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Microlensing: Exploring the Dark Corners of the Galaxy with a Thousand Tiny Flashlights

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In microlensing, the light from a background source star is bent by the gravitational potential of an intervening lens. The resulting light curve reveals the nature of the lens. Because no light from the lens itself is necessary to make this measurement, microlensing is able to probe both faint and dark objects, including distant planetary systems and black holes. The advent of high-cadence, wide-field microlensing surveys and the first microlensing programs in space have revolutionized the field and opened new areas of investigation including the search for dark binaries and understanding planet occurrence in different Galactic environments. I will review recent results from these programs and their potential to help us understand Galactic structure.

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1. Introduction

1.1 Essentials of Microlensing

Microlensing is the gravitational lensing of one star's light by another star. At least this is how it was originally conceived by Einstein in his 1936 paper "Lens-like Action of a Star by the Deviation of Light in a Gravitational Field" [1]. This is a good starting point for understanding microlensing, but as we will see, microlensing encompasses far more than just stars[1].

Einstein (1936) provides a simple description of microlensing. First, if two stars at arbitrary distances are perfectly aligned along the line of sight, the light from the background star will appear as a ring with radius

$$\theta_{\rm E} = \sqrt{\kappa M_{\rm L} \pi_{\rm rel}} \quad \text{where} \quad \pi_{\rm rel} = \frac{\rm AU}{D_{\rm L}} - \frac{\rm AU}{D_{\rm S}} \quad \text{and} \quad \kappa = 8.14\,{\rm mas}\,{\rm M}_{\odot}^{-1}. \tag{1.1}$$

The size of $\theta_{\rm E}$ depends on both the lens mass $M_{\rm L}$ and the distances to the lens and source, $D_{\rm L}$ and $D_{\rm S}$, respectively. Second, if the alignment is less than perfect, i.e. the stars appear ever-so-slightly displaced from each other, instead of a perfect ring the light will be split into two images, major and minor (aka large and small) located at

$$y_{\pm} = \pm\frac{1}{2}\left(u \pm \sqrt{u^2+4}\right) \tag{1.2}$$

where u is the separation between the source and lens as a fraction of the Einstein radius. Figure 1 illustrates these two images. Although the radius of the Einstein ring, and there for the separation of these two images, is too small ($\theta_{\rm E} \sim 1$ mas) to be resolved even with modern telescopes, there is still an overall magnification effect

$$A(u) = \frac{u^2+2}{u\sqrt{u^2+4}}. \tag{1.3}$$

Later papers by Tikhov (1938), Liebes (1964), and Refsdal (1964) expand the theory of microlensing [3, 4, 5][2]. In particular, they discuss how microlensing would be observed in practice. Our galaxy contains billions of stars all moving on their own individual orbits. As the Sun executes its own orbit through the Galaxy, we see the other stars moving relative to each other like cars on a highway. Sometimes those stars come into conjunction with each other, i.e. two stars at very different distances will align with each other along our line of sight. As this happens, a microlensing event occurs. The lens-source separation in Equations 1.2 and 1.3 is a function of time. As shown in Figure 1 the images therefore change as a function of u and hence as a function of time, leading to a varying magnification. The microlensing light curve is the observed change in brightness due to the lensing effect as a function of time.

1.2 Microlensing as a Type of Gravitational Lensing

Because microlensing results in multiple images of the background source, it is a subset of strong lensing. However, microlensing differs from galaxy-cluster scale lensing in one important

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[1] Also note that there is a separate branch of microlensing that studies the effects of individual stars of a galaxy lens on the images of a multiply-imaged quasar (e.g. see Section 7 of [2]).

[2] The reader is also referred to more comprehensive reviews of modern microlensing (e.g. [2, 6, 7]).

