

CAMPAIGN 9 OF THE *K2* MISSION: OBSERVATIONAL PARAMETERS, SCIENTIFIC DRIVERS, AND COMMUNITY INVOLVEMENT FOR A SIMULTANEOUS SPACE- AND GROUND-BASED MICROLENSING SURVEY

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ABSTRACT

K2's Campaign 9 (*K2*C9) will conduct a ~ 3.4 deg² survey toward the Galactic bulge from 7/April through 1/July of 2016 that will leverage the spatial separation between *K2* and the Earth to facilitate measurement of the microlens parallax π_E for $\gtrsim 120$ microlensing events, including several planetary in nature as well as many short-timescale microlensing events, which are potentially indicative of free-floating planets (FFPs). These satellite parallax measurements will in turn allow for the direct measurement of the masses of and distances to the lensing systems. In this white paper we provide an overview of the *K2*C9 space- and ground-based microlensing survey. Specifically, we detail the demographic questions that can be addressed by this program, including the frequency of FFPs and the Galactic distribution of exoplanets, the observational parameters of *K2*C9, and the array of resources dedicated to concurrent observations. Finally, we outline the avenues through which the larger community can become involved, and generally encourage participation in *K2*C9, which constitutes an important pathfinding mission and community exercise in anticipation of *WFIRST*.

Keywords: binaries: general – Galaxy: bulge – gravitational lensing: micro – planets and satellites: detection – planets and satellites: fundamental parameters

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1. INTRODUCTION

Results from the *Kepler* Mission have revolutionized our understanding of the frequency and distribution of exoplanets that orbit close-in to their host stars. To-date it has identified 4175 planet candidates (Mullally et al. 2015) and has confirmed 1039 as bona fide exoplanets⁵⁷. These discoveries have led to a wealth of insights into ex-

oplanet demographics, including the apparent ubiquity of small planets (e.g., Fressin et al. 2013) and the occurrence rate and orbital architectures of systems with multiple transiting planet candidates (e.g., Fabrycky et al. 2014), along the quest to measure η_{\oplus} .

The mechanical failure of the second of *Kepler*'s four reaction wheels in 2013 signaled an end to the primary mission but heralded the genesis of its extended *K2* Mission, which is in the midst of a series of ~ 80 -day campaigns performing high-precision photometry for targets along the Ecliptic (Howell et al. 2014). Orienting the spacecraft to point along its velocity vector (+VV) allows *K2*'s Campaign 9 (*K2*C9) to observe toward the Galactic bulge while it is simultaneously visible from Earth, enabling the first microlensing survey from the ground and from space.

In this white paper we detail the joint space- and ground-based microlensing survey enabled by *K2*C9. We begin with a brief overview of the geometric principles and observational implementation of the microlensing technique in §2. Then, in §3 we discuss the scientific questions to which *K2*C9 will provide access. This is followed by a description of the observational parameters of *K2*C9 in §4. In §5 we summarize the ground-based resources that will be employed concurrently with *K2*C9, as well as their scientific goals. We detail the goals and implementation of a 50-hour *Spitzer* program that will take simultaneous observations during the last 13 days of *K2*C9 in §6. Finally, and most critically, in §7 we focus on the channels through which the greater community can participate in this community-driven microlensing

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experiment.

2. GRAVITATIONAL MICROLENSING OVERVIEW

In this section we provide a brief overview of the theoretical background and observational implementation of gravitational microlensing. See Gaudi (2012) for a deeper exploration of the fundamental mechanics of lensing, particularly in the context of searches for exoplanets. Readers who possess a foundational understanding of the technical details of microlensing should proceed to §3.

2.1. Lensing Geometry

A microlensing event occurs when the light from a background “source” star is magnified by the gravitational potential of an intervening foreground “lens” system in a way that is detectable by a given observer. When describing the temporal evolution of an event, as is shown in Figure 1, the coordinate system keeps the lensing body fixed at the origin such that all of the lens-source relative proper motion is encapsulated in the trajectory of the source. The light from the source is split into two images that, in the case of perfect observer-lens-source colinearity, trace out the Einstein radius θ_E , the angular scale for microlensing phenomena.

For a lensing system with total mass M_ℓ the Einstein ring is defined as:

$$\theta_E \equiv \sqrt{\kappa M_\ell \pi_{\text{rel}}}, \quad \pi_{\text{rel}} = \pi_E \theta_E = \text{AU}(D_\ell^{-1} - D_s^{-1}), \quad (1)$$

where $\kappa \equiv 4G/(c^2 \text{AU}) = 8.144 \text{ mas}/M_\odot$, π_{rel} is the relative lens-source parallax, and D_ℓ and D_s are the distances to the lens and source, respectively. Normalizing the relative lens-source parallax to θ_E yields the microlens parallax π_E . For typical microlensing surveys toward the Galactic bulge, θ_E is of-order a milliarcsecond or smaller, meaning that the images of the source are not spatially resolved.

There are four parameters that specify a microlensing event due to a single lensing mass. The first is t_0 , the time of closest approach of the source to the lens. Second is u_0 , the angular distance of the closest approach of the source to the lens, normalized to θ_E . The Einstein crossing time t_E is defined via:

$$t_E \equiv \frac{\theta_E}{\mu_{\text{rel}}}, \quad (2)$$

where μ_{rel} is the relative lens-source proper motion. Last is ρ , the angular radius of the source star, θ_* , normalized to θ_E :

$$\rho \equiv \frac{\theta_*}{\theta_E}. \quad (3)$$

The magnification A of a point-like background source star by a single lensing mass then is:

$$A(u) = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}, \quad (4)$$

where u is the angular separation of the lens and source at a given time normalized to θ_E .

If the lensing system contains an additional mass whose position is roughly coincident with that of one of the images at any point during the event, the additional gravitational potential introduced by the second body will distort the magnification structure of the event. In the

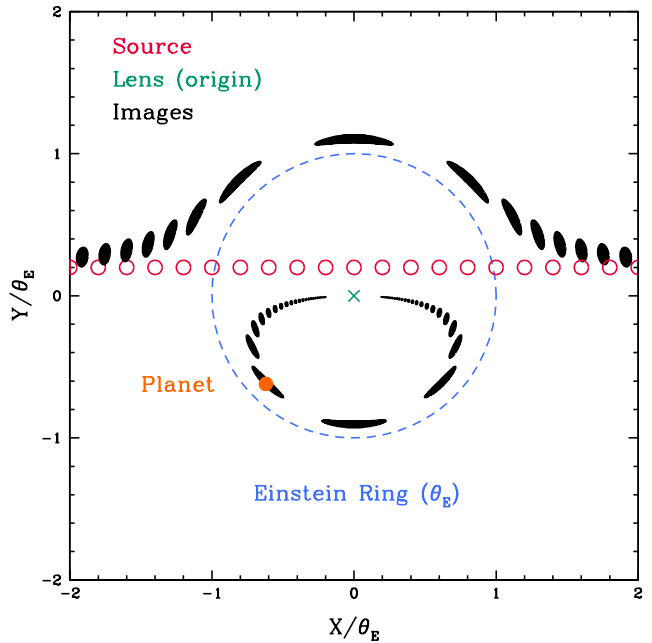


Figure 1. The face-on geometry of the temporal evolution of a microlensing event due to a single lensing mass. The green cross at the origin denotes the fixed lens position, the red open circles identify the trajectory of the source, and the filled black ellipses show the paths of the two images created during the event. In the case of exact observer-lens-source colinearity, the two images would merge to create a circle with radius equal to θ_E . The introduction of a second body, such as a planet marked by the filled orange circle, approximately coincident with one of the images will introduce additional magnification structure to the light curve.

case of a static two-body lensing system, such as a planet orbiting a host star, these perturbations allow for the measurement of three additional parameters. The mass ratio q of a lens comprised of a planet of mass M_p and a star of mass M_* is given by:

$$q = \frac{M_p}{M_*}. \quad (5)$$

The instantaneous projected angular separation of the two bodies, normalized to θ_E , is denoted by s . Finally, α gives the angle of the source trajectory relative to the star-planet binary axis. See Gould (2000) and Skowron et al. (2011) for a more complete discussion of microlensing notation conventions.

The mass ratio q and the separation s of the two lensing masses define the topology governing the location and morphology of the caustics (Erdl & Schneider 1993; Dominik 1999), closed curves in the plane of the lens that identify where the magnification of a point-like source formally diverges to infinity. For a lens system comprised of two point masses, there are either one, two, or three non-intersecting caustics. If the second lensing body is low-mass ($q \ll 1$), there is typically a central caustic located near the primary star and either one (for $s > 1$) or two (for $s < 1$) planetary caustics, whose position and morphology can be approximated analytically for $q \ll 1$ and $s \neq 1$ (Bozza 2000; Chung et al. 2005; Han 2006). For $s \sim 1$, there is one caustic. See Schneider & Weiss (1986) and Dominik (1999) for the exact values of s where these caustic topologies change for arbitrary q .

The light curve, caustic geometry, and source trajectory for an example planetary event are shown in Figure 2.

2.2. From Observables to Parameters

2.2.1. Observational Methodology

Due to the relatively small detectors that were available at the time when microlensing planet surveys were first initiated, they followed a two-tiered strategy that was first advocated by Gould & Loeb (1992). The microlensing event rate, even toward the Galactic bulge, where the surface density of stars is the highest, is such that an arbitrary source star in the bulge comes within $\sim\theta_E$ of a foreground lensing star only once every $\sim 100,000$ years. To detect a few hundred events per year, it is thus necessary to monitor tens of millions of stars. Survey telescopes with bigger apertures and the largest available fields of view (FoVs), such as the Optical Gravitational Lensing Experiment (OGLE; Udalski 2003) and the Microlensing Observations in Astrophysics collaboration (MOA; Bond et al. 2001; Sumi et al. 2003), would monitor many tens of square degrees of high stellar density, low extinction fields toward the bulge with cadences of once or twice per night. These cadences were sufficient to detect and alert the primary events themselves but insufficient to accurately characterize planetary perturbations. Networks of smaller telescopes, such as the Microlensing Follow-up Network (μ FUN; Gould et al. 2006) and the Probing Lensing Anomalies Network (PLANET; Albrow et al. 1998), with more readily available narrow-angle detectors, would then monitor a subset of the most promising of these alerted events with the cadence and wider longitudinal coverage required to characterize the planetary anomalies.

Large format detectors, with FoVs of a few square degrees, have facilitated a transition to a phase in which microlensing has been able to increase the planetary yield, by imaging tens of millions of stars in a single pointing with the cadence necessary to detect the primary microlensing events as well as the planet-induced deviations, and for the detections themselves to be obtained in an unbiased and automated fashion, circumventing the biases introduced by the reliance on subjectivity and human judgment for the selection of follow-up targets. Furthermore, additional groups such as the Wise observatory (Shvartzvald & Maoz 2012), RoboNet (Tsapras et al. 2009), and MiNDSTeP (Dominik et al. 2008, 2010) have provided greater access to events through improved longitudinal coverage and higher-cadence observations. The Korean Microlensing Telescope Network (KMTNet), an array of three 1.6m telescopes located at Cerro Tololo Inter-American Observatory (CTIO) in Chile, South African Astronomical Observatory (SAAO) in South Africa, and Siding Springs Observatory (SSO) in Australia (Kim et al. 2010, 2011; Kappler et al. 2012; Poteet et al. 2012; Atwood et al. 2012), represents the next realization of the automated survey strategy, with its ability to conduct a ~ 16 square-degree survey with a ~ 10 -minute cadence using a homogeneous network of telescopes (Henderson et al. 2014a).

