensing models. **c.** Results from the microlensing model given initial and optimized input parameters. **d.** A comparison between the modelled light curve and observations of the microlensing event.

As observed in the above example, microlensing events caused by free-floating planets are fleeting, lasting only a couple of days. Equation 1 generally relates the timescale of a microlensing event to the lens mass as $t_E \sim \sqrt{M/M_J}$ days. This equation is only proportional, as degeneracies may contribute to short-duration microlensing events unrelated to lens mass (e.g. due to high velocity planets, close lens-mass distances). However, given an environment such as the Galactic Bulge, we expect massive objects to reflect the spatial and velocity distributions measured for the Bulge stellar population. Therefore, as the Einstein timescale of a microlensing event decreases, the likelihood that the lensing object is a free-floating planet increases because the probability that the lens maintains a increasingly high velocity goes to zero. The cursory nature of free-floating planet observations alone makes their observation difficult, and requires observation cadences of ideally several visits per hour (Han et. al. 2004). **Relate the necessary observational cadence back to the leading telescopes that are used in microlensing surveys.**

Finally, follow-up observations of microlensing events are virtually impossible, meaning that confirmation of a free-floating planet can only be achieved through comparison with observations of other microlensing events and statistical probabilities.

Discuss the prospects for free-floating planet detection in the upcoming decade(s), particularly with WFIRST and Euclid. In particular, Deacon (2018) introduces an intriguing method of detecting free-floating exoplanets through a water-dependent color term borne out of synergies between WFIRST / Euclid and ground-based surveys. See also the following white papers from the 2020 Decadal Survey: Gaudi et. al. 2019, Yee et. al. 2019.

3. FREQUENCY

In the wake of every major discovery, we want to know whether our observation was an anomaly or commonplace, the exception or the rule. Understanding of the frequency of free-floating planets helps answer this question, shedding light on the volatility of planetary systems and guiding future searches for habitable planets (particularly if planet ejection proves to be a common stage in planetary evolution).

A pioneering study by Sumi et. al. sparked controversy in the quest to understand free-floating planet frequency. Using observations from both the MOA and OGLE groups, Sumi et. al. (2011) estimate a mass function for microlensing objects based on characteristic Einstein timescales. In Section 2 we discussed how as the timescale of a microlensing event decreases, the probability that the event was caused by a planet increases because we expect lens velocities to conform to the velocity dispersion of their environment (in this case, the Galactic Bulge). Therefore, Sumi et. al. (2011) reasonably assume that microlensing events with timescales of $t_E < 2$ days were caused by planets. Although the authors do not explicitly differentiate between free-floating and wide-orbit planets among the sample of planetary lenses, they do note the lack of detection of a host star within 10 AU of any planetary microlensing events. Further observations from direct imaging confirm that the majority of these planets are likely to be unbound.

By first observing the distribution of lensing events with $0.3 < t_E < 200$ days, then fitting this distribution to a series of power-law and log-normal distribution functions, Sumi et. al. (2011) find the frequency of unbound planets to be about 1.8 times that of main-sequence stars (Figure 3). This result is significant, because it implies that planet ejections are remarkably common; we expect every planetary system to to eject a planet throughout its evolution, on average.

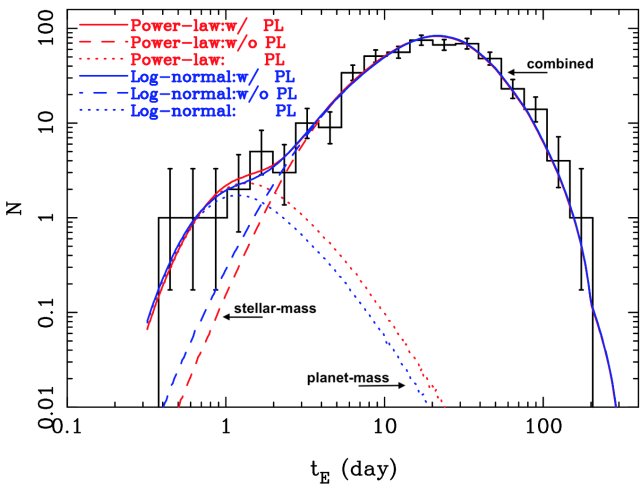

Figure 3. Observed histogram (black) and theoretical mass functions (red, blue) for microlensing objects observed by MOA and OGLE. Red and blue lines indicate mass functions fit to a power-law and log-normal distributions, respectively. Dotted and dashed lines indicate the frequency of microlensing events due to free-floating planets and more massive objects, respectively. Solid lines represent the total mass function for all objects within the given sample. Frequency (N) is normalized by number of main-sequence stars. Figure 3 reveals the frequency of free-floating planets to be roughly twice that of main-sequence stars.

