Rogue Planets

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1 Introduction

Rogue planets are solitary wanderers of the cosmos, not bound to any star. Unlike the planets featured in science fiction, which often orbit within elaborate multi-star systems, rogue planets wander the cosmos alone. Imagine life in such isolated worlds, far from the interactions of any neighbors nearby.

In this paper, I will explore the formation, observation, and potential destinies of rogue planets. I will discuss various theories regarding their origins and describe the distance characteristics associated with each type. Next, I will cover the mechanisms behind the two primary methods of observing rogue planets, gravitational microlensing and direct imaging, and share the findings so far. Finally, I will share a very interesting study simulating the interactions between a rogue planet and another planetary system.

2 Formation

Rogue planets, also known as free-floating planets or isolated planetary-mass objects (iPMO), are planet-sized astronomical objects that are not gravitationally bound to any stars.

To qualify as a rogue planet, an object just needs to have planetary mass. Therefore, rogue planets can have very different origins. Most rogue planets are formed by the collapse of gas clouds (star-like) or ejected from an ordinary planetary system (planet-like).

2.1 Star-like

Some rogue planets are formed similarly to stars. In the star-forming regions, gas clouds collapse due to gravitational attraction between the molecules. However, if the mass of the star is below the limiting mass of deuterium fusion (about 13 M_J)[1]. Because there is no nuclear fusion producing energy, the sub-brown dwarfs will gradually cool down. Despite not qualifying as planets, these stars are relatively massive "planets", around 1 M_J.

2.2 Planet-like

Other rogue planets are ejected from ordinary planetary systems. During the early stages of the planetary system formation, they are ejected from the protoplanetary disk by gravitational interactions. This is common, especially for higher-massed host stars and multibody systems, where gravity is strong or unpredictable. A simulation showed that 17.5% of the $1M_\odot$ stars eject rogue planets of a total mass of $19.8M_E$ and a median mass of $0.8M_E$ to space.[5] These ejected rogue planets are typically low in mass, around $1M_E$.

3 Observation

Unlike stars, rogue planets do not emit light themselves. They cannot be directly observed. There are two techniques to observe rogue planets: gravitational microlensing and direct imaging

3.1 Gravitational Microlensing

From general relativity, objects with mass cause a curvature in space-time. This curvature affects the trajectory of light passing near the object, bending it similarly to how a lens bends light. As in Figure 1, to observers on the earth, this bending of light makes it appear as though the light is emanating from different directions, creating multiple images of the source.

