White Paper: Exoplanetary Microlensing from the Ground in the 2020s

JENNIFER C. YEE1, *

JAY ANDERSON2, RACHEL AKESON3, ETIENNE BACHELET4, CHARLES BEICHMAN3, ANDREA BELLINI2, DAVID BENNETT5, APARNA BHATTACHARYA5,6, VALERIO BOZZA7,8, SEBASTIANO CALCHI NOVATI3, WILL CLARKSON9, DAVID R. CIARDI10, ANDREW GOULD11,12,13, CALEN B. HENDERSON10, SAVANNAH R. JACKLIN14, SOMAYEH KHAKPASH15, SHUDE MAO16, BERTRAND MENNENSON17, DAVID M. NATAR18,†, MATTHEW PENNY13, JOSHUA PEPPER15, RADEK POLESKI13, CLÉMENT RANC5,‡, KAILASH SAHU2, Y. SHVARTZVALD17,‡, R.A. STREET4, TAKAHIRO SUMI19, AND DAI SUKE SUZUKI20

1 Harvard-Smithsonian Center for Astrophysics, 60 Garden St. MS-15, Cambridge, MA 02138
2 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD, 21218, USA
3 IPAC, Mail Code 100-22, Caltech, 1200 E. California Blvd., Pasadena, CA 91125, USA
4 Las Cumbres Observatory, 6740 Cortona Drive, Suite 102, Goleta, CA 93117, USA
5 Code 667, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
6 Department of Astronomy, University of Maryland, College Park, Maryland, USA
7 Dipartimento di Fisica “E.R. Caianiello”, Università di Salerno, Via Giovanni Paolo II 132, 84084, Fisciano, Italy
8 Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Italy
9 Department of Natural Sciences, University of Michigan-Dearborn, 4901 Evergreen Road, Dearborn, MI 48128
10 IPAC/NExScI, Mail Code 100-22, Caltech, 1200 E. California Blvd., Pasadena, CA 91125, USA
11 Max-Planck-Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany
12 Korea Astronomy and Space Science Institute, Daejon 34055, Republic of Korea
13 Ohio State University, 140 W 18th Ave, Columbus, OH, USA
14 Department of Physics and Astronomy, Vanderbilt University, VU Station 1807, Nashville, TN 37235, USA
15 Lehigh University
16 Tsinghua Center for Astrophysics and Department of Physics, Tsinghua University, Beijing, China 100084
17 Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
18 Center for Astrophysical Sciences and Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA
19 Department of Earth and Space Science, Graduate School of Science, Osaka University, 1-1 Machikaneyama-cho, Toyonaka, Osaka 560-0043, Japan
20 Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa 252-5210, Japan

* Primary author; jyee@cfa.harvard.edu; 617-495-7594
† Allan C. and Dorothy H. Davis Fellow
‡ NASA Postdoctoral Program Fellow

arXiv:1803.07921v1 [astro-ph.EP] 21 Mar 2018
1. OVERVIEW

Microlensing can access planet populations that no other method can probe: cold wide-orbit planets beyond the snow line, planets in both the Galactic bulge and disk, and free floating planets (FFPs). The demographics of each population will provide unique constraints on planet formation.

Over the past 5 years, U.S. microlensing campaigns with *Spitzer* and *UKIRT* have provided a powerful complement to international ground-based microlensing surveys, with major breakthroughs in parallax measurements and probing new regions of the Galaxy. The scientific vitality of these projects has also promoted the development of the U.S. microlensing community.

In the 2020s, the U.S. can continue to play a major role in ground-based microlensing by leveraging U.S. assets to complement ongoing ground-based international surveys. *LSST* and *UKIRT* microlensing surveys would probe vast regions of the Galaxy, where planets form under drastically different conditions. Moreover, while ground-based surveys will measure the planet mass-ratio function beyond the snow line, adaptive optics (AO) observations with ELTs would turn all of these mass ratios into masses and also distinguish between very wide-orbit planets and genuine FFPs. To the extent possible, cooperation of U.S. scientists with international surveys should also be encouraged and supported.