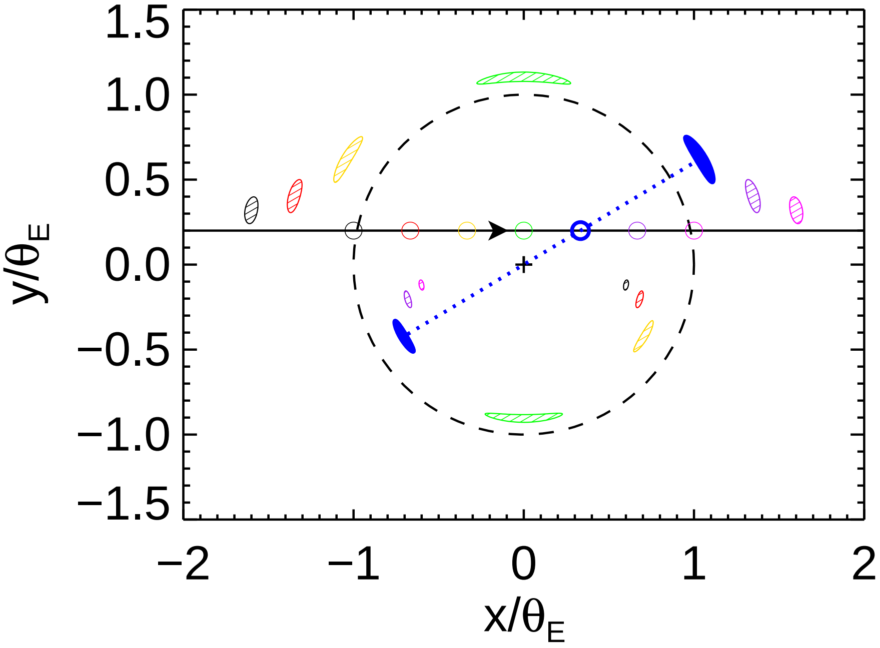

Figure 1: A face-on view of microlensing. The background source star (circle) is shown traveling from left to right relative to the lens star (+). The corresponding images of the source are also shown. The case shown in blue emphasizes that the images of the source appear along the line between the source and lens with the larger, major image just outside the Einstein ring (dashed black circle) and the smaller, minor image just inside the Einstein ring.

way. Usually, when we think of strong lensing, we think of how the gravitational lensing effect which enables us to study distant galaxies and quasars at large z by amplifying their light. This is the study of the background source, i.e. the object being imaged. In contrast, for microlensing, the interest is in the *lens*. The form of the lightcurve (and the underlying images) reflects the gravitational potential of the lens star. The goal is to reconstruct information about the lens by modeling the shape of the lightcurve. The nature of the source and details of its light are irrelevant[3]. In this sense, the source is analogous to a flashlight: it is just a tool used to study the lens.

2. Applications of Microlensing

So far we have assumed that the lens is a star, but the underlying theory depends only on the assumption that the lens is a point mass (or a collection of point masses). In fact, the very first microlensing searches were carried out not to detect microlensing with stars, but to determine whether or not Massive Compact Halo Objects could account for dark matter [11, 12, 13]. This application reflects the power of microlensing: it can detect objects regardless of their light output, including objects that do not emit light. Hence, microlensing can be used to find stellar mass black

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[3] The exception is work by Bensby et al. that took advantage of the magnification effect to take spectra of dwarf stars in the Bulge [8, 9, 10]

holes and other stellar remnants that are isolated or in wide binaries. It can also find brown dwarfs or free-floating planets.

The primary motivation of modern microlensing surveys is the search for planets orbiting the lens stars, so I will begin by discussing planetary microlensing in detail. However, on a broader scale microlensing offers a unique way to study galactic structure. Consider that microlensing is a random process depending on the motions of individual objects within the Galaxy. Then the underlying population of microlenses reflects the underlying population of the Galaxy. A complete statistical analysis of a microlensing survey has the potential to tell us about the complete mass function of the Galaxy ranging from free-floating planets all the way up to isolated black holes.

2.1 Planetary Microlensing

To first order, planetary companions to the lens star can be thought of as perturbations. The lens star is far more massive, so it will dominate the deflection of the light and hence, the microlensing light curve. However, if there is a planet near one of the images, it will further deflect the light, distorting the image and the light curve [14, 15]. Hence, the sensitivity of an individual event to planets, depends on the paths traced by the images, which in turn reflects the path of the source. Additionally, if the lens star is perfectly (or nearly perfectly) aligned with the source, such that the source is imaged into a ring, that event will be extremely sensitive to planets because such large images are easily perturbed and have complete angular coverage about the lens star [16].