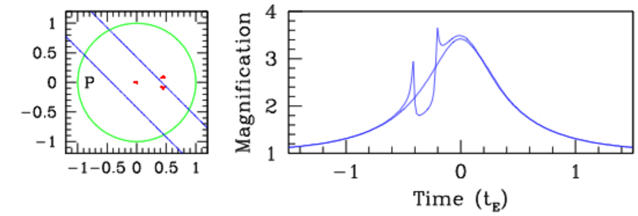

Figure 4. Left: An illustration of the Einstein ring for a lensing event (green) encasing two possible background source light trajectories (blue), one passing through planetary caustics (red) and one missing the caustic zones. **Right:** The resulting light curves from the two given trajectories. The trajectory of light that intercepts planetary caustics reveals sharp distortions from an otherwise smooth microlensing signal.

Following the Sumi et. al. (2011) publication, Clanton & Gaudi (2016) attempt to distinguish between free-floating and wide-orbit planets among the Sumi et. al. (2011) population of planetary lenses. They do so by combining the Sumi et. al. (2011) mass function with a planet population model that includes wide-spread, bound planets (Clanton & Gaudi 2016). They then compare this combined stellar and planetary population model to the observed timescale distribution function (Figure 3) in order to determine the frequency of planetary lenses that can be explained by wide-orbit planets. The difference in these values indirectly determines the frequency of free-floating planets.

(Clanton & Gaudi 2016) also statistically identify a selection of wide-orbit planets by identifying observable tracers of planet-star binary lenses. They identify such evidence of binaries as either a) a long-duration, low-magnitude bump in the light curve due to additional microlensing magnification by the host star or b) sharp distortions of the light curve due to planetary caustics - "sweet spots" in the gravitational field of the combined planet-star system at which the magnification of a point source goes to infinity [Han & Kang (2003), Mao & Paczynski (1991)] (Figure 4).

I find it curious that the (Clanton & Gaudi 2016) selection of observable wide-orbit planets was calculated statistically. I would like to learn more about why they didn't simply look through the MOA and OGLE data directly to determine this selection.

Clanton & Gaudi (2016) find that some of the excess planetary lenses noted by Sumi et. al. (2011) are bound, wide-orbit planets; however, they confirm (if adjust) the former result, estimating the frequency of free-floating exoplanets to be roughly 1.5 times that of main-sequence stars.

Mroz et al. (2017) directly oppose the findings of Sumi et. al. (2011) and Clanton & Gaudi (2016), observing the ratio of free-floating planets to main-sequence stars to be about one half. They assert that the previous results conflicted with both surveys of young stars and theoretical models of planetary evolution. They observe no excess of planetary lenses for $t_E < 2$ days (Figure 5). I am curious about what the results from Mroz et al. (2017) imply for planetary evolution.

4. HABITABILITY

In the study of exoplanet formation and evolution, all roads lead to habitability. The potential discovery of life on other planets is too alluring to miss any opportunity in looking for it. In the following analyses, we define "habitable" traditionally, referring to any planet that is able to support liquid water on its surface (Kasting et. al. 1993).

The limitations of habitability on free-floating planets primarily revolve around their potential source of energy. On Earth, all organisms depend on a continuous energy source - either the Sun or geothermal heating from Earth's core - to sustain life. When separated

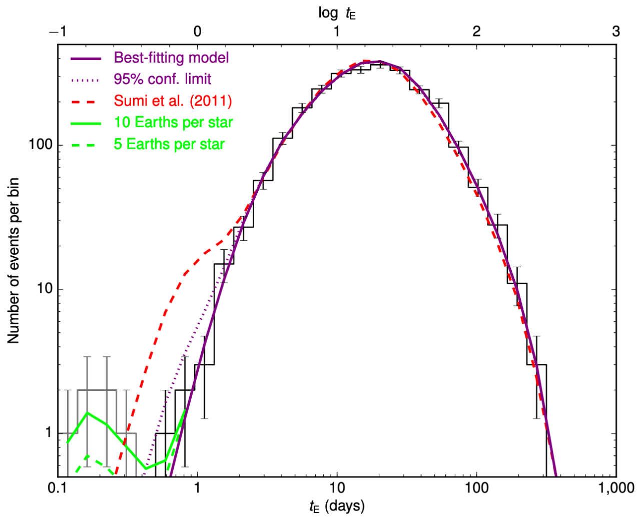

Figure 5. Observed histogram (black) and theoretical mass function (purple) for ∼2,500 objects observed by OGLE. These results directly conflict with the intial study by Sumi et. al. (2011).