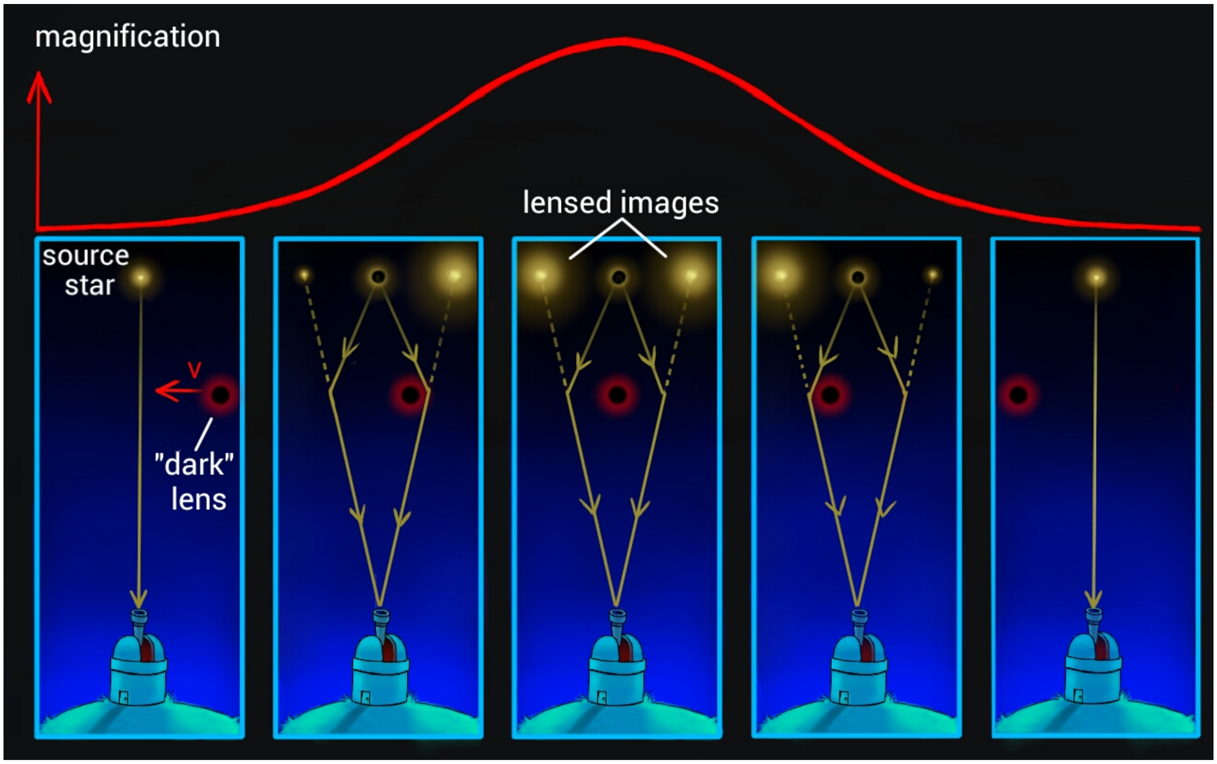

Figure 1: Gravitational lensing. The "dark" lens is the rogue planet. [8]

If the source, lens, and observer are aligned collinearly, the images will combine into a ring called the Einstein ring, as in Figure 2.

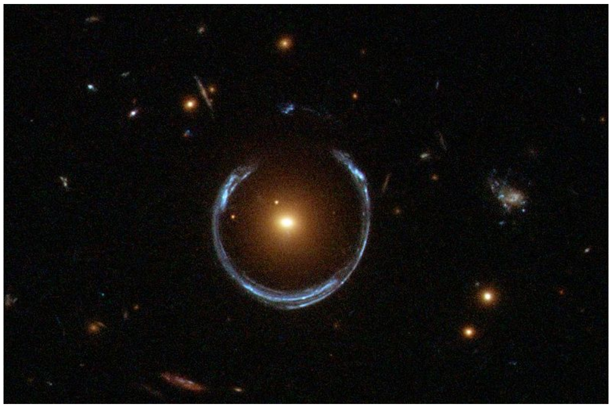

Figure 2: Example of an Einstein ring taken from Hubble[7].

It can be shown that the angular radius of the Einstein ring θ is given by

$$\theta = \sqrt{\frac{4GM}{c^2}\frac{D_S - D_L}{D_S - D_L}}, [2] \tag{1}$$

where M is the mass of the lens (rogue planet), D_S is the distance between the observer and the light source, D_L is the distance between the observer and the lens, and G is the gravitational constant.

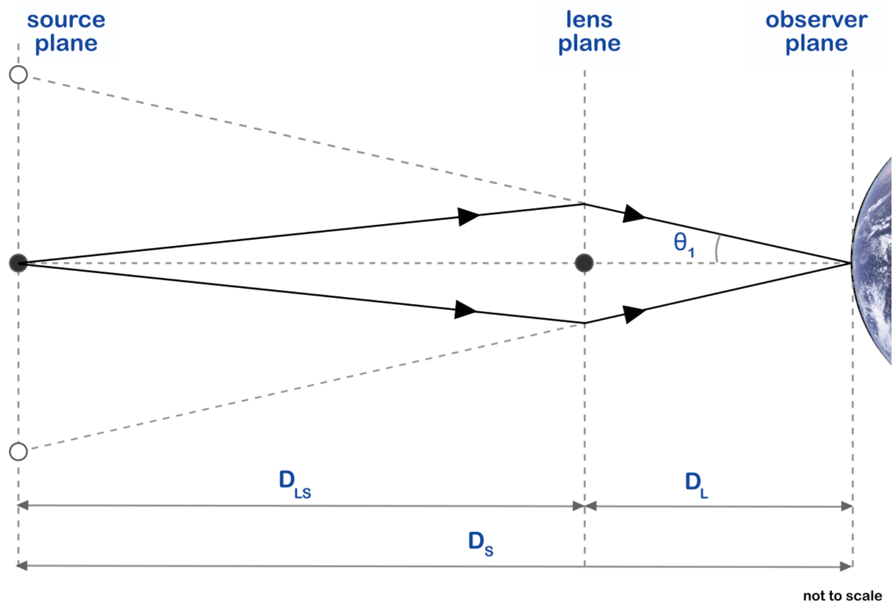

Figure 3: The geometry of a symmetrical Einstein ring. D_{LS} denotes the distance between the lens and the source, and θ_1 denotes the angular radius of the Einstein ring.