An alternative way to think about microlensing is through the magnification map. We have a mathematical description for the magnification produced by a particular lens. Using Equation 1.3, we can calculate what the magnification of a source will be at any point relative to a lens star. For a point lens, this map has the basic properties of being radially symmetric, being larger with smaller u, and diverging to infinity as $u \rightarrow 0$. A planet will perturb this map as in Figure 2. To a first approximation, the strongest perturbations happen at source locations that place one of the images at the location of the planet. Along the “caustics,” the magnification will diverge to infinity. Note that there are usually two sets of caustics, the planetary and central caustics. A planetary caustic reflects a perturbation of an image created when the source is well-separated from the lens, whereas the central caustic reflects the perturbation of an exceptionally large, ring-like image created when the source is directly behind the lens star.

Any number of microlensing light curves can be created given a magnifcation map for a particular lens by tracing different paths through that map. For example the path shown in Figure 2 maps onto the light curve shown in Figure 3. The main difficulty in microlensing is reconstructing the underlying map (and lens system) based on only the light curve, which is effectively a 1D slice of a 2D map. This leads to a number of degeneracies, which may or may not be resolved by a full model. These degeneracies range from the trivial to the severe (see for example [18, 19, 20, 21]). For example, the magnification map is symmetric across the star-planet axis, meaning that two different source trajectories can give rise to the observed light curve. Whether or not this matters to the interpretation of the lens depends on the circumstances. Alternatively, sometimes the light curve can be explained by more than one lens system.

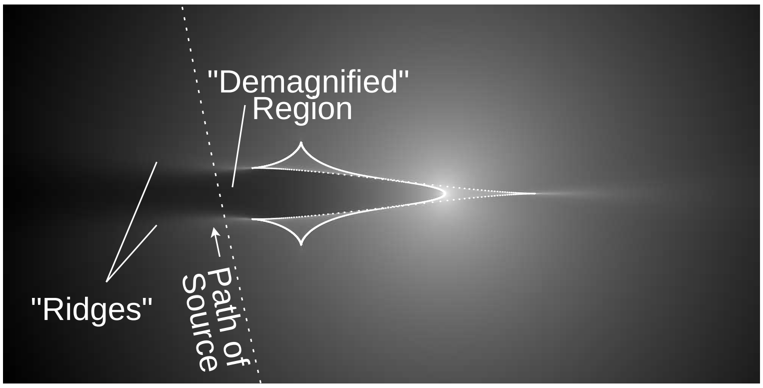

Figure 2: Magnification map for OGLE-2014-BLG-0124 [17]. The presence of the planet distorts the underlying magnification pattern due to the lens star. The caustic is the white outline; in this case the central and planetary caustics are merged into a single, resonant caustic. The path of the source produces the light curve shown in Figure 3.