2. THE GALACTIC DISTRIBUTION OF PLANETS

![Figure 1](image)

*Figure 1.* The Galactic distribution of known planets found by various techniques (circles). Microlensing is the only technique that can routinely find planets at distances of more than a few kpc (Left: dashed arc = solar circle, dotted circles = 1, 2 kpc from the Sun). TCP J05074264+2447555 (TCP J0507) is a microlensing event discovered in an all-sky transient survey that has a planet (Nucita et al. 2018). *LSST* observations of the Galactic plane would enable the discovery of planets over $\ell \sim (-90, 90)$ degrees (i.e., $X > 0$). Right: UKIRT-2017-BLG-001Lb (UB17001; Shvartzvald et al. 2018) demonstrates NIR microlensing surveys can reach closer to the Galactic center ($x$).
Recent discoveries demonstrate that microlensing planet searches can reach new areas of the Galaxy outside the traditional Galactic bulge fields. Figure 1 shows that microlensing is the only technique that probes planets on kpc scales. An adjusted LSST observing strategy that includes the Galactic plane and a continuation of the UKIRT microlensing survey, would measure variations in planet frequency on a Galactic scale. This would provide a powerful probe of how the star-formation environment (e.g., Galactic disk vs. bulge) affects planet formation.

Comparing the planet frequency in the disk and bulge would benefit from three things:

- better distance estimates for microlensing events, i.e., through space-based parallax measurements or AO (see below),
- more bulge planets, i.e., by observing a large number of far-disk sources through the bulge, which requires high-cadence IR surveys at \( b \sim 0 \),
- finding guaranteed disk planets, i.e., from disk-disk lensing from LSST plane surveys.

2.1. Galactic Plane Microlensing with LSST

TCP J05074264+2447555 was a microlensing event discovered toward the Galactic antecenter (\( \ell = 178.7 \) deg; Jayasinghe et al. 2017) in data from the ASAS-SN survey (Shappee et al. 2014; Kochanek et al. 2017). Intensive ground-based follow-up observatories revealed a planetary signal (Nucita et al. 2018). This demonstrates the potential of an all-sky transient survey to find microlensing events that can be followed up with other telescopes to search for planetary signals. Indeed, survey+follow-up strategies (Gould & Loeb 1992) have been in place for two decades to balance the need to monitor large numbers of stars to find microlensing events with the need for high-cadence (> few/day) observations to find planets in those events.

Gould (2013b) showed that LSST could conduct a microlensing survey on an unprecedented scale that covers > 2000 square degrees of the Galactic plane. He estimates that LSST could find \( \sim 250 \) Galactic plane microlensing events per year, 10% of which would be high-magnification (i.e., have an extremely high detection efficiency for finding planets; Griest & Safizadeh 1998). If real-time microlensing alerts and targeted follow-up observations from 1–2-m class telescopes were combined with such a survey, these high-magnification events would give a likely return of \( \sim 8–10 \) planets per year (Gould et al. 2010). In addition, follow-up observations (although not at the much longer timescale) could target the few events with bright, giant sources, which are the most likely events to reveal the lower mass-ratio planets (Gould 1997; Beaulieu et al. 2006; Hwang et al. 2018). The Galactic distribution of planets as a function of \((\ell, b)\) can be inferred by inferred from the measured planet frequencies along different lines of sight.

The primary requirement for an LSST microlensing survey of the Galactic plane is that instead of systematically avoiding the Plane, it surveys the Plane at a cadence of once every 3 to 4 days, i.e., the same cadence as for other fields. This cadence would allow sufficient time to discover, alert, and predict high-magnification microlensing events, so that they could be followed up with other facilities, as is planned for other transients discovered by LSST. A higher cadence would allow earlier detection and more robust prediction of microlensing
events. In addition, a network of 1-2 m telescopes (similar to Las Cumbres Observatory; Brown et al. 2013) would be needed to follow up the most promising events.