However, for a static two-body lens system, additional information beyond the seven microlensing observables described in §2.1 is needed to determine the fundamental properties of the planetary system (M_* , M_p , D_ℓ).

There are currently two primary methods to achieve this with minimal model dependence, both of which require measuring θ_E , typically by rearranging Equation (3) and combining multiband photometry to determine θ_* with a measurement of ρ through a detection of finite-source effects (Yoo et al. 2004).

2.2.2. Microlensing Parallax

The first avenue is by determining π_E , which can be measured from the distortion in the observed light curve due to the acceleration of the Earth relative to the light expected for a constant velocity (Gould et al. 1994; Hardy & Walker 1995; Gould et al. 2009). This can be accomplished in three different ways, each with its own observational challenges. Terrestrial parallax can be measured when multiple observatories at different longitudes monitor a high-magnification event simultaneously with extremely high cadences (Hardy & Walker 1995; Holz & Wald 1996; Gould et al. 2009). Orbital parallax can be measured for events with timescales that are a significant fraction of a year and requires good observational coverage (Gould 1992; Alcock et al. 1995). Finally, satellite parallax can be measured by leveraging the long spatial base line (~ 1 AU) between a space telescope and the Earth (Refsdal 1966; Gould 1992; Gould et al. 1994; Gould 1995). Then, by combining π_E with θ_E the total mass of the lensing system can be determined via Equation (1), yielding the masses of the individual components of the lensing system. Furthermore, by assuming the source is located in the Galactic bulge, D_ℓ can also be extracted.

Recently, *Spitzer* has been employed to measure satellite parallaxes. A pilot 100-hour program in 2014 made the first satellite parallax measurement of an isolated star (Yee et al. 2015b). The light curve, shown in Figure 3, clearly demonstrates the shifts in t_0 and u_0 that arise from the ~ 1 AU separation between the Earth and *Spitzer* and that alter the magnification of the source in the ground-based light curve compared to that seen in the space-based light curve. The 2014 *Spitzer* campaign also resulted in the first satellite parallax measurement for a microlensing exoplanet (Udalski et al. 2015b). In the case of that event, the precision of π_E via satellite parallax ($\sim 2.5\%$) was an order of magnitude better than that obtained through orbital parallax ($\sim 22\%$), emphasizing the importance of space telescopes for improving the precision on (M_* , M_p , D_ℓ). An 832-hour *Spitzer* campaign in 2015 observed 170 additional events, helped to refine the methodology (see Yee et al. 2015a), and led to π_E measurements for a cold Neptune in the Galactic disk (Street et al. 2015), a massive stellar remnant (Shvartzvald et al. 2015), and a myriad of other astrophysically interesting objects.

2.2.3. Flux Characterization

The second channel for converting microlensing observables into the fundamental parameters (M_* , M_p , D_ℓ) involves constraining the flux of the primary lensing mass: the host star. Determining θ_E from color information and finite-source effects and assuming a value for D_s gives one mass-distance relation for the lens system. Then, measuring the lens flux F_ℓ and applying a mass-luminosity relation (Bennett et al. 2007) provides a second mass-distance relation, given a value of the extinction toward

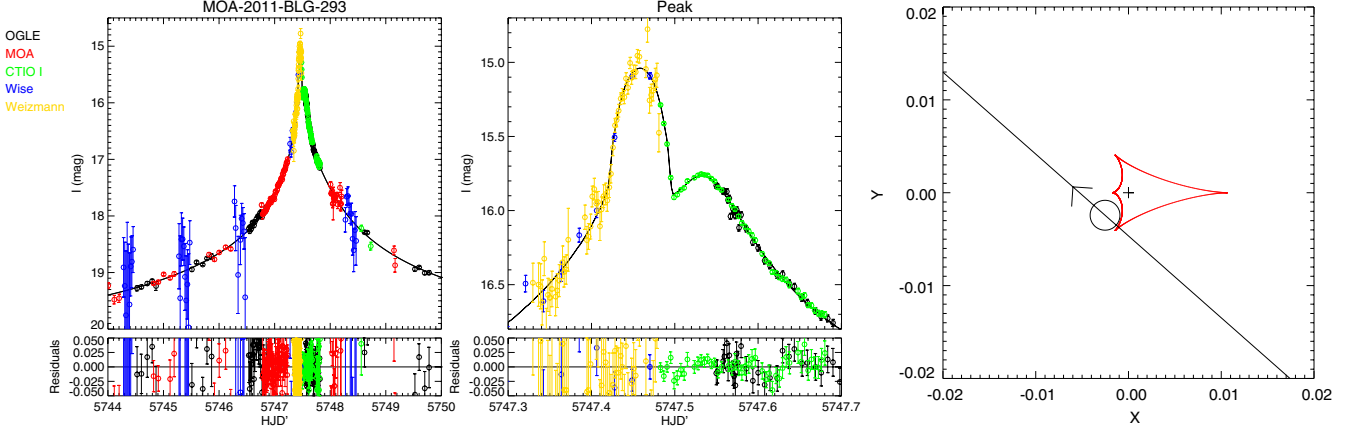


Figure 2. Light curve (left and middle panel) and caustic geometry and source trajectory (right panel) for the microensing event MOA-2011-BLG-293 (Yee et al. 2012). The deviation from a smooth, temporally symmetric light curve is highlighted by the structure at peak (middle panel) that arises when the source passes over the central caustic (right panel).

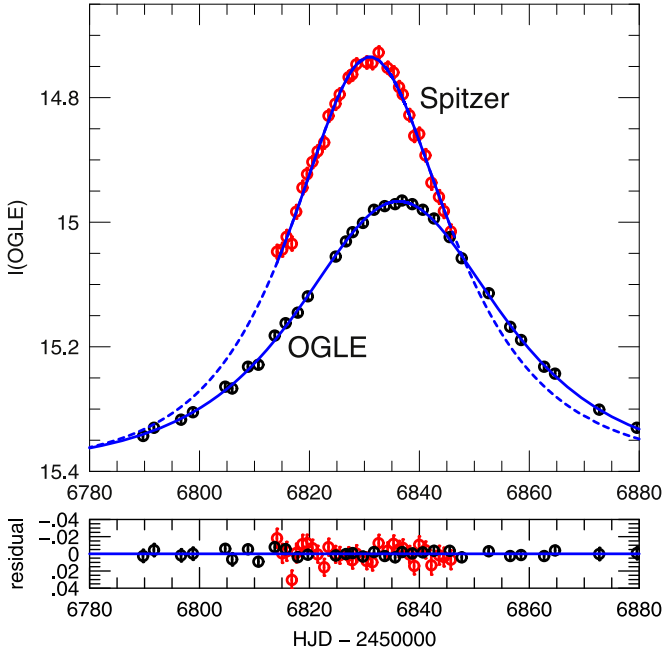


Figure 3. Light curve of the microensing event OGLE-2014-BLG-0939 as seen by *Spitzer* (red points) and OGLE (black points) (Yee et al. 2015b). The spatial baseline between *Spitzer* and the Earth alters the geometry of the event as seen from each location, inducing a shift in the time and magnitude of the peak amplification of the light from the background source star. This shift allows for a measurement of the satellite parallax, helping to determine the mass of and distance to the lensing system, which in this case is an isolated star.

the lens. Combining these two allows for the unique determination of (M_*, M_p, D_ℓ) . The extinction is known for any line-of-sight within the OGLE-III footprint (see Nataf et al. 2013). Therefore, measuring F_ℓ gives an additional technique for deriving the fundamental parameters of the lensing system.

It is important to note that this does not necessarily require waiting for the lens and source to be resolved. In fact, there are several ways by which F_ℓ can be constrained, including:

1. measuring a color-dependent centroid shift,

2. imaging the lens after it is spatially resolved from the source,
3. inferring F_ℓ by measuring the elongation of the point spread function (PSF) of the unresolved microlensing target (lens+source) as the lens and source begin to separate, and
4. promptly obtaining high-resolution follow-up photometry while the lens and source are unresolved.

Henderson (2015) discusses the challenges and possibilities for items 2–4 specifically in the context of KMTNet planetary detections. Henderson et al. (2014b) furthermore identified the subset of past microlensing events with μ_{rel} sufficiently high that the lens and source can be spatially resolved in $\lesssim 10$ years with current high-resolution facilities. Here we focus only on the fourth option.

Measuring F_ℓ this way requires near-infrared (NIR) observations at two different epochs: the first while the source is magnified and the event is ongoing, the second with a high-resolution facility after the event is over and the source has returned to its baseline brightness. By modeling the ground-based light curve, which includes both magnified and unmagnified NIR data, the NIR flux of the source can be measured precisely. Then, the high-resolution NIR observation at baseline will resolve out all stars not dynamically associated with the event to a high probability. By subtracting the NIR source flux from the second, unmagnified, observation, any detected flux that is in excess of the source flux can be ascribed to the lens, breaking the degeneracy by searching for the light from the planet’s possible host. The NIR flux characterization method has been applied to a handful of planetary events (Bennett et al. 2007; Dong et al. 2009; Janczak et al. 2010; Sumi et al. 2010; Batista et al. 2011, 2014, 2015; Fukui et al. 2015).