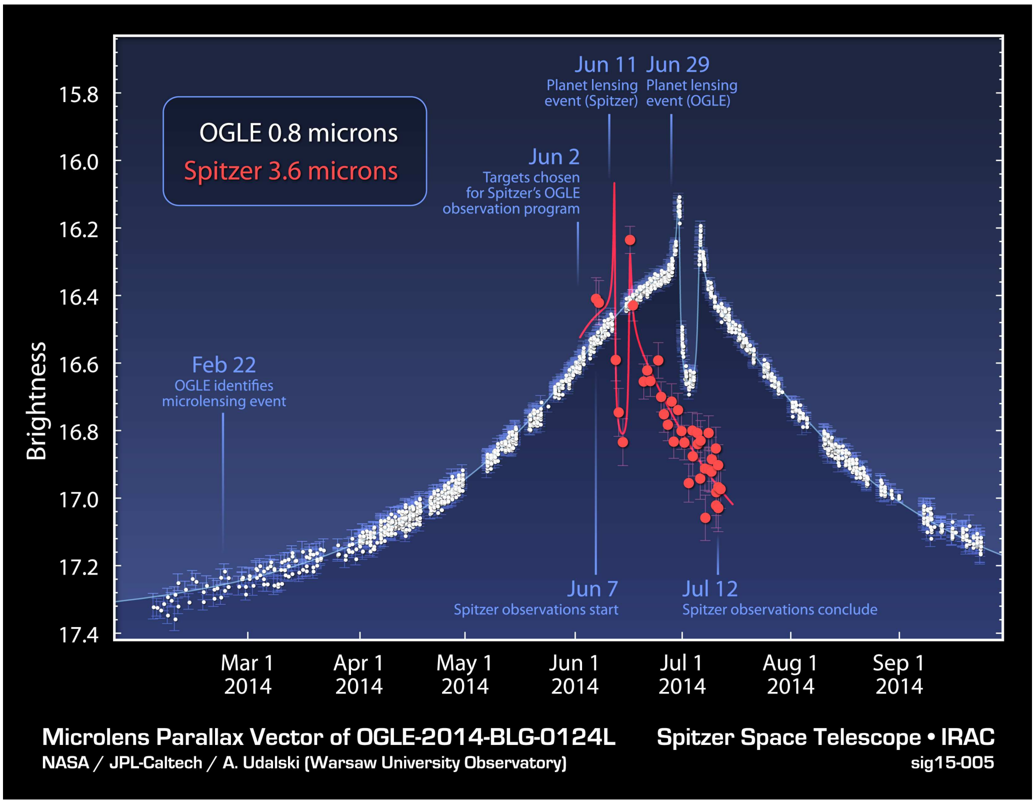

Figure 3: The light curves of OGLE-2014-BLG-0124 as seen from OGLE (white) and *Spitzer* (red). The planetary perturbation is seen from *Spitzer* ~ 20 days before it is seen from Earth because of the microlens parallax effect. Image credit: NASA/JPL-Caltech/Warsaw University Observatory.

3. Modern Microlensing Surveys

Observational microlensing is shaped by the tension between the rarity of microlensing events and the fleeting nature of planetary perturbations. Even in the densest stellar fields, i.e. in the direction of the Galactic Bulge, the probability of a microlensing event is one in a million [22]. At the same time, the typical planetary perturbations last between a few hours and a few days [14, 15]. This means that conducting an ideal microlensing survey requires monitoring millions of stars several times per hour, 24 hours per day. In the past, this was impossible, so the work was split between surveys with cadences of ~ 1 day^{-1} to detect events and followup teams, which would monitor some subset of microlensing events at a much higher cadence. This strategy has resulted in the majority microlensing planet discoveries to date. However, it makes statistical analyses difficult because of the complex selection function. While some statistical analyses have been done (e.g. [23, 24, 25, 26, 27]), a truly objective microlensing survey would yield more precise and more complete results.

Over the past decade, there has been a major push to increase the size of the cameras used for microlensing surveys to increase the field of view and therefore the cadence at which microlensing events can be observed. The goal is to image a large enough area of the sky to detect large numbers of microlensing events while observing them at a high enough cadence to detect and characterize planetary perturbations. In the past couple of years this goal has been achieved, and surveys will soon eclipse followup groups as the primary sources of planet detections.

There are four modern microlensing surveys: OGLE, MOA, Wise, and KMTNet. The Optical Gravitational Lensing Experiment (OGLE) has a 1.3m telescope based at Las Campanas Observatory and it is the most powerful, single site microlensing survey currently operating [28]. In the 2015 microlensing season, OGLE IV discovered 2145 microlensing events[4], which may be contrasted with the dozens of events discovered annually by OGLE II in the late 1990s or the hundreds of events per year from OGLE III in the 2000s . The Microlensing Observations in Astrophysics (MOA) survey has a telescope based at Mt. John Observatory in New Zealand [29]. In 2015, they found 576 microlensing events with some overlap with the OGLE survey. Wise Observatory in Israel[5] is also conducting a microlensing survey, but they do not issue real-time microlensing alerts [30, 27]. Finally, the Korea Microlensing Telescope Network was commissioned in 2015 [31]. It has 1.6m telescopes located at three sites: CTIO in Chile, SAAO in South Africa, and SSO in Australia. This global distribution of telescopes combined with the large field of view (4 square degrees) means that this survey can monitor 16 square degrees continuously with a 10 minute cadence, which is more than sufficient to detect Earth-mass ratio exoplanets [31, 32]. These new and upgraded surveys have and are continuing to revolutionize the field of microlensing.