from their parent stars, free-floating planets lose a vital sources of energy. Therefore, in order to investigate the habitability of unbound planets, we must estimate the probability that they a) maintain life-supporting oceans and core temperatures and b) encounter external sources of energy throughout their trajectories.

Abbott & Switzer (2011) explore the former case in an analysis of "Steppenwolf" planets, or Earth-like, free-floating planets that harbor subglacial oceans. The authors define "Earth-like" to signify free-floating planets within an order of magnitude of Earth mass and water complement, a similar composition of radioactive nuclides, and an age close to Earth's.

To qualify as a Steppenwolf planet, a free-floating planet must maintain a high enough temperature to prevent the entirety of its water complement from freezing. Without a consistent source of external heat, the presence or absence of subglacial oceans balances on the planet's internal geothermal heat flux. The time span within which a free-floating planet may harbor life is therefore dependent on a) the half-life of its supply of radionuclides, and b) the decay of radiation due to its heat of formation. Higher-mass planets hold greater potential for maintaining lingering geothermal heat from formation; however, as planet mass increases, high-mass planets quickly fall short of our perception of "Earth-like". Therefore, Abbott & Switzer (2011) consider insulating phenomena which may ensure a liquid subglacial ocean despite low planetary masses. Such phenomena include layers of frozen gas, atomic contaminants that lower the melting point of water, and a range of planetary radionuclide compositions and water complements.

Abbott & Switzer (2011) summarize their findings in Figure 6, in which they relate the necessary planet mass to maintain liquid subglacial oceans given a particular pair of ice and ocean thickness.

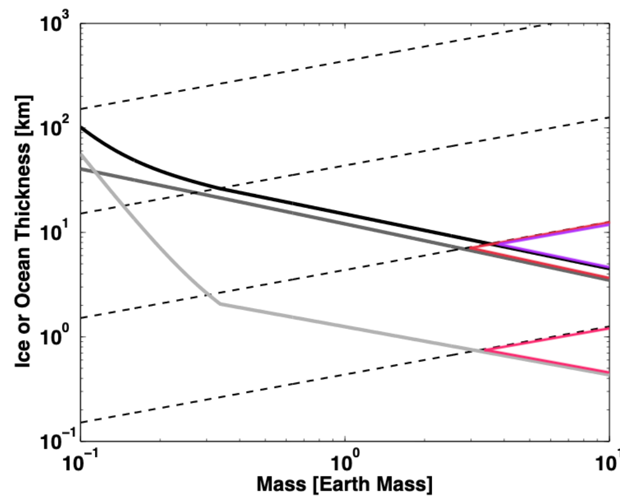

Figure 6. Illustration of the required planet mass to maintain a liquid subglacial ocean given constraints on the ice and ocean thickness. Solid lines represent various models of ice thickness assuming a range of water complement melting points and convection processes. Dotted lines represent ocean thickness. A planet is thought to achieve a subglacial ocean when its ocean thickness exceeds its ice thickness (colored in purple, red, and pink for the various models).

Di Stefano & Ray (2016) explore the latter possibility for free-floating planet habitability: the interception of external heat sources throughout the trajectory of a free-floating planet. They define what they refer to as the "globular cluster opportunity", or the unique combination of stellar density, stellar age, quiescence (absence of star formation), and orbital stability that may offer a consistent source of energy for ambient free-floating planets. They pose that such an environment may be sufficient to support life on free-floating planets that have become bound within the globular cluster.

Di Stefano & Ray (2016) find that there are large regions within globular clusters that may support stable habitable-zone orbits in which planets could remain long-term.

How will future observations inform our understanding of habitability on free-floating planets?

5. CONCLUSIONS

What are the leading methods for detecting exoplanets, and what challenges do they pose?

What have previous studies of free-floating exoplanets determined about their frequency, and what promise do future surveys hold?

How do we connect theoretical speculation regarding the habitability of free-floating planets to tangible observables in the upcoming decade(s)?

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