3. SCIENTIFIC DRIVERS

*K2*C9 represents an extraordinary opportunity to make progress in several regimes of exoplanet demographics. Its 3.4 deg^2 survey will be the first space-based campaign dedicated to exoplanetary microlensing, facilitating π_E

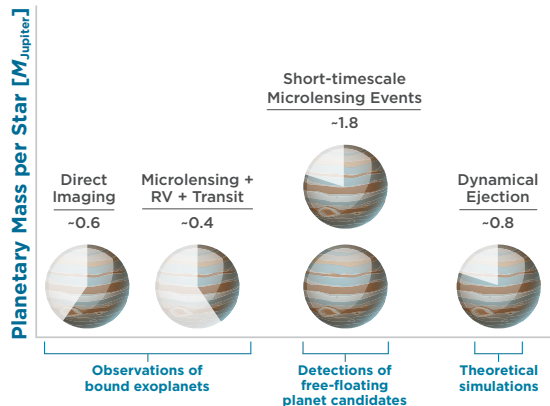


Figure 4. Estimates of planetary-mass material per star from different observational techniques and for theoretical predictions. MOA’s result indicates that free-floating planet (FFP) candidates account for $\sim 1.8 M_{\text{Jup}}$ per star. The upper limit of planetary material bound to stars from direct imaging (Bowler et al. 2015) yields, at most, one-third of this amount. Including transit results from *Kepler* (Fressin et al. 2013) and RV and microlensing planets (Clanton & Gaudi 2014b) brings the total mass of bound planets per star to $\sim 1.0 M_{\text{Jup}}$. Thus, if all FFP candidates are truly FFPs, these objects dominate the mass budget of planet formation. Moreover, theoretical simulations of gravitational dynamics during planetary formation and evolution (Pfyffer et al. 2015) only account for $\sim 40\%$ of the amount of FFPs inferred by MOA, under the most optimistic scenario. Deriving the true mass function of FFPs with *K2C9* will address and help resolve this tension.

measurements for $\gtrsim 120$ events (see §4.2). In contrast with the 2014 and 2015 *Spitzer* programs, which require $\gtrsim 4$ days between target selection and observation, *K2C9* will be able to measure π_E for short-timescale events (t_E of-order 1 day), which are potentially indicative of free-floating planets (FFPs). Microlensing’s intrinsic sensitivity to bound planets beyond the snow line makes it an indispensable complement to radial velocity, transit, and direct imaging exoplanet searches that seek to improve demographic understanding and provide input for planet formation models. Furthermore, planetary systems with satellite parallax constraints will better our understanding of the frequency and distribution of planets at a wide range of distances from Earth. We lastly note that, as with *Spitzer*, it will be possible to probe the stellar remnant population (Shvartzvald et al. 2015), measure the mass of isolated objects such as stars and brown dwarfs (Zhu et al. 2015a), and determine the fundamental parameters for binary star systems (Zhu et al. 2015b).

3.1. Free-floating Planets

Sumi et al. (2011) announced the discovery of an excess of short-timescale microlensing events, with $t_E < 2$ days, discovered by the MOA survey, which they inferred to be caused by a population of “unbound or distant planetary-mass” objects with masses comparable to that of Jupiter and outnumbering main sequence stars by 2:1. Their results imply that these FFP candidates account for $\sim 1.8 M_{\text{Jup}}$ of planetary-mass objects per star on the main sequence, as highlighted in Figure 4.

Such a plenitude of FFPs stands in stark contrast to observations of bound planetary systems. Combining the

detailed statistical analysis of exoplanets discovered by microlensing and radial velocity surveys out to an orbital period of $\sim 10^5$ d (Clanton & Gaudi 2014b) and including planets with small radii inaccessible to RV surveys and planets orbiting more massive host stars (Fressin et al. 2013) only accounts for $\sim 0.4 M_{\text{Jup}}$ of bound planetary mass material per star. Extending out to the farthest reaches of stellar systems and adding, optimistically, cold-start-based upper limits from direct imaging searches for loosely bound planets around young stars only contributes at most an additional $\sim 0.6 M_{\text{Jup}}$ (Bowler et al. 2015). Furthermore, simulations by Pfyffer et al. (2015) of the formation and evolution of planetary systems without eccentricity damping eject planets at a rate that is a factor of ~ 2 lower than is needed to explain the MOA result.

If the short-timescale events discovered by MOA are in fact FFPs, these objects must thus dominate the mass budget of planet formation. Additionally, their abundance is severely underestimated by even the most detailed theoretical models of planetary dynamics. However, short-timescale microlensing events can also be caused by stars with large proper motions in the Galactic bulge or low-mass planets bound to but widely separated from their host star. It is thus of crucial importance to investigate the nature of events with short t_E and determine whether they are indeed caused by free-floating planetary-mass objects.

Satellite parallax measurements made with *K2* during C9 will help verify whether the cause of each of these short-timescale events is, in fact, a low-mass object. The NIR source flux measurements enabled with ground-based facilities (see §5) will then set the stage for follow-up high-resolution NIR observations that will help distinguish between a planet that is bound to but widely separated from its host star and one that is truly free-floating (see §2.2.3).

K2C9 presents another method for vetting FFP candidates. *K2* will take continuous observations with a photometric precision that is better than that attained by the ground-based telescopes. High-quality uninterrupted coverage of the source trajectory makes it possible to detect potential host stars, and with an efficiency that will be much higher than was possible for the Sumi et al. (2011) sample. Poleski et al. (2014) explored the regime in which a perturbation due to a bound planetary companion for an event with a large impact parameter u_0 would instead be classified as arising from a free-floating exoplanet.

3.2. Galactic Distribution of Exoplanets

Figure 5 shows planet mass M_p as a function of planetary system distance from Earth D_p for all verified exoplanets, with M_p and D_p data taken from the NASA Exoplanet Archive⁵⁸ (Akeson et al. 2013). While the 34 microlensing detections account for only $\sim 4\%$ of the 844 total such planets, they constitute $\sim 40\%$ (32 out of 78) of those with $D_p > 1000$ pc and $\sim 70\%$ (26 out of 36) of those with $D_p > 2000$ pc. We note that only half of the microlensing-discovered exoplanets have mass constraints either via π_E or NIR flux measurements, while

⁵⁸ <http://exoplanetarchive.ipac.caltech.edu/>

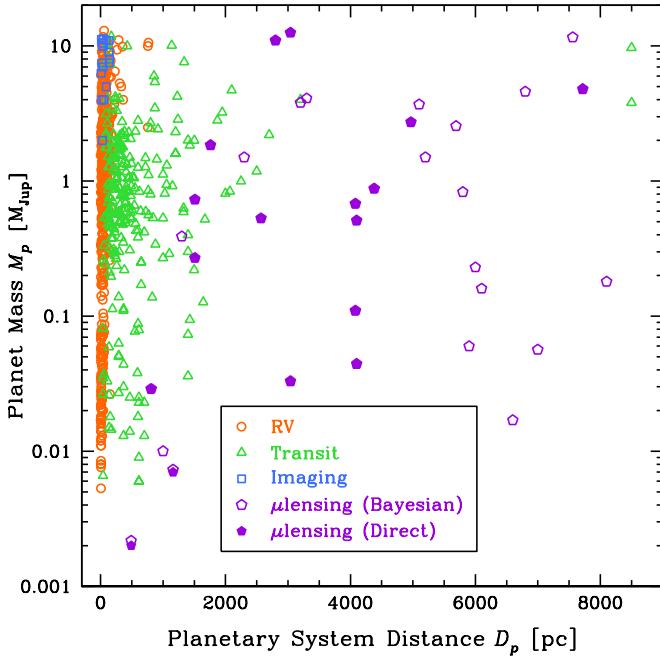


Figure 5. Planet mass M_p as a function of the distance to the planetary system from Earth D_p , with points styled according to discovery technique. The data were taken from the NASA Exoplanet Archive (Akeson et al. 2013). Of the 844 planets shown here, only 34 were discovered by microlensing. However, microlensing exoplanets are responsible for the vast majority of known systems with $D_p \gtrsim 2000$ pc ($\sim 70\%$). Efforts such as *K2C9* will improve our understanding of planet demographics throughout the Galaxy by helping to directly measure planet distances out to the bulge.

the rest rely on characterization through Bayesian analysis. There are thus only 17 microlensing planets (in 15 systems) with directly measured distances.

In order to best understand the frequency of planets in different stellar environments, it is crucial that any selection effects be well understood (see Street et al. 2015), a problem made tractable by the *K2C9* automated survey. Such an approach will not only then improve our understanding of planet demographics from the Solar neighborhood to the Galactic bulge but will also allow us to investigate planet occurrence rate as a function of, e.g., metallicity (Montet et al. 2014). Perhaps most compelling is that bound planetary systems with satellite parallax-derived masses and distances are invaluable as we strive toward a comprehensive picture of exoplanet demographics that can reconcile detections obtained using multiple techniques (Clanton & Gaudi 2014a,b, 2015).

4. *K2C9* OBSERVATIONAL SETUP

Gould & Horne (2013) identified that a repurposed *Kepler* spacecraft could be utilized as a microlens parallax satellite. They estimated that a 90-day survey of the Ecliptic that is coordinated with ground-based observatories would result in π_E measurements for several hundred microlensing events, including ~ 12 planetary in nature. *K2C9* is, in essence, a realization of this idea.

4.1. Campaign and Spacecraft Parameters

K2C9 will conduct an 86-day microlensing survey toward the Galactic bulge from 7/April through 1/July of 2016. The spacecraft will be re-oriented to point along its

velocity vector (+VV), enabling it to observe the bulge during a window when it is simultaneously visible for ground-based telescopes. The field center for C9 is located at (RA, Dec) = (18:01:25, -21:46:47). A minimum of 2.8 million pixels, or 3.4 deg^2 , will be dedicated to the microlensing survey, with the remaining $\sim 15\%$ of the downloadable area devoted to the *K2*'s Director's Discretionary Target program. In §4.2 we discuss the methodology used to determine the exact superstamp, or roughly contiguous selection of pixels to be downloaded, that will comprise the microlensing survey area for *K2C9*.

Figure 6 shows the orbits of the Earth, *Kepler*, and *Spitzer* (which will contribute simultaneous observations for the final 13 days of C9; see §6) throughout C9. The projected separation between *Kepler* and the Earth as viewed from the center of the *K2C9* superstamp, D_\perp , changes throughout the duration of the campaign, and dictates the range of θ_E for which the geometry will be most favorable for measuring π_E . We have created short movies to help visualize the temporal evolution of D_\perp over the course of C9 and to facilitate intuition about the satellite parallax effect. To browse and utilize both still-frame pdfs and animated gifs, please visit:

http://www.astronomy.ohio-state.edu/~henderson/k2c9_parallax_animations/

In addition to the re-orientation of the spacecraft, *K2C9* will feature several modifications to its standard observing procedure. To attain the survey area quoted above, *K2C9* will utilize a mid-campaign data downlink in order to increase the number of microlensing events for which π_E will be measured. This will divide the campaign into two halves denoted as C9a and C9b. Furthermore, careful exploration by the *K2* team has approved the possibility to add, to the target list for both C9a and C9b, postage stamps for individual microlensing events that will have been detected by the ground-based survey groups (see §5.1) and that will be ongoing and expected to peak during *K2C9*, increasing the number of events for which π_E can be measured. The deadlines for including ongoing events are listed in Table 1. A postage stamp for such an ongoing event will consist of a square of a few hundred pixels. To account for the additional data to be downlinked, each campaign half will be shortened by an amount of time that is proportional to the number of postage stamps included in the target list for these ongoing events. Given the low fractional cost of such events, the time required to account for these ongoing events will be small: of-order 20 minutes per 1,000 pixels, a factor that is likely less than the uncertainty in the data storage requirements onboard the spacecraft. We discuss the implementation and projected yields of this endeavor in §4.2.

All observations will be long cadence (i.e., 30-minute sampling). Within the first week after C9a and C9b have each concluded, the corresponding cadence pixel files will be available through the Mikulski Archive for Space Telescopes (MAST)⁵⁹. The pipeline-processed target pixel files for the full campaign will be posted to MAST on 26/September/2016. Table 1 describes all of the observational parameters for *K2C9*.