4. Recent Microlensing Discoveries

4.1 Examples of Planetary Discoveries

The larger fields-of-view mean more data and more data means that microlensing events are being discovered earlier in their evolution and earlier in the microlensing season. In the second

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[4] http://ogle.astrouw.edu.pl/ogle4/ews/2015/ews.html

[5] Note that this is unrelated to the Wide-field Infrared Survey Explorer (WISE).

full season of OGLE-IV, the OGLE Early Warning System announced the discovery of OGLE-2012-BLG-0026 on February 13, when the Bulge is visible for $\lesssim 2$ hr night^{-1}. Because of this early alert, we were able to track the evolution of this event and recognize that it would be a high-magnification microlensing event. By mobilizing telescope resources around the globe, especially the Microlensing Follow-Up Network (MicroFUN), we obtained dense coverage of the event over peak. As a result, two planets with mass ratios $q = 1.3 \times 10^{-4}$ and $q = 8 \times 10^{-4}$ were discovered [33]. This is an example of how followup groups and surveys work together.

However, the case of OGLE-2012-BLG-0406 illustrates how followup data is becoming less important. Poleski et al. (2014) show that this $q \sim 6 \times 10^{-3}$ planetary perturbation was adequately covered by the OGLE-IV survey data alone [34]. The addition of dense followup data decreases the uncertainties [35], but the OGLE data alone capture the basic properties of the event.

A faster cadence also means routine characterization of shorter timescale microlensing phenomena. This includes the possibility of detecting free-floating planets, which produce events lasting only a few hours. Sumi et al. (2011) studied the distribution of event timescales from MOA-II [36]. They found an excess of short timescale microlensing events that cannot be accounted for by the stellar population. They posited an additional population of free-floating planets to explain this excess. This comprehensive analysis of microlensing survey data is an early example of what we can expect from surveys in the future.

4.2 Microlensing Parallax

The biggest uncertainty in microlensing is that the shape of the light curve alone only gives relative information about the lens. For example, modeling a planetary perturbation will yield the mass ratio between the planet and the host star, but it will not directly yield the mass of that host star. As long as the mass ratio is small enough ($q \lesssim 10^{-3}$), the system obviously contains a planet, but the exact nature of the planet is unknown. However, there is also a significant gray area (e.g. $q \sim 10^{-2}$) for which the planetary nature of the object is ambiguous without knowing the mass of the host.

One way to overcome this challenge is to measure higher-order effects in the microlensing light curve. Measuring both the angular size of the Einstein ring through finite source effects and microlens parallax $\pi_{\rm E}$ allows a direct measurement of the lens mass and its distance:

$$M_{\rm L} = \frac{\theta_{\rm E}}{\kappa \pi_{\rm E}} \quad ; \quad D_{\rm L}^{-1} = \theta_{\rm E}\pi_{\rm E} + D_{\rm S}^{-1}. \tag{4.1}$$

$D_{\rm S}$ is the distance to the source, which can generally be assumed to be 8 kpc.

Finite source effects are literally the effect on the light curve attributable to the fact that the source is a star with a finite size rather than a perfect point source. The observed magnification of the source's light is the integration of the magnification pattern across the face of the source star. Hence, if the source crosses a caustic, instead of observing the magnification diverge to infinity, this feature is rounded out. The degree of rounding gives a measurement of the source size $\rho = \theta_\star/\theta_{\rm E}$. Since the angular size of the source $\theta_\star$ can be inferred from the source color and surface brightness relations [37], this yields a measurement of $\theta_{\rm E}$.

In microlensing, the microlens parallax vector gives the displacement of the lens-source trajectory from the expectation of rectilinear motion observed from a single location. This is related to the physical parallax by

$$\pi_{\rm E} = \frac{\pi_{\rm rel}}{\theta_{\rm E}}. \tag{4.2}$$

There are two ways of observing parallax effects in microlensing. First, observations are generally not taken from an inertial frame. The Earth and various space telescopes are all accelerating platforms. This acceleration can be seen in the light curve of the microlensing event, provided the event timescale is a significant fraction of the orbit [38, 39, 40]. Second, a microlensing event from two different locations will have a different observed light curve for each location because of the parallax effect [41, 42, 43, 44].