2.2. NIR Microlensing in the Galactic Center

The UKIRT microlensing survey\(^1\) has demonstrated that operating at NIR wavelengths permits the discovery of planets close to the Galactic center. Figure 1 shows that the first such planet (UKIRT-2017-BLG-001Lb; Shvartzvald et al. 2018) is deep into the regions too extincted to be accessed by optical surveys. Gould (1995) shows that lenses close to the Galactic Center are especially well characterized since their timescales can be related directly to their distances. Furthermore, probing lines of sight closer to the plane could reveal variations in planet populations that parallel variations in the stellar populations.

Observing microlensing events at \( b \sim 0 \) requires NIR observations because of the high extinction, preferably in \( K \)-band. An optimal NIR survey to find planets would fulfill all of the usual microlensing requirements: wide field-of-view camera, cadence of \( \gtrsim 1 \text{ hr}^{-1} \), in the Southern hemisphere, and preferably with multiple sites. Although UKIRT does not meet all of these requirements, it has proven to be a capable microlensing survey telescope (Shvartzvald et al. 2017, 2018). If more time were devoted to such a survey, it could achieve the necessary cadence to discover Neptune mass-ratio planets (1 hr\(^{-1}\)). In addition, Prime focus Infrared Microlensing Experiment (PRIME) is a joint Japan-U.S.-South Africa NIR telescope being built in South Africa. It will have a 1.3 deg\(^2\) FOV and should see first light in 2020. A simultaneous UKIRT survey can complement PRIME in temporal coverage, but UKIRT is also unique in having K-band observations, which is necessary probe all the way to the Galactic center. A survey with VISTA would also improve temporal coverage.

3. THE PLANET MASS FUNCTION

Recent results from Suzuki et al. (2016) and Udalski et al. (2018) show a peak in the mass-ratio distribution at \( q = m_p/M_\star \sim 2 \times 10^{-4} \) and suggest that the frequency of planets falls off rapidly toward lower mass ratios. However, the precise mass ratio at which this peak occurs is poorly constrained from the current observations, and the nature of the drop-off toward lower mass ratios is barely probed. Figure 2 shows the mass-ratio distribution (and its large uncertainties at small mass ratios) from Suzuki et al. (2016). If current ground-based microlensing surveys are continued over the next decade, they will precisely measure the location of the break in the mass-ratio distribution. Constraining the behavior of the low mass-ratio end of the distribution requires going to space (Bennett et al. 2018).

The mass ratio at which this break occurs must be explained by planet formation theories, and the more precise the measurement, the stronger the constraint on the physics of planet formation. Better yet, would be to measure the absolute masses and separations of the planets. This would enable us to test how planet formation depends on various factors. Some key questions that can be addressed through absolute mass measurements are

- Is the planet mass-ratio function more fundamental than the planet mass function (as suggested by Pascucci et al. 2018 and Udalski et al. 2018)? And, the closely related question, does planet formation depend on stellar mass and if so, in what way?

\(^1\) UKIRT survey light curves are publicly available through the NASA Exoplanet Archive.
Figure 2. Left: The planet mass-ratio distribution measured by Suzuki et al. (2016) shows a break at mass-ratios $q \sim 2 \times 10^{-4}$, but the lack of planet discoveries at $q < 4 \times 10^{-5}$ leads to a large uncertainty in the mass-ratio function below the break. Right: Pascucci et al. (2018) also see a break in the mass-ratio function for Kepler planets with $P < 100$ days but at $q \sim 3 \times 10^{-5}$ and find that it is independent of host mass. Over the next decade, ground-based microlensing surveys will precisely determine the mass ratio at which this break occurs for planets beyond the snow line. With ELTs, we can transform this into a mass distribution, allowing us to assess implications for planet formation theory.

- How does the mass-ratio function vary with separation from the star? Specifically, how does the $q \sim 2 \times 10^{-4}$ break in the mass-ratio function seen by microlensing at snow-line distances relate to the break in the mass-ratio function seen by Kepler at $q \sim 3 \times 10^{-5}$ for $P < 100$ days (Pascucci et al. 2018)?

- How do microlensing results (which are biased toward M dwarf host stars) compare to results from radial velocity and transits (which are biased toward FGK dwarfs)? Absolute mass measurements would enable direct comparisons to the results from these other techniques by allowing the sample to be divided by host star mass.