⁵⁹ <https://archive.stsci.edu/>

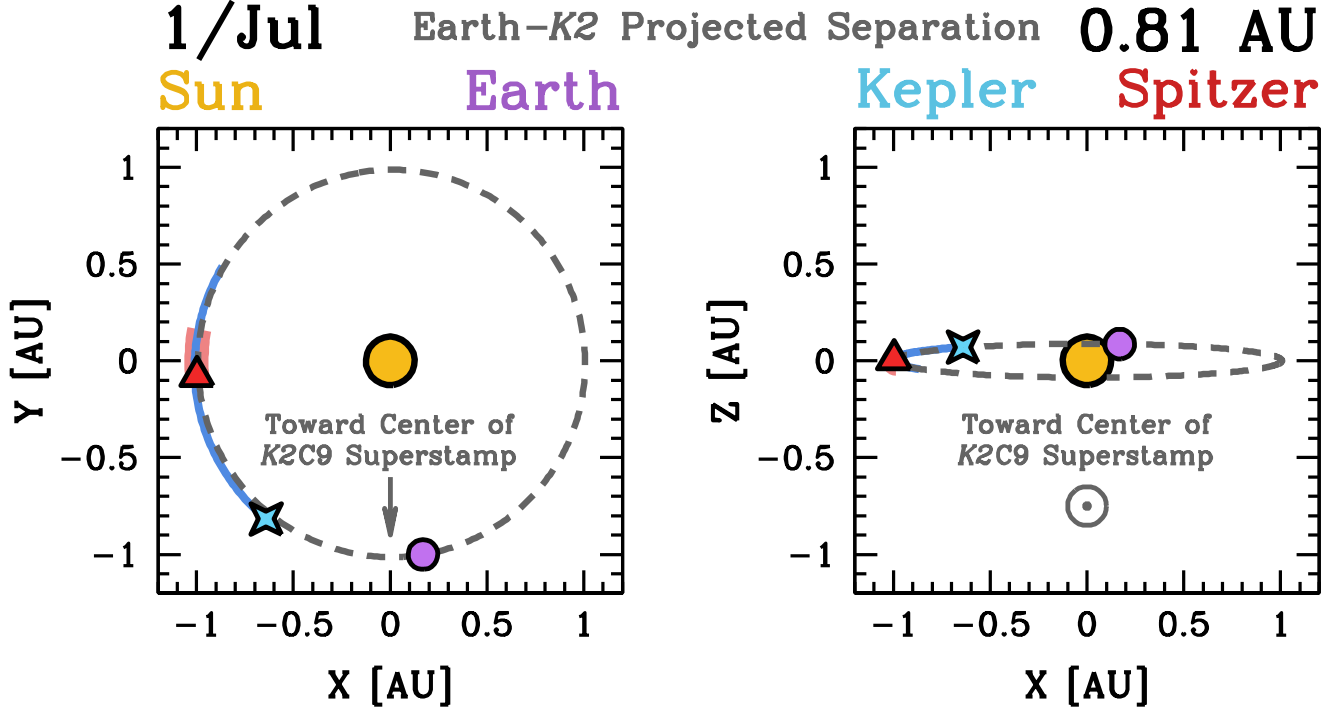


Figure 6. The temporal evolution of the orbits of the Earth, *Kepler*, and *Spitzer* throughout C9. We have furthermore created short videos to help visualize and make intuitive the satellite parallax effect as it will be measured during *K2C9*. Both still-frame pdfs and animated gifs, along with a brief README file, can be found here: http://www.astronomy.ohio-state.edu/~henderson/k2c9_parallax_animations/.

Table 1
K2C9 Observational Parameters

Key Dates ^a	
<i>Superstamp pixel selection deadline</i> C9a	25/January
Ongoing event upload deadline	1/March
Observing window	7/April–18/May
Raw data available at MAST	24/May
<i>Mid-campaign break (data downlink)</i> C9b	19–21/May
Ongoing event upload deadline	25/April
Observing window	22/May–1/July
Raw data available at MAST	6/July
Processed data available at MAST	26/September
Superstamp Center (approximate)	
RA (hh:mm)	17:57
Dec (dd:mm)	-28:24
Aperture [m]	0.95
Plate Scale [″ pixel ⁻¹]	3.98
Pixels [×10 ⁶]	2.8
Survey Area [deg ²]	3.4
Cadence [min]	30

^a All dates are in 2016.

4.2. Pixel Selection

The *K2* camera has a full FoV of 105 deg². However, only a few percent of the pixels can be downloaded due to limited data storage. Prior *K2* campaigns thus observed a postage stamp of pixels for each individual pre-selected target star. Since C9 will conduct an automated survey to detect lensing events, which are transient and inherently unpredictable, the pixels that will be downloaded will instead form a roughly contiguous region, or superstamp. The highest scientific return of *K2C9* comes from

the events that are observed both from *K2* and from the ground. We select the survey superstamp to optimize the predicted number of events observed from Earth since the ground-based event rate is far better understood than that expected for *K2*.

To predict the ground-based event rate across the full *K2C9* FoV we use the framework presented by Poleski (2016). He showed that the number of standard events, or events well-described by a single-lens model (i.e., excluding two-body lensing events or single-lens events with strong finite-source effects), detected by the OGLE-III survey is a linear function of the product of two observables that can be measured relatively easily: the surface density of red clump (RC) stars (N_{RC}), and the surface density of all stars brighter than the completeness limit ($N_*(I < 20 \text{ mag})$). The reasoning behind this linear relation is a simple model: the event rate should be a product of number of potential lenses (which correlates with N_{RC}) and the number of potential sources (approximated by $N_*(I < 20 \text{ mag})$). RC stars are used because it is possible to use a color-magnitude diagram to identify and count them in all but the highest-extinction regions. The final formula of Poleski (2016) modifies this product slightly by varying the brightness limit and the exponent of N_{RC} as such:

$$\frac{\gamma(t_E > 8 \text{ d})}{\text{deg}^{-2}\text{yr}^{-1}} = 0.767 \left(\frac{N_{\text{RC}}}{10^3 \text{ deg}^{-2}} \right)^{0.55} \times \left(\frac{N_*(I < 20.5 \text{ mag})}{10^6 \text{ deg}^{-2}} \right) - 14.6, \quad (6)$$

to better fit the data. Here $\gamma(t_E > 8 \text{ d})$ is the observed number of standard events per year per deg² with t_E

longer than 8 d. The limit on the event timescale was applied in order to reduce the impact of the varying OGLE-III observing cadence, and it removed 14% of events in the best-observed fields. The $\gamma(t_E > 8 \text{ d})$ was estimated based on the catalog of standard microlensing events in the OGLE-III survey (Wyrzykowski et al. 2015). The OGLE-III catalog is the largest database of microlensing events selected in a uniform way and with minimal contamination from false positives. Poleski (2016) limited the sample to events observed in fields with an average of 165 epochs per year. The N_{RC} values were taken from Nataf et al. (2013) and N_* values were calculated based on Szymański et al. (2011).

The *K2*C9 superstamp should balance yielding the highest possible event rate with facilitating ground-based tiling strategies with the highest cadences and coverage of the superstamp. Such a task is complicated by the fact that, unlike the *K2*C9 footprint, most ground-based cameras are aligned with the equatorial coordinate grid. For the superstamp pixel selection we divide every *K2* channel of 1100×1024 pixels into an 11×10 grid, resulting in $6.6' \times 6.8'$ regions. Each such region is included or excluded as a whole. Some regions that have a high expected event rate will subtend small areas with high extinction that do not contribute to the event rate, but we do not exclude these sub-regions. Some of the bulge regions with high event rate are beyond the OGLE-III footprint and thus are not included in the RC density study by Nataf et al. (2013). However, we are able to extrapolate the Nataf et al. (2013) N_{RC} values since they correlate with the Galactic bulge density profile of Kent (1992).

We use this correlation to estimate N_{RC} across the entire *K2*C9 footprint. We find $N_*(I < 20.5 \text{ mag})$ values using the reference images of the ongoing OGLE-IV survey (Udalski et al. 2015a). The OGLE-IV reference images do not cover full Galactic bulge, but the missing areas show low event rates in optical bands. We estimate the event rate for each $6.6' \times 6.8'$ region and select those with the highest event rate until we have accumulated the current estimate of the total survey area of 2.8 million pixels. One of the regions with the highest event rate as selected in this manner is located in the northern bulge region at $(l, b) = (2.8^\circ, +3.7^\circ)$. Given the high observational cost of covering this single $6.6' \times 6.8'$ region from the ground we reject it from the final *K2*C9 superstamp. All other selected regions fall in five *K2* channels. We note that the area of the final superstamp has been observed by microlensing surveys for many years and that many variable stars have been catalogued. Specifically, there are up to 1000 RR Lyr stars per deg^2 (Soszyński et al. 2011). Such information about variable stars will be used to improve photometry of microlensing events and will allow independent studies that are not the primary science driver for the *K2*C9 microlensing experiment.

Figure 7 shows the 2.8 million pixels, or 3.4 deg^2 (see Table 1 for all *K2*C9 parameters), that comprise the final *K2*C9 superstamp. Equation (6) predicts that 105 standard events will occur within the superstamp throughout the entire bulge observing season (early February through early November). Including events with $t_E > 8 \text{ d}$ and scaling to the higher cadence of OGLE-IV (20 min) gives 285 events. Including non-standard events results

in as many as 320 events. Out of these, 121 should peak during *K2*C9, but it is not guaranteed that the peak for every event will be seen in the *K2* data, particularly given the shift induced by the satellite parallax. Similarly, there can be events that are found in the *K2* data that are below the detection threshold for ground-based surveys. We note that in some cases the microlens parallax can be measured using ground-based and satellite photometry event if a satellite did not observe the peak of the event (Calchi Novati et al. 2015). Additional events will probably be recovered in the ground-based data after the campaign.

The deadline by which the superstamp must be finalized and sent to NASA is 25/January/2016. However, even after this date it will be possible to add to the target list postage stamps that correspond to microlensing events within the *K2*C9 FoV (but outside the superstamp) that have been detected by the ground-based surveys. The deadline for adding events that are expected to peak at any point during *K2*C9 is 1/March/2016. Similarly, the deadline for events detected by ground-based surveys that are expected to peak during C9b is 25/April/2016. We estimate there to be 10 and 35 events detected before these dates, respectively, but emphasize the numbers strongly depend on the observing strategy for the OGLE, MOA, and RoboNet surveys, which would be the facilities identifying these events. Given the morphology of the microlensing event rate across the bulge, the majority of these events will be located close to the survey superstamp. Furthermore, only a subset of these additional ongoing events will actually *peak* during *K2*C9 because of the relatively long delay between the selection dates and the start of observations.

Finally, we note that covering the *K2*C9 superstamp with ground-based surveys requires observations of a larger area than the area of the *K2*C9 superstamp, given the gaps between the *K2* channels (e.g., near $\text{RA} = 270.5^\circ$). Any microlensing events and other time-variable sources that are not seen by *K2* but that are within the areas covered by the ground-based surveys will have high-cadence multi-wavelength coverage, allowing in-depth study.