Let us evaluate some numbers. Take $M = M_J$, $D_S = 8000\,\text{Mpc}$, and $D_L = 4000\,\text{Mpc}$, we get $\theta = 31\mu\text{arcsec}$. Typical earth-based telescopes have resolutions of around 0.4 arcsecond, which is way larger. Because M for rogue planets is usually very small, the Einstein ring is not resolvable.

However, during a microlensing event, the observer will see multiple images concentrated closely. This leads to an intensity amplification of the observed image. The amplification factor A is given by the formula

$$A = \left|\frac{u^2 + 2}{u\sqrt{u^2 + 4}}\right|, [9] \tag{2}$$

where $u = \frac{b}{D_L \theta}$. b is the distance between the lens and the original light path, and θ is the angular radius of the Einstein ring defined above.

In Figure 4, I plotted A vs. u as in Equation (2).

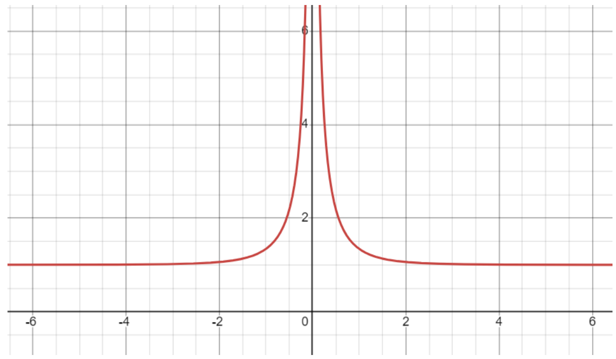

Figure 4: Graph of A vs. u.

As $u \to 0$, $A \approx \frac{2}{x\sqrt{4}} = \frac{1}{x}$. The A behaves like an inverse function that approaches infinity.

As $u \to \infty$, $A \approx \frac{u^2}{u\sqrt{u^2}} = 1$. The amplification factor will never go below 1 for positive u.

In reality, the source, lens, and observer will not align perfectly, so b will not be exactly 0. Typically, the A can reach 100. Consider the relation between the amplification factor and time. As the rogue planet traverses closer to the light path, there will be a peak in A. The whole microlensing event, where amplification is observed, typically lasts a few days to a few months[9], depending on the speed of the traversing planet.

Figure 5 shows a typical Amplitude vs. time graph of a microlensing event of star OGLE-2005-BLG-006. The time period t_E is approximately 150 days, and the intensity of the star is magnified approximately by 1.3 orders of magnitude.

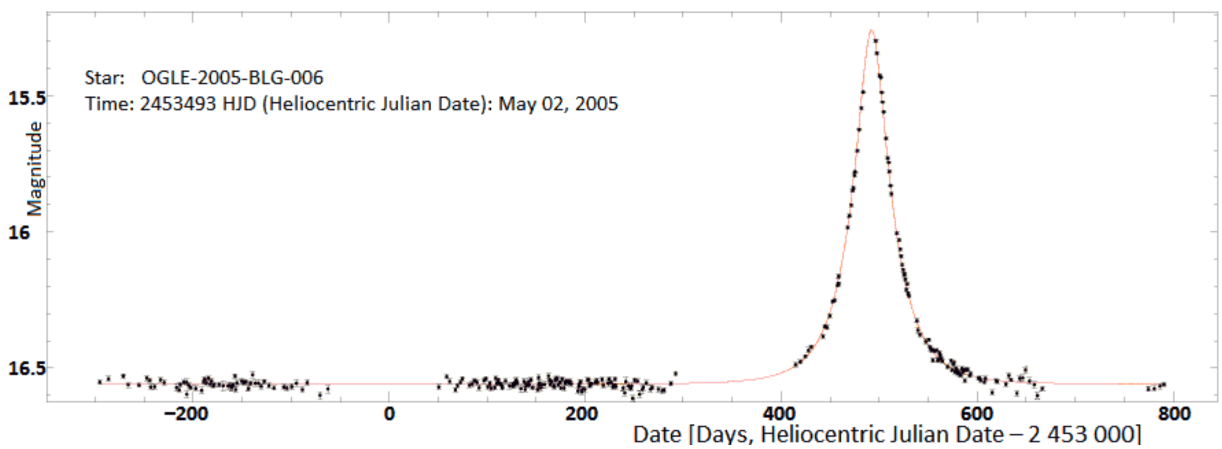

Figure 5: Example light curve of gravitational microlensing event - OGLE-2005-BLG-006 [10]

3.2 Direct Imaging

Microlensing requires the light source, the planet, and the earth to be somewhat aligned perfectly, which is not very common.