One major result from measuring lens masses through parallax and finite source effects was the discovery of brown dwarf binaries. Microlensing has found some of the lowest-mass brown-dwarf–brown-dwarf binaries. One example is OGLE-2009-BLG-151/MOA-2009-BLG-232 in which the primary is $0.018 M_\odot$ and the secondary is $0.0075 M_\odot$ [45]. Figure 5 of [46] shows these binaries in context with other known low-mass binaries.

4.3 *Spitzer* Parallaxes

Recently, *Spitzer* time has been allocated to microlens parallax experiments, vastly increasing the number of events with parallax measurements. The Einstein ring projected onto the observer plane is typically about 10 AU. Because *Spitzer* is ~ 1 AU from the Earth (a significant fraction of the Einstein ring size), it observes a different apparent alignment between the source and lens stars, and hence, a different light curve.

So far, the 2014 and 2015 *Spitzer* Microlensing Campaigns have observed over 200 microlensing events [47, 48]. In 2014, we demonstrated the feasibility of measuring microlens parallaxes with *Spitzer* by observing ~ 60 microlensing events. In this campaign, we made the first mass measurement for an isolated star using space-based microlens parallax observations [49]. We also made the first space-based parallax measurement for a microlensing planet [17]. Figure 3 shows the light curves of this event as observed from the ground and from *Spitzer*, as well as the sequence of events for scheduling observations for this event. The ~ 20 day offset between the two light curves is due to the parallax effect. Note that all decisions were made without reference to the *Spitzer* light curve since those data were not reduced until after the campaign ended, so the fact that the planetary perturbation was captured by the *Spitzer* data was entirely fortuitous. The 2015 campaign has already yielded a microlens parallax measurement for a second planet (OGLE-2015-BLG-0966 [50]). In addition, we discovered a wide binary whose primary is likely to be a non-accreting stellar remnant. The parallax measurement from *Spitzer* was crucial for constraining the mass of the primary, which identifies it as a likely stellar remnant [51].

In addition to these individual discoveries, the *Spitzer* campaign has opened new possibilities for statistical studies from microlensing. The microlens parallax measurement itself yields a very good statistical estimate of the distance to the individual lenses, and when combined with finite source effects (which are usually measured for planets and binaries) yields a precise measurement of the lens distance (Equation 4.1). With these distance measurements, we can locate the individual lenses in the Galaxy, effectively mapping out the underlying population of objects including those that do not emit light (e.g. black holes). One of the major goals of these campaigns is to make the first measurement of the distribution of planets as a function of Galactic distance, and test the effect of galactic environment on planet formation by comparing the relative abundance of planets in the Disk and the Bulge [47, 52].

In 2016, there will be a third *Spitzer* microlens parallax campaign [53, 54]. In addition, Campaign 9 of the *K2* mission (*K2C9*), also in 2016, will use the *Kepler* satellite to conduct a microlens parallax campaign [40, 55]. While the *Spitzer* campaigns are targeted to specific microlensing events discovered from the ground, the *K2* campaign will take advantage of the large field-of-view to conduct a survey-like experiment. *K2* will download a large superstamp for the duration of the 80-day campaign. The primary advantage of this approach is that *K2C9* will be able to measure parallaxes for shorter timescale microlensing events that occur in the superstamp. This is a particularly interesting opportunity for measuring parallaxes of candidate free-floating planet events (timescales of ~ 1 day). Such events cannot be observed by the *Spitzer* program because the lag time between scheduling and the start of observations is too long.

5. The Future of Microlensing

Looking farther into the future, the *WFIRST* satellite is expected to launch in 2024 [56]. Thirty percent of this mission will be dedicated to a microlensing survey of the Galactic Bulge. The *WFIRST* microlensing mission will discover planets on a scale similar to the *Kepler* mission. The highly precise photometry available from space will lead to the discovery of thousands of exoplanets. This mission will complement other search techniques by finding planets as small as Mercury at distances of a few AU; planets this small and distant cannot be found by any other technique. Furthermore, many of these planets will have precise masses and known Galactic distances. [57] shows how *WFIRST* will combine various pieces of information, including microlens parallax, to obtain precise mass and distance measurements for its lenses. This mission will revolutionize the field of microlensing and our understanding of planets beyond the snow line.

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