4.3. Photometric Methodology

Potentially the most important task of the Microlensing Science Team (MST) is to develop the tools necessary to extract photometry from the *K2*C9 data. Accurate photometry of faint stars in very crowded fields must be measured from *K2* images that have large pixels ($4''$), a PSF that is poorly sampled and at some level variable, and a non-uniform intra-pixel response. Figure 8 underscores this with a CDF of the stellar density in one of the regions central to the *K2*C9 superstamp, where there are ~ 3 stars per Kepler pixel with $I \lesssim 20$. These problems are further complicated by the drift of stars across the focal plane that is caused by the torque of the Solar wind and is of-order 1 pixel/6 hours.

The majority of the MST members are working on some aspect of the photometry problem, with support from both their proposed co-investigators and also volunteers. Members of the MST will develop several photometric pipelines to process the *K2*C9 data. The first, relying on difference imaging software designed for ground-based images, will provide quick-look photometry with

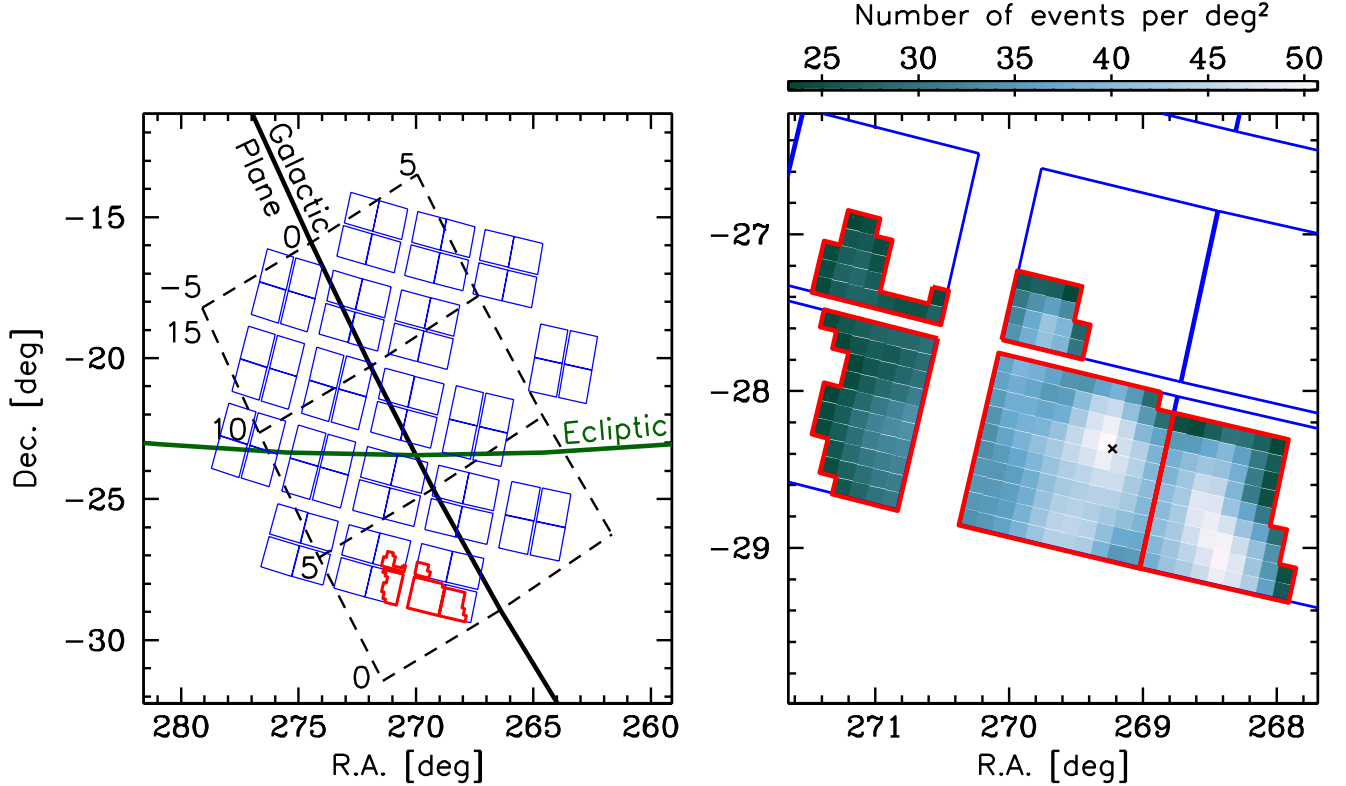


Figure 7. The full *K2*C9 FoV (outlined in blue) and the final superstamp (red) as selected by the methodology described in §4.2. In the right panel the black cross identifies the center of the region used to create Figure 8. These 2.8 million pixels, or 3.4 deg^2 (see Table 1 for all *K2*C9 parameters), will produce an estimated ~ 120 events that will peak in the ground-based data during the campaign. Some number of ongoing events located outside the superstamp may be added to the target lists for C9a and C9b.

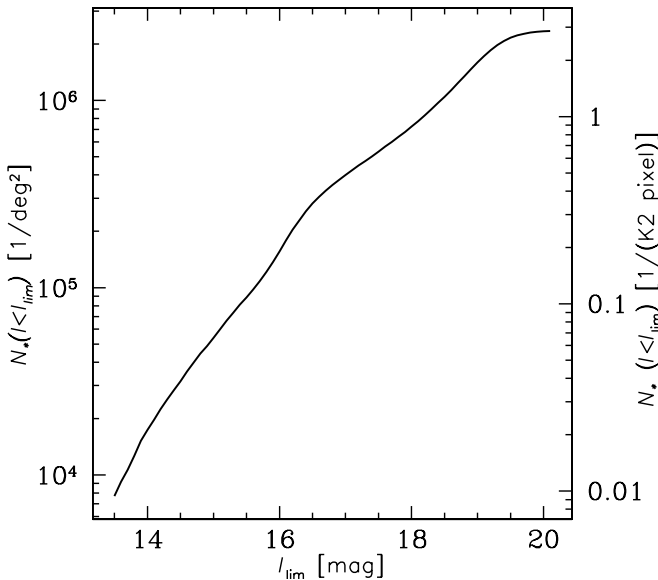


Figure 8. The cumulative distribution function of the number of stars brighter than a given limiting magnitude per square degree (left axis) and per *K2* pixel (right). The data were taken from the OGLE-III maps of Szymański et al. (2011) for an $8' \times 17'$ subfield centered on $(\text{R.A., Dec}) = (269.225^\circ, -28.3681^\circ)$. The plot extends to $I \sim 20$, at which there are ~ 3 stars, on average, per *Kepler* pixel. This underscores one of the many challenges of performing crowded-field photometry toward the Galactic bulge with *K2* data.

no reliance on additional data. A second technique will construct difference images for individual pixels and then fit the light curve parameters. Thirdly, forward model difference imaging will use ground-based images and/or photometric catalogs to enable accurate modeling of the *K2*C9 images. We will briefly describe the plans for all pipelines here, which are being developed and tested on data taken during Campaign 0 of the dense open cluster NGC 2158.

Difference image analysis (DIA; Tomaney & Crotts 1996; Alard & Lupton 1998) uses convolution to match the PSF of a high-quality reference image to that of a generally poorer-quality target image in order to enable the reference image to be subtracted from the target image, leaving only variable objects with non-zero flux in the residuals that comprise the difference image. It is typically used on well-sampled ground-based images for which the variations in the PSF are caused by time-dependent changes in the seeing. The *K2* data differ significantly from the usual application of DIA in that the PSF does not differ significantly over the entire data set, and that the PSF is severely undersampled, suggesting that without significant modification, standard DIA software packages might not work well on *K2* data. Early experiments with Campaign 0 data of NGC 2158 seem to confirm this. However, Penny & Stanek (2016, in prep) showed that by first convolving the *K2* images with a Gaussian in order to produce a well-sampled PSF, an algorithm that pairs the ISIS package (Alard & Lupton 1998; Alard 2000) with rudimentary detrending against

pointing shifts could produce photometry of quality sufficient to detect and measure the variability of almost all known variable stars in the NGC 2158 cluster, including, most importantly, those with magnitudes and amplitudes similar to the microlensing events that will be observed in *K2*C9. The *K2*C9 pipeline based on this method will produce a light curve for every pixel in the *K2*C9 superstamp, as each pixel will contain several stars (see Figure 8). Quick-look DIA light curves of known microlensing events will be delivered to the Exoplanet Follow-up Observing Program (ExoFOP) site (see §7.1) as soon as they are processed. A full catalog of light curves for all pixels will be hosted on the NASA Exoplanet Archive at a date to be determined once the pipeline’s performance has been evaluated.

A second difference imaging technique being investigated involves extending the detrending procedure on resolved stars to individual pixels, or combinations of pixels. Applying the procedure to pixel-by-pixel light curves will generate a series of residual images. These can be used in a similar fashion to classical difference images in that they can be used to identify the locations of variable stars, including microlensing events. One approach to extracting photometry for variable stars is to combine the modeling of the intrinsic shape of the light curve profile with the detrending procedure. By iteration, it is thus possible to find an optimal set of light curve parameters. This method has been applied on eclipsing binaries within NGC 2158 using a simple model for the shape of the eclipse profiles. Preliminary results have yielded a photometric precision of a few millimag for 15th-magnitude eclipse eclipsing binaries, and this same approach can be taken for microlensing events.

A final methodology involves forward modeling the *K2* images using either star catalogs or higher-resolution ground-based images as the input. Forward modeling refers to the process of producing a generative model of the *K2* data by modeling the process by which stars cause charge to be collected in *Kepler*’s pixels. For our purposes, this will involve the production of a model image for each 30-minute cadence from a model of the *Kepler* pixel response function (PRF) and a set of input data. This model image will then be subtracted from the actual data, enabling photometry of the much less crowded variable sources that remain in the subtracted image. For each cadence the *Kepler* PRF (as a function of wavelength and position) will be fit for (using well measured *Kepler* PRFs as strong priors) together with the pointing, roll, and distortion of the focal plane in order to produce each model image. If, rather than a catalog, ground-based images are used for the input, a convolution kernel that matches the ground-based PSF to *Kepler*’s will be fit for instead of the PRF itself. Because the pipeline for this method will rely on other data and the technique is new and will likely require more computing power, we expect the outputs of the pipeline to be delayed relative to the DIA-based pipeline. However, we expect the photometry from this pipeline to improve significantly upon that from the DIA pipeline, enabling many additional microlensing events to be detected and measured from *K2*.