Another approach is direct imaging. Typically, planets are very faint light sources. However, hot, newly formed planets can be detected through their thermal emissions. The mass of the planet can be estimated from its luminosity and age. Due to temperature constraints, the majority of rogue planets identified through direct imaging are found in young star clusters. They are generally hot, massive, and close to the sun.

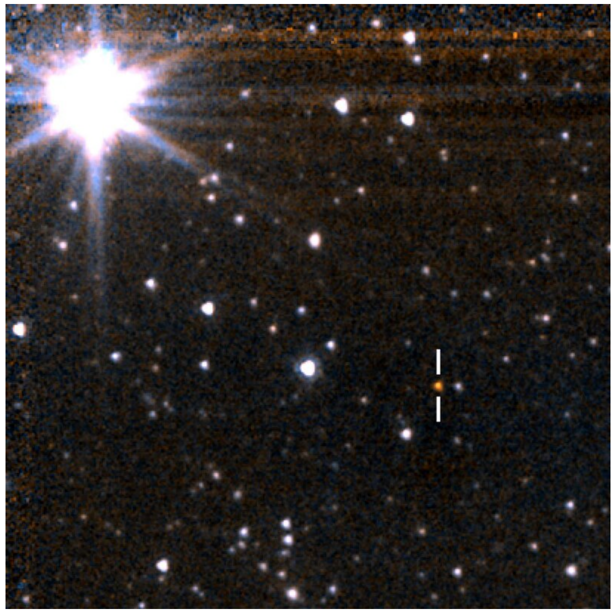

Figure 6: WISE J0830+2837 (marked orange) observed with the Spitzer Space Telescope. Its surface temperature is 300-350 K.[3]

3.3 Results

Many planetary-massed objects have been detected by direct imaging, but most are too close to a star to be considered as isolated The first rogue planet was discovered in 1998 via direct imaging. By the 2010s, a small but growing group of candidates had been discovered via gravitational microlensing. By now, around 40 rogue planets have been discovered through direct imaging and 10 through microlensing.

In 2011, a group of astrophysicists published studies from observing 50 million stars in the Milky Way. They found 474 incidents of gravitational microlensing, ten of which were brief enough to be planets of around Jupiter's size with no associated star in their vicinity.[11]

The smallest rogue planet detected through microlensing, OGLE-2016-BLG-1928, has the size of around the earth. It was discovered in September 2020. Its microlensing event has a timescale t_E of approximately 0.0288 days or 41.5 minutes and an Einstein radius $\theta_E = 0.842 \pm 0.064\mu$arcsec. [6]

Although only a few have been observed, surveys of these bodies allow researchers to estimate their abundance. It is estimated that two Jupiter-massed rogue planets exist for every star in our galaxy. This suggests a vast population of such free-floating planets, but due to the limitations of our observation, most remain unseen.

4 Fate

What will be the fate of rogue planets? Will they drift forever in space, become captured by another star, or even crash into it? Given the emptiness of the universe, most rogue planets will likely roam the vastness of interstellar space indefinitely. However, some may occasionally interact with a star, or even a planetary system.

A study from Goulinski and Ribak in 2017[4] numerically simulated the three-body interaction of a rogue planet with a star that hosts a single planet in a circular orbit.

Their setup is shown in Figure 7. A bound planet of mass m_B orbits a star of mass M at a radius r_B, while a rogue planet of mass m_f approaches at an angle θ_i relative to the planetary orbit, with an impact parameter described by $d = \sqrt{a^2 + b^2}$.