WFIRST will address these questions by measuring masses for many of its host stars. However, a high-resolution follow-up imaging campaign from the ground would also allow mass measurements for planets discovered by ground-based microlensing surveys over a much larger range of environments.

Flux measurements of the lens stars (well after the microlensing event) can be combined with measurements of the angular Einstein ring radius (from the microlensing event) to yield masses of the host stars (and thus planets) and distances to the systems. In addition, AO observations can be used to rule out host stars for FFP candidates discovered by microlensing (e.g., Mróz et al. 2018). AO constraints on flux from a host can be significantly enhanced by measurement of the IR flux of the source star to a precision of $\sim 1\%$, which requires $\sim 1$ day$^{-1}$ NIR surveys simultaneous with optical surveys.

The primary challenge for making a flux measurement of the lens star is one of resolution. By definition, the microlensing lens and source stars are superposed to within $\sim 1$ mas at the time of the lensing event. Furthermore, the bulge microlensing fields are extremely
crowded, so it is not uncommon to have one or more unrelated stars blended into the PSF of the event at $\sim 1''$ seeing. However, a single, AO image taken several years after the event can both resolve the source and lens stars as well as unrelated, non-coincident stars. Such measurements have already been performed in several cases (e.g., Bennett et al. 2010; Batista et al. 2014; Beaulieu et al. 2018), but, because of the resolution limit of current facilities, these measurements are restricted to events with high proper motions and/or those that occurred $\gtrsim 10$ years ago. In contrast, the next generation of extremely large telescopes (e.g., TMT and GMT), by virtue of their large diameters, could measure the fluxes for all (or nearly all) microlensing planets within 5 years of their discovery.

The efficiency of such a program would be vastly improved by enabling a “less-than-perfect fast” mode for AO observations with 30-meter class telescopes. AO systems are being designed with the aim of achieving deep imaging with maximum contrast and optimal Strehl ratios for the purpose of directly detecting exoplanets. By contrast, the program proposed here is simply trying to resolve two stars. Thus, it is not necessary to achieve either optimal Strehl or deep imaging (a 5–10 min exposure is sufficient), which means that the overheads in slew, settle, and acquisition time are the limiting factors to carrying out a campaign to systematically image all microlensing planet hosts. A little forethought to allow faster observations (allowing for suboptimal performance) with future AO systems would vastly improve the scientific yield of ground-based microlensing surveys at relatively modest cost.

REFERENCES

Batista, V., et al. 2014, ApJ, 780, 54
Beaulieu, J.-P., et al. 2006, Nature, 439, 437
Beaulieu, J.-P., et al. 2018, AJ, 155, 78
Bennett, D. P., et al. 2010, ApJ, 713, 837
Bennett, D., et al. 2018, White Paper: The WFIRST Exoplanet Microlensing Survey
Brown, T. M., et al. 2013, PASP, 125, 1031
Gould, A. 1995, ApJL, 446, L71
Gould, A. 1997, arXiv:96.08045
—. 2013a, ApJL, 763, L35
—. 2013b, arXiv:1304.3455
Gould, A., & Loeb, A. 1992, ApJ, 396, 104
Gould, A., et al. 2010, ApJ, 720, 1073
Griest, K., & Safizadeh, N. 1998, ApJ, 500, 37
Hwang, K.-H., et al. 2018, AJ, 155, 20
Jayasinghe, T., et al. 2017, ATel, 10923
Kochanek, C. S., et al. 2017, PASP, 129, 104502
Mróz, P., et al. 2018, AJ, 155, 121
Nucita, A. A., et al. 2018, arXiv:1802.06659
Pascucci, I., et al. 2018, arXiv:1803.00777
Shappee, B. J., et al. 2014, ApJ, 788, 48
Shvartzvald, Y., et al. 2017, AJ, 153, 61
Shvartzvald, Y., et al. 2018, arXiv:1802.06795
Suzuki, D., et al. 2016, ApJ, 833, 145
Udalski, A., et al. 2018, arXiv:1802.02582