The MST and many members of the larger exoplanetary microlensing community have worked to secure a substantial network of ground-based resources that will observe in concert with *K2*C9. We broadly classify them according to four primary scientific motivations — automated survey, high-cadence follow-up, multiband photometric monitoring, and NIR source flux measurement — and discuss each in greater detail below. Figure 9 provides a map of the contributing observatories and Table 2 lists the parameters of each facility. It is important to note that the specifications of available resources and their exact observing plans are subject to modification prior to the start of *K2*C9; the final version of this paper will contain a more accurate accounting. We then conclude with a discussion of the value of and efforts for real-time modeling of microlensing events during *K2*C9.

5.1. Automated Survey

The OGLE survey has been monitoring the Galactic bulge for microlensing phenomena for the last 24 years. Since the discovery of the first microlensing event toward the Galactic bulge (Udalski et al. 1993), OGLE has detected over 17,000 microlensing phenomena. The vast majority of them were alerted to the community via the OGLE Early Warning System⁶⁰ (Udalski et al. 1994). In its current fourth phase, the OGLE-IV survey discovers over 2,000 real-time microlensing events annually, which constitutes about 90% of lensing events toward the bulge. The OGLE-IV facilities are located at the Las Campanas Observatory (LCO) in Chile. The 1.3m Warsaw telescope and 256 Megapixel, 32-CCD detector mosaic camera, which covers 1.4 square degrees, have been used by OGLE-IV since 2010. In 2016 OGLE-IV will continue its extensive monitoring of the Galactic bulge fields, adjusting somewhat the observing strategy to maximize coverage of the *K2*C9 superstamp. Also, considerable effort will be undertaken to detect a significant number of promising microlensing events outside the main superstamp region.

MOA has similarly spent over a decade monitoring of the Galactic bulge to detect exoplanets via microlensing. The second generation of MOA, MOA-II, is a 1.8m telescope with a 2.2 deg² FoV located at Mt. John University Observatory (MJUO) in New Zealand. It will continue its concerted effort to reduce data daily and publish and circulate alerts of new microlensing events through their Transient Alert System⁶¹. Both OGLE-IV and MOA-II will observe the entire *K2*C9 superstamp with a cadence that is $\lesssim 1$ hour. Each will conduct their survey in a primary filter, *I* for OGLE-IV and MOA-red for MOA-II, with occasional observations in *V* for both surveys for source color measurements. Table 2 provides a detailed list of the parameters of each facility.

The Las Cumbres Observatory Global Telescope (LCOGT) network, which consists of multiple telescopes at several northern and southern hemisphere sites, will also perform survey-mode operations during *K2*C9. At each of CTIO, SAAO, and SSO they expect to have equipped one 1.0m telescope with a 26' \times 26' Sinistro imager to provide survey capabilities at a wider range of sites and longitudes. Wise Observatory in Israel will

⁶⁰ <http://ogle.astrouw.edu.pl/ogle4/ews/ews.html>

⁶¹ <https://it019909.massey.ac.nz/moa/>

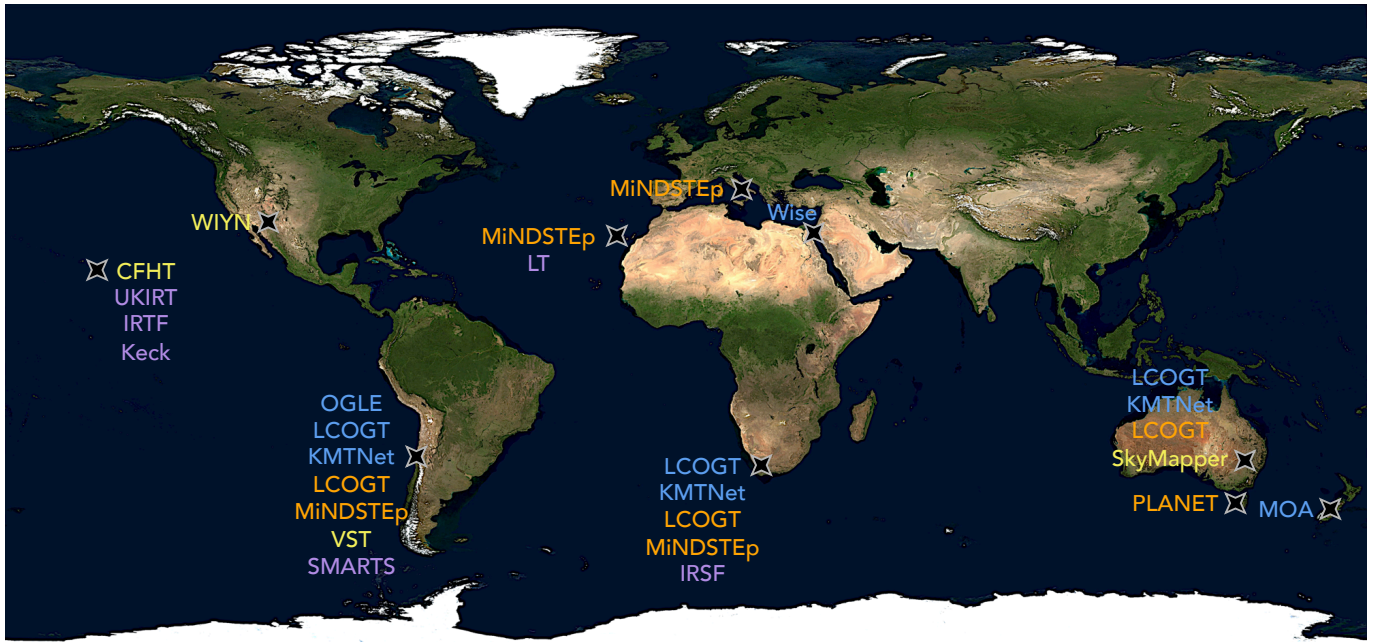


Figure 9. A map of all ground-based telescopes that the MST and others have procured to observe during *K2C9*. Each is color-coded according to its primary scientific goal: automated survey (blue), high-cadence follow-up (orange), multiband photometric monitoring (yellow), and NIR source flux measurement (purple). Such a concerted effort will help to optimize the scientific return of *K2C9*.

operate the Jay Baum 0.71m telescope, with a 1.0 square-degree FoV, to cover the *K2C9* superstamp with 6 fields at a cadence of ~ 30 minutes, and will use a blue-blocking Astrodon exoplanet filter that permits only $\lambda > 5000\text{\AA}$. Finally, KMTNet will tile a substantial fraction of the *K2C9* superstamp in *I*-band with a cadence of ~ 10 minutes. Together, OGLE-IV, MOA-II, LCOGT, and KMTNet will provide the dense coverage necessary to detect microlensing events and, in the case of OGLE-IV and MOA-II, generate and circulate alerts for new events on a \sim daily timescale. Such information is not only crucial for constructing a database of known microlensing events within the *K2C9* superstamp but also for providing real-time updates to targeted follow-up groups (see §5.2) and quick-look photometry for real-time modeling analysis (see §5.5), which itself is also useful for follow-up observations across all wavelengths.

5.2. High-cadence Follow-up

Although the current generation of microlensing surveys are able to observe many square degrees at an \lesssim hourly cadence, there are many advantages of collecting yet higher-cadence follow-up photometry of individual events. The first is for event characterization. While survey groups are indeed able to detect events as well as the perturbations induced by the presence of a planet, observing at a rate of several times more frequently can provide the most robust interpretation of the lens system, particularly in the case of high-magnification events (Yee et al. 2012; Han et al. 2013; Yee et al. 2014; Gould et al. 2014). Furthermore, a higher cadence is optimal for securely detecting higher-order effects in light curves, including orbital and terrestrial parallax (see §2.2.2) as well as orbital motion in the lensing system (Dominik 1998; Albrow et al. 2000; Shin et al. 2011; Skowron et al. 2011; Jung et al. 2013), which causes the location and mor-

phology of the caustics to change as a function of time. A final benefit is that smaller-aperture smaller-FoV facilities can obtain observations if time is anticipated to be lost due to technical problems or weather for a survey telescope at a similar longitude.

To this effect LCOGT will operate two 1.0m telescopes each at CTIO and SAAO and one 1.0m at SSO, all with a $15' \times 15'$ FoV, as well as a 2.0m telescope at SSO with a $10' \times 10'$ FoV. These will produce concentrated *i*-band observations of selected events during *K2C9*. The PLANET collaboration will operate the 1.3m Harlingen telescope at the University of Tasmania, Greenhill Observatory (UTGO). During the campaign it will be primarily dedicated to follow-up of *K2C9* microlensing targets in *V* and *I* with a $20' \times 20'$ FoV camera. The observations will be coordinated with other facilities operated by LCOGT and the MST. PLANET will provide real-time photometry of the observed microlensing events and alerts for potential anomalies. MiNDSTeP will contribute continuous high-cadence extended *V* and *I*-band observations from the Danish 1.54m telescope at ESO's La Silla observatory in Chile, equipped with a two-color EMCCD lucky imaging camera with a $45'' \times 45''$ FoV, operated at 10 Hz time resolution (Skottfelt et al. 2015), and continuous high-cadence *I*-band observations from the Salerno University 0.6m telescope located in Fisciano, Italy, equipped with a CCD camera with a $22' \times 22'$ FoV. MiNDSTeP also expects to provide *I*-band observations from the MONET-South 1.2m telescope at SAAO in South Africa, equipped with a back-illuminated CCD camera and a FoV of $12.6' \times 12.6'$, and from the 1m SONG Hertzprung telescope at Tenerife, equipped with an EMCCD lucky imaging camera with a $40'' \times 40''$ FoV. Additionally, the SMARTS 1.3m telescope at CTIO, the 2.0m Liverpool Telescope (LT) at La Palma, and the 3.0m Infrared Telescope Facility (IRTF) at Mauna Kea,

the primary purpose of all of which is for NIR source flux measurement for short-timescale events (see §5.4), will take high-cadence follow-up observations in optical bands. The parameters of each of these resources is included in Table 2.

5.3. Multiband Photometric Monitoring

Multiband time-series photometry plays two critical roles for *K2*C9, and in both cases the goal of the observations is to measure the color and magnitude of the source star. Firstly, knowledge of the source color will be invaluable in measuring all parameters of the microlensing events seen from *Kepler*. This is because the events seen by *Kepler* will be highly blended, and will be in the so-called pixel lensing regime (Crotts 1992; Baillon et al. 1993), wherein the impact parameter u_0 , timescale t_E , and the source flux relative to blended light are strongly degenerate (see Riffeser et al. 2006 for an overview). The impact parameter must be measured in order to determine the parallax, so if the degeneracy is not broken it is only possible to measure one-dimensional parallaxes (Gould 2014). However, if the source magnitude in the *Kepler* bandpass can be inferred from ground-based monitoring of the event in one or more filters, and if the timescale is also measured from the ground-based event, the impact parameter for *Kepler* can be measured. *Kepler*'s bandpass is broad, covering $\sim 430\text{--}880$ nm, and so covers *BVR* or *griz* bandpasses, though with only partial overlap of *B*, *g*, and *z*. Reconstruction of the source's *Kepler* magnitude K_p can best be done with knowledge of the source magnitude in several filters that cover the *Kepler* bandpass (especially in regions where there is significant differential extinction), but it can also be achieved to lesser accuracy with just a single color.