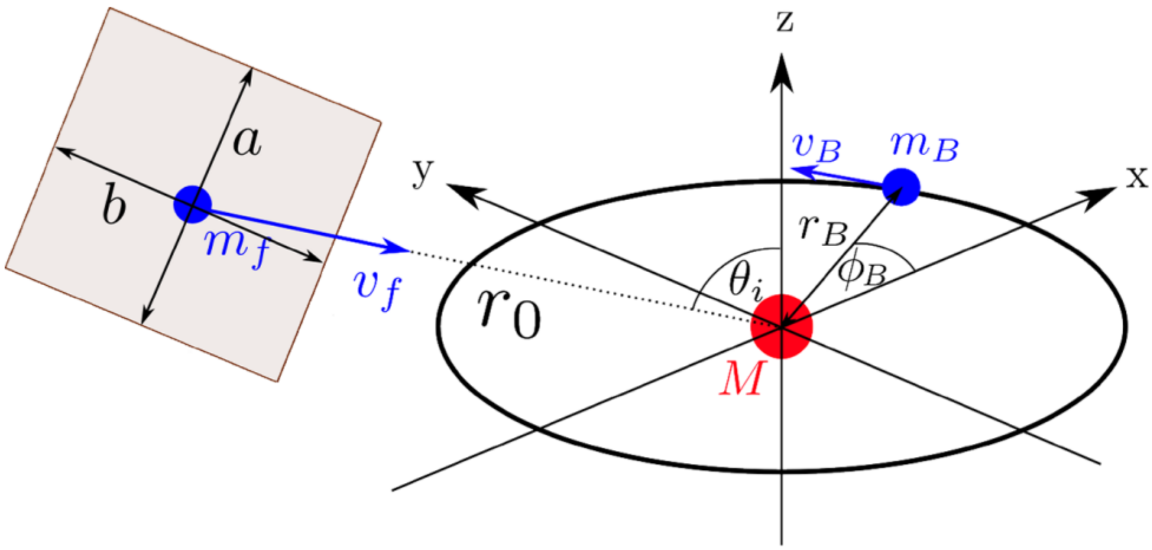

Figure 7: Schematic diagram of the simulation

They first simulated a Jupiter-mass rogue planet approaching with $v_{f\infty} = 0$ and $\theta_i = 90$ (in the plane of the bound planet). Different initial values of impact parameter b and bound planet phase angle ϕ were given. Based on the final kinetic and potential energies E of the bodies, the outcomes of each simulation were classified into three scenarios shown in Figure 8:

- Capture: $E_f < 0, E_B < 0$. The rogue planet is captured into an orbit around the star.
- Flyby: $E_f \geq 0, E_B < 0$. The rogue planet is temporarily attracted by the star but ultimately flies away.
- Exchange: $E_f \geq 0, E_B < 0$. The rogue planet displaces the bound planet, taking its place.

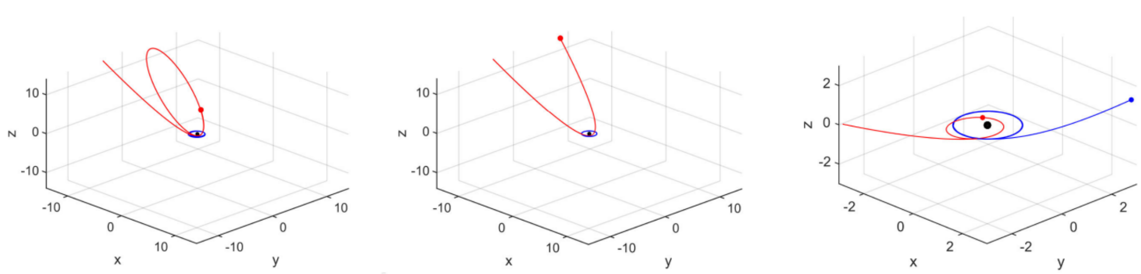

Figure 8: The three outcomes: capture, flyby, and exchange.

The capture or flyby cases are

Figure 9 illustrates the grid of results under different b and ϕ_B parameters. The probabilities of capture and flyby are approximately 50%, while exchanges are exceedingly rare.

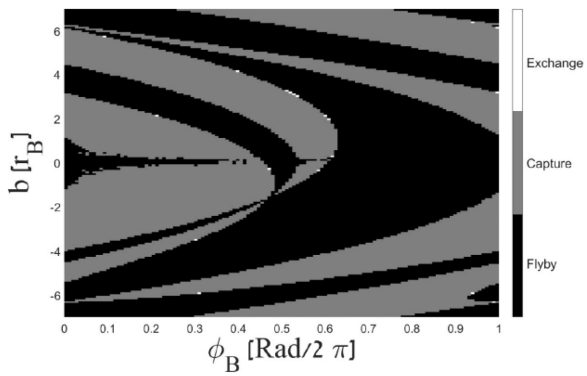

Figure 9: Outcome map. Simulated with $m_f = M_J$, $v_{f\infty} = 0$, and $\theta_i = 90°$

The result above was simulated with $v_f = 0$ at infinitely far away. The higher the initial velocity $v_{f\infty}$, and therefore the higher the initial energy, of the rogue planet, the more likely it will fly by the star instead of being captured, and vice versa.

An encounter with a rogue planet could be indicated by the misalignment of the planet's orbital axis with the star's spin axis. Planetary systems generally inherit their angular momentum from the protostellar disc, which aligns the spin axis of the star with the orbits of its planets. If a rogue planet is captured, it also often settles into a highly eccentric orbit. Misaligned orbits could hint at past interactions with free-floating planets.

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