The second application of a source color is the measurement of the source's angular diameter through a color-angular diameter relation. This becomes important if the microlensing light curve displays finite-source effects, as this allows the conversion of these effects into a measurement of the angular Einstein ring radius θ_E (Yoo et al. 2004), which together with microlens parallax π_E can be used to fully solve the event and measure the lens mass M_ℓ and the lens-source relative parallax π_{rel} (see §2.2.2). The angular diameter measurements are best made using the widest practical wavelength baseline; $V - I$ has sufficient baseline and is regularly used in practice, and $r - z$ has a similar baseline but may be more useful in regions of high extinction. If NIR measurements are possible, then visual minus NIR colors can be used and may prove to be more accurate.

In all cases, measurements of the source color must be made using time-series photometry in order to separate the varying, magnified source flux from any blended light whose magnitude is constant in time. For short-timescale FFP events, there may not be enough time to alert follow-up observations to obtain multicolor observations, so it is necessary to survey the entire C9 superstamp with a cadence of at least a few hours in each filter in order to ensure the color measurements are possible.

There are several facilities that will contribute the aperture and FoV necessary to obtain multiband photometric monitoring across the *K2*C9 superstamp. Table 2 details the parameters of each of them. The OGLE and MOA surveys will obtain occasional *V*-band data

(see Table 2), which will provide source color measurements for some events. But, as explained above, it is important to measure the source color for all events, regardless of timescale or magnitude, and to do so in multiple filter combinations and across long wavelength baselines. The Canada France Hawai'i Telescope (CFHT) on Mauna Kea, with a 3.6m aperture and 1.0 deg^2 FoV, will take *gri* data twice per night. SkyMapper, a 1.3m telescope with a 5.6 deg^2 FoV located at SSO, will cycle through *griz* every 2–3 hours. The one-degree imager on the WIYN 3.5m at Kitt Peak will take *r*- and, less frequently, *i*-band images. Lastly, the 2.6m ESO-operated VLT Survey Telescope (VST), which has a $1.0 \text{ square-degree}$ FoV and is located in Cerro Paranal, will contribute *V* and *r* observations ~ 3 times per night. However, even with the involvement from all of these observatories, telescope and instrument scheduling means that the color coverage is not complete over the entire campaign. There is thus a significant role to be played by follow-up observations. Additionally, there will be no survey-style multiband coverage for events outside the superstamp, so color follow-up observations are essential for interpretation of events monitored by *K2* outside the superstamp.

5.4. NIR Source Flux Measurement

By tiling the *K2*C9 superstamp with NIR facilities it will be possible to determine the NIR source flux of most if not all microlensing events. As discussed in detail in §2.2.3, such an effort will provide a second method by which to directly measure (M_*, M_p, D_ℓ) that is independent from π_E . *K2*C9, then, will provide a large control sample with which we can refine and calibrate the flux characterization-derived results with satellite parallax values, which moreover is crucial pathfinding work in advance of *WFIRST* (Spergel et al. 2015), as NIR flux characterization may be the dominant mechanism by which to derive the fundamental parameters of the planetary systems *WFIRST* will detect. Additionally, NIR source flux measurements are integral to ultimately deriving the strongest constraints possible on the nature of FFP candidates.

The United Kingdom Infrared Telescope (UKIRT), with a 3.8m aperture and a 0.20 deg^2 FoV, will conduct an automated survey of the *K2*C9 superstamp through the campaign with a cadence of 2–3 observations per night. In principle this will be sufficient to measure the NIR source flux for all microlensing events save those with the very shortest timescales. As these are characteristic of FFPs, one of the primary scientific drivers for *K2*C9, the MST have worked to procure an array of NIR facilities able to trigger NIR follow-up for these events. Specifically, the SMARTS 1.3m at CTIO, the IRTF at Mauna Kea, the LT at La Palma, and the 1.4m Infrared Survey Facility (IRSF) at SAAO will all target individual microlensing events to guarantee NIR source flux measurements.

Table 2
Ground-based Observing Resources Concurrent with *K2*C9

Strategy	Group/Telescope	Site	Aperture [m]	FoV	Filter(s)	Cadence [obs/unit time]	Availability ^a (K9C9: 7/April–1/July)
Automated Survey	OGLE	LCO	1.3	1.4 deg ²	<i>I</i>	20 minutes	7/April–1/July ^b
	MOA	MJUO	1.8	2.2 deg ²	<i>V</i> MOA-red ^c	1–2/night 15–90 minutes	7/April–1/July ^b
	LCOGT	CTIO SAAO SSO	1.0 1.0 1.0	26′ × 26′ 26′ × 26′ 26′ × 26′	<i>i</i> <i>i</i> <i>i</i>	nightly nightly nightly	7/April–1/July 7/April–1/July 7/April–1/July
	Wise KMTNet	Wise Observatory CTIO SAAO SSO	0.71 1.6 1.6 1.6	1.0 deg ² 4.0 deg ² 4.0 deg ² 4.0 deg ²	Astrodon ^d <i>I</i> <i>I</i> <i>I</i>	~30 minutes ~10 minutes ~10 minutes ~10 minutes	7/April–1/July 7/April–1/July ^b 7/April–1/July ^b 7/April–1/July ^b
	LCOGT	CTIO SAAO SSO	1.0 (2) ^e 1.0 (2) ^e 1.0	15′ × 15′ 15′ × 15′ 15′ × 15′	<i>gi</i> <i>gi</i> <i>gi</i>	— — —	7/April–1/July 7/April–1/July 7/April–1/July
	LT SMARTS	La Palma CTIO	2.0 2.0 1.3	10′ × 10′ 10′ × 10′ 6.3′ × 6.3′	<i>i</i> <i>gi</i> <i>I</i> <i>V</i>	— — — —	7/April–1/July 7/April–1/July 7/April–1/July 7/April–1/July
High-cadence Follow-up	IRTF	Mauna Kea	3.0	60′′ × 60′′	<i>I</i>	—	20–25/May, 28/May–3/June, 6–10, 14–20, 24–26, 28/June
	MINDSTEP	La Silla Fisciano SAAO Teide UTGO	1.54 0.6 1.2 1.0 1.3	45′′ × 45′′ 22′ × 22′ 13′ × 13′ 40′′ × 40′′ 20′ × 20′	<i>VI</i> <i>I</i> <i>I</i> <i>I</i> <i>VI</i>	— — — — —	15/April–1/July 7/April–1/July 7/April–1/July 7/April–1/July 7/April–1/July
	PLANET						
	CFHT	Mauna Kea	3.6	1.0 deg ²	<i>gri</i>	3 hours	TBD
	SkyMapper	SSO	1.3	5.6 deg ²	<i>griz</i>	2–3 hours	7/April–1/July
	WTYN	Kitt Peak	3.5	0.53 deg ²	<i>i</i>	30 minutes	9–14/May, 27/May–4/June, 5–9/July
Multiband Photometric Monitoring	VST	Cerro Paranal	2.6	1.0 deg ²	<i>r</i> <i>Vr</i>	nightly ~3/night	7/April–1/July
	UKIRT	Mauna Kea	3.8	0.2 deg ²	<i>H</i>	2–3/night	7/April–1/July
	SMARTS	CTIO	1.3	2.4′ × 2.4′	<i>H</i>	targeted	7/April–1/July
	IRSF	SAAO	1.4	7.7′ × 7.7′	<i>JHK</i> ^f	TBD	TBD
	LT	La Palma	2.0	6′ × 6′	<i>H</i>	targeted	7/April–1/July
NIR Source Flux Measurement	IRTF	Mauna Kea	3.0	60′′ × 60′′	<i>H</i>	targeted	20–25/May, 28/May–3/June, 6–10, 14–20, 24–26, 28/June
	Keck	Mauna Kea	10.0	40′′ × 40′′	<i>H</i>	4 ToO triggers	7/April–1/July ^g

^a Only dates during *K2*C9 are considered here, though many contributing facilities may observe within the *K2*C9 superstamp prior to and following C9.
^b Observations of the *K2*C9 superstamp will occur during the entire bulge observing season, guaranteeing coverage of events that peak before and after C9.
^c The MOA-red filter is well approximated by $R+I$.
^d This filter blocks light with $\lambda < 5000\text{\AA}$.
^e LCOGT will operate multiple telescopes with the specified aperture at the specified site.
^f IRSF will take data in all three filters (*JHK*) simultaneously.
^g The Keck ToOs are only guaranteed possible during Caltech and U of C system allocations on Keck 2.

A final, experimental venture to this end is the use of NIRC2 on Keck to trigger target-of-opportunity (ToO) observations of hand-picked short-timescale events. The MST was awarded four such ToO triggers during *K2*C9, the goal being to obtain the first epoch of magnified NIR data for short-timescale FFP candidates described in §2.2.3. It is true that all of the NIR resources that have hitherto been discussed are able to accomplish this task. Nevertheless, as the second epoch must necessarily be taken with a high-resolution facility, if the first epoch can be taken using the same instrument on the same telescope, all uncertainty introduced by calibrating the data is removed, allowing for the strongest possible lens flux constraints. In Table 2 we provide a catalog of the parameters of all observatories.

5.5. Real-time Modeling

Along with the aggregation of telescopes listed above, a real-time modeling effort will be essential to the success of *K2*C9. While *K2* itself and many of the ground-based facilities will operate in an automated fashion, all targeted data collection efforts, and in particular those contributing NIR imagers, will benefit from and rely on some form of real-time event analysis. This capability helps efficaciously allocate resources to events with high observational and/or scientific priority via rapid interpretation of the temporal evolution of the events. In specific, predictions by real-time modeling efforts help to predict caustic crossings in order to guarantee the dense observations necessary to constrain the microlensing observables (see §2.1). Furthermore, the rapid and robust determination of short-timescale microlensing events is crucial for any NIR facilities. Having a well-developed modeling pipeline is of paramount importance for eliminating false positives and utilizing the Keck ToO triggers on the candidates most likely to yield secure FFP detections. A prompt classification of anomalous events can also be useful for deploying additional ToO facilities for genuine planetary events, identifying stellar binary contaminants, and preventing the use of expensive facilities on less interesting events. Within the microlensing community, there are several active groups providing real-time modeling of binary and planetary events. These groups have developed their own codes using different algorithms that naturally provide independent checks for the proposed solutions. The modeling of binary microlensing events is made particularly difficult by the existence of caustics (see §2.1), which rapidly change their shapes for small variations in the parameters and may abruptly create peaks or dips in the light curves. For this reason, many disconnected local minima for the chi-squared function can coexist in the parameter space. With the purpose of making the exploration as exhaustive and fast as possible, two strategies have been proposed to set the initial conditions of downhill fitting: a grid search in the parameter space, or template-matching from a wide library of light curves (Mao & Di Stefano 1995; Liebig et al. 2015).

6. SYNERGY BETWEEN *K2*C9 AND *Spitzer* MICROLENSING

From June 18 to July 26 in 2016, *Spitzer* will also be able to observe the Galactic bulge, and this leads to a 13-day overlap with the *K2*C9 window.

Gould, Yee, and Carey have an accepted *Spitzer* program to conduct a two-satellite microlensing experiment (PI: A. Gould, Gould et al. 2015). The primary goal of this *K2* plus *Spitzer* endeavor is to demonstrate the idea of using an additional satellite to break the four-fold degeneracy that is present in the case of observations from a single-satellite (in addition to those from the ground) (Refsdal 1966; Gould 1994). In a single-satellite experiment (e.g., *K2*C9 or *Spitzer*), the microlens parallax vector is given by

$$\pi_E = \frac{AU}{D_\perp} \left(\frac{\Delta t_0}{t_E}, \Delta u_0 \right). \quad (7)$$

Here $\Delta t_0 \equiv t_{0,\text{sat}} - t_{0,\oplus}$ and $\Delta u_0 \equiv u_{0,\text{sat}} - u_{0,\oplus}$ are the differences in the peak times and impact parameters as seen from the two sites, respectively. While the light curves can yield $t_{0,\text{sat}}$ and $t_{0,\oplus}$ unambiguously, they can only yield the absolute values of impact parameters, $|u_{0,\text{sat}}|$ and $|u_{0,\oplus}|$. Hence, Equation (7) is four-fold ambiguous (see, e.g., Figure 1 of Gould 1994):

$$\pi_E = \frac{AU}{D_\perp} \left(\frac{t_{0,\text{sat}} - t_{0,\oplus}}{t_E}, \pm |u_{0,\text{sat}}| \pm |u_{0,\oplus}| \right). \quad (8)$$

This degeneracy typically leads to two distinct solutions for the lens mass and distance. Although the four-fold degeneracy can be broken in specific cases (e.g., planetary events or high-magnification events), and can be approached statistically for a sample of events (Calchi Novati et al. 2015), it can only be systematically broken by obtaining observations from a second, misaligned, satellite (Refsdal 1966; Gould 1994). The addition of *Spitzer* (*Kepler* to *Kepler* (*Spitzer*) fulfills such a requirement, as is shown in Figure 10. Figure 11 shows the light curve for an event with parameters typical of a lens in the Galactic disk as seen by the Earth, *Kepler*, and *Spitzer*. Observations with *Spitzer* can easily identify the correct solution, leading to the unique determination of the lens mass and distance.

An ensemble of single-lens events for which the four-fold degeneracy has been broken can be used to test the Rich argument, i.e., the assumption that is used to statistically break the four-fold degeneracy (Calchi Novati et al. 2015). For events with θ_E measurements, the resolution of this four-fold degeneracy can directly yield precise mass and distance measurements of the lens system without requiring any additional arguments or observations (Zhu et al. 2015b). The inclusion of a second satellite can also break the 1-D continuous parallax degeneracy in events with a binary lens system. Since θ_E is nearly always measured in such cases, this leads to more precise measurement of the mass of the binary lens, which is critical for identifying binaries involving stellar remnants (e.g., Shvartzvald et al. 2015).

With 50 hours of *Spitzer* time, ~ 25 events that fall inside the *K2*C9 superstamp are expected to be observed. This subset will include several binaries that remain active when *Spitzer* observations begin, and ~ 20 relatively bright single-lens events selected from a sample of ~ 50 events that will peak within a 30-day window that is centered on June 24, the midpoint of the 13-day overlap window. These events will follow the standard *Spitzer* event selection procedure (Udalski et al. 2015b): they are selected based on ground-based observations, uploaded to

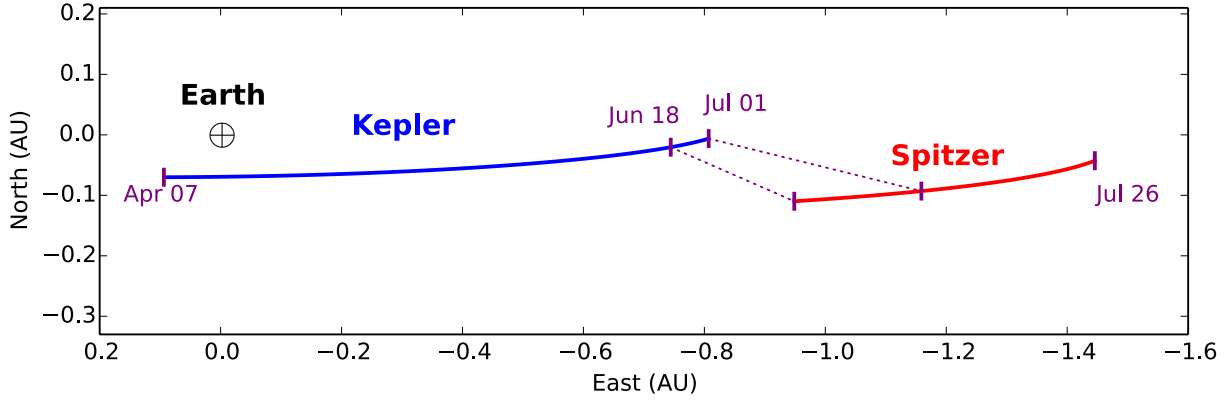


Figure 10. The projected positions of *Kepler* and *Spitzer* with respect to the Earth, as seen from the center of the *K2C9* superstamp during their respective campaign periods.

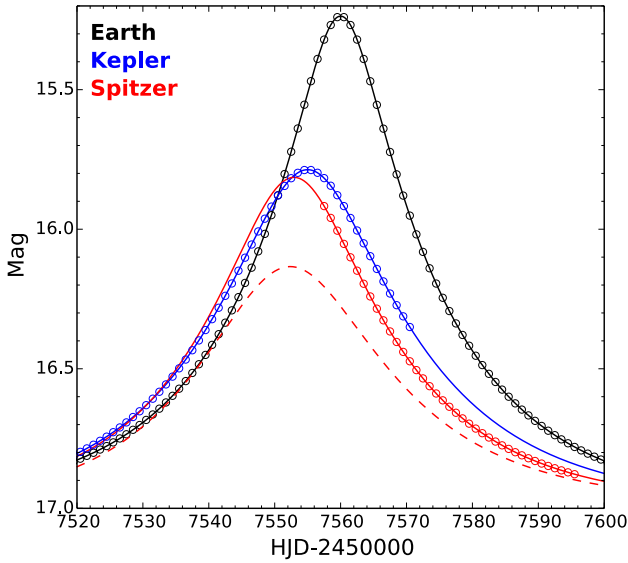


Figure 11. An example event in which the four-fold degeneracy can be broken by combining observations from the Earth, *Kepler*, and *Spitzer*. With observations from the Earth and *Kepler*, there are four allowed solutions of π_E , which lead to two distinct predictions for the light curve as seen by *Spitzer*. The *Spitzer* observations can easily identify the correct solution. This event has typical parameters for disk lenses ($u_0 = 0.2$, $t_E = 30$ days, $\pi_{E,N} = \pi_{E,E} = 0.2$).

the *Spitzer* spacecraft on Mondays, and observed starting the following Thursday.

7. COMMUNITY INVOLVEMENT

K2C9 is designed to provide access to a myriad of compelling science goals in a way that is community-driven. One of the most critical components of this white paper is the description and dissemination of the opportunities for involvement for personnel outside of the field of exoplanetary microlensing. Here we describe the online access to relevant data products. The MST and all coauthors of this white paper are also in the process of drafting a data policy that will govern the use of and access to the photometry produced by the contributing ground-based resources. It is our hope and intention that this will encourage involvement in exoplanetary microlensing generally and *K2C9* specifically and will help to maxi-

mize the scientific yield of *K2C9*.

7.1. ExoFOP Interface

During the *Kepler* primary mission, the NASA Exoplanet Science Institute (NExSci) developed a website for coordination and collation of ground-based follow-up observation activities by the *Kepler* Science Team. During the extended *K2* mission, this site was transitioned for support of the entire *Kepler* community and renamed the Community Follow-up Observing Program (CFOP). CFOP enables users to share images, spectra, radial velocities, stellar parameters, planetary parameters, observational parameters, free-form observing notes, false-positive alerts, and any type of file the users wish to upload. Currently, CFOP contains over 100,000 files and 25,000 parameters on 7,500 *Kepler* objects of interest — all uploaded by registered users and available for use by the community. In 2015, CFOP was used as the basis for an expanded site (ExoFOP) to support the *K2* mission, and will be used in the future to support TESS, NN-EXPLORE RV targets, and eventually *WFIRST* exoplanet (coronagraphic and microlensing) targets. For *K2*, ExoFOP includes all targets and users can upload the same types of files and data as above, and can designate target status such as ‘planet candidate,’ ‘false positive,’ or ‘eclipsing binary.’ To date, users have uploaded over 40,000 files and identified over 200 planet candidates. CFOP and ExoFOP are developed and operated by NExSci with funding from the *Kepler* project (for CFOP) and from the NASA Exoplanet Archive (for ExoFOP).

As *K2C9* will not be driven by pre-identified targets, ExoFOP support for the microlensing campaign will be specifically tailored. The general strategy was designed in discussions with the MST. The three main components will be:

1. a sortable table containing all microlensing events identified within the *K2C9* superstamp,
2. detailed information for each event (e.g., cursory single-lens fit parameters and magnitudes), and
3. a graphical display of available telescope resources.

The event list will be driven by events collected by LCOGT’s RoboNet (Tsapras et al. 2009), which accrues

events and photometry from the dedicated ground-based microlensing projects OGLE, MOA, and LCOGT. Basic information about all events, such as cursory single-lens fit parameters (t_0 , t_E , u_0) and current apparent magnitude, will be available in a single, sortable table, similar to the *K2* campaign tables currently on ExoFOP. The detailed information for each event will include quick-look photometry, images, and detailed real-time modeling results. Information collated by RoboNet will be automatically available and users will also be able to upload data, model parameters, files, and free-form observing notes. The telescope resources display will have a large-scale calendar version covering the full duration of *K2*C9, as well as the ability to generate a detailed visualization of the observability of the *K2*C9 superstamp for each ground-based site for a single day. The goal of these graphics is to help coordinate the timing of ground-based observations. In addition, there will be a search interface covering all data and user notes.

The ExoFOP website⁶² is open to the entire community. In ExoFOP, all data and uploaded files are visible to all users. To upload content, users must have an account and be logged in. The same user account works on both CFOP and ExoFOP and a user account can be requested by following the link on the ExoFOP home page.

7.2. *K2*C9 Visibility Tool

The *K2fov* tool (Mullally et al. 2016) allows users to check whether a list of input target coordinates will fall within the *K2* FoV during a user-specified campaign. This functionality has been expanded for *K2*C9 and is available through an in-browser application⁶³. Given that many of the teams representing ground-based resources will eschew a proprietary period for their data and will act to host the photometry on ExoFOP, this allows users to determine if a desired target will have publicly available data across a wide range of wavelengths and cadences.

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⁶³ <http://k2c9.herokuapp.com/>

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