Predictions for the Detection and Characterization of a Population of Free-floating Planets with K2 Campaign 9

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Abstract

K2 Campaign 9 (K2C9) offers the first chance to measure parallaxes and masses of members of the large population of free-floating planets (FFPs) that has previously been inferred from measurements of the rate of short-timescale microlensing events. Using detailed simulations of the nominal campaign (ignoring the loss of events due to Kepler’s emergency mode) and ground-based microlensing surveys, we predict the number of events that can be detected if there is a population of 1 $M_{\text{Jupiter}}$ FFPs matching current observational constraints. Using a Fisher matrix analysis, we also estimate the number of detections for which it will be possible to measure the microlensing parallax, angular Einstein radius, and FFP mass. We predict that between 1.4 and 7.9 events will be detected in the K2 data, depending on the noise floor that can be reached, but with the optimistic scenario being more likely. For nearly all of these, it will be possible to either measure the parallax or constrain it to be probabilistically consistent with only planetary-mass lenses. We expect that for between 0.42 and 0.98 events it will be possible to gain a complete solution and measure the FFP mass. For the emergency-mode truncated campaign, these numbers are reduced by 20 percent. We argue that when combined with prompt high-resolution imaging of a larger sample of short-timescale events, K2C9 will conclusively determine if the putative FFP population is indeed both planetary and free-floating.

Key words: gravitational lensing: micro – planets and satellites: detection

1. Introduction

The large population of free-floating or loosely bound, Jupiter-mass planets (hereafter FFPs) inferred by Sumi et al. (2011) remains difficult to explain (Clanton & Gaudi 2017). After accounting for various possible forms of the stellar and sub-stellar mass function, Sumi et al. (2011) found that an excess of short-timescale microlensing events could be explained by a population of $1.9^{+1.3}_{-0.8}$ Jupiter-mass objects per main sequence star. Extrapolation of the measured low-mass initial mass functions (IMFs) of nearby, young clusters and associations (e.g., Peña Ramírez et al. 2012; Lodieu 2013) down to 1 Jupiter mass can only explain about ~10 percent of the events that are seen. Statistical surveys of wide-separation, young exoplanets with high-contrast imaging (Quanz et al. 2012; Bowler et al. 2015; Durkan et al. 2016; Reggiani et al. 2016) place strong limits on the abundance of bound planets that could potentially be mistaken for FFPs, even for cold-start models that predict young planets will be faint. Finally, synthesizing the results of surveys that cover a wide range of parameter space (Clanton & Gaudi 2014, 2016) and summing up all of the planetary mass, and assuming upper limits are measurements, yields a result that is at least a factor of two smaller than the amount of mass locked up in the inferred FFP population (Henderson et al. 2016).

Theory does not seem to offer a convenient way out of the impasse. Veras & Raymond (2012) found that tens of giant planets would need to be formed by each star in order to explain the measured FFP abundance if planet–planet scattering were the cause, and simulations by Pfyffer et al. (2015) demonstrate that more modest planetary systems can only eject a small fraction of the necessary giant planets (Henderson et al. 2016). Without a central, stationary gravitational sink, circumbinary planetary systems have recently been shown to eject significantly more giant planets than single-star systems (Smullen et al. 2016; Sutherland & Fabrycky 2016), but only a small fraction of stellar systems are binaries with sufficiently small orbits to form circumbinary systems (~10 percent with periods less than 1000 days, Raghavan et al. 2010), and so giant planet formation and ejection in such systems would need to be unreasonably prolific. A similar issue faces the channel of ejection during post-main sequence evolution (Veras et al. 2016).

K2 Campaign 9 (K2C9, Gould & Home 2013; Howell et al. 2014; Henderson et al. 2016) offers the first opportunity to observationally challenge, or indeed confirm, the inference of Sumi et al. (2011) with more than just improved statistics. Simultaneous satellite observations (Refsdal 1966; Gould 1994) enable the measurement of the microlens parallax $\pi_l$, which can place a strong constraint on the nature of the lens and go some way toward breaking the fundamental microlensing timescale degeneracy between mass, distances, and relative velocity (see Henderson et al. 2016; Henderson & Shvartzvald 2016, for a thorough review of the relevant theory and observational techniques). Satellite parallax measurements have now been made for a large number of events with Spitzer (Dong et al. 2007; Calchi Novati et al. 2015; Shvartzvald et al. 2015, 2016; Udalski et al. 2015b; Yee et al. 2015; Zhu et al. 2015; Bozza et al. 2016; Poleski et al. 2016; Street et al. 2016), but Spitzer requires several days lead for scheduling observations (see, e.g., Figure 1 of Udalski et al. 2015b), precluding its use for observing FFP events.

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1 Sagan Fellow.
2 When assuming a three-component power-law stellar mass function; assuming another mass function would not significantly alter the result relative to the statistical uncertainties.
which have timescales of ~1 day. Instead, one must blindly
survey a large area of sky from Earth and a satellite
simultaneously in order to have a chance to detect FFPs. This
is what K2C9 enables.

Here we perform simulations to determine whether K2C9
can detect a sufficient number of FFP events to place
interesting constraints on the FFP population. In Section 2
we describe our simulations. In Section 3 we present our
results, and in Section 4 we discuss their implications for
characterizing the FFP population. We conclude in Section 5.

2. Simulations

To simulate the combination of ground-based and K2C9
surveys, we used the simulation code originally presented by
Penny et al. (2013), which has been renamed GULLS.6 By
producing artificial images, the code simulates photometry of
gravitational microlensing lightcurves with lens and source
stars drawn from a Galactic population synthesis model. The
code has been modified extensively to allow for the simulation
of ground-based observations, to include the effects of parallax,
and to add the estimation of event-by-event parameter
uncertainties using Fisher matrix analysis. As the general
mechanics of the code are described in detail by Penny et al.
(2013), we only describe the modifications here. There are a
few instances where mistakes were made in setting up the
simulations, but were not significant enough to justify
rerunning the simulation; in each case we note the mistake below.

2.1. Lightcurves and their Parameterization

In this paper we are only interested in FFP events, which are
isolated lenses. We therefore simulate single-lens lightcurves
with finite-source effects but no limb-darkening,7 using the
method of Witt & Mao (1994) to compute the magnification.
We parameterize the lightcurve using the time of closest
approach between the lens and source as seen by the Kepler
spacecraft $t_{0,\text{Kep}}$, the impact parameter of this closest approach
$u_{0,\text{Kep}}$, and the Einstein radius crossing time $t_{\text{E, Kep}}$ in the inertial
frame moving with Kepler at time $t_{0,\text{Kep}}$. The relative angular
radius of the source is

$$\theta = \theta_s / \theta_E,$$

where $\theta_s$ is the angular radius of the source star and

$$\theta_E = \sqrt{\kappa M \pi_{\text{rel}}},$$

is the angular Einstein radius, where $\kappa = 8.144$ mas $M_\odot^{-1}$ is a
constant, $M$ is the lens mass, and $\pi_{\text{rel}} = au(D_l^{-1} - D_s^{-1})$ is the
relative parallax, with $D_l$ and $D_s$ being the lens and source
distance, respectively (see, e.g., Gould 2000). Microlensing
parallax is parameterized by the vector $\vec{\pi} = (\vec{\pi}_N, \vec{\pi}_E)$, with
components in the north and east directions, and is defined as

$$\vec{\pi} = \frac{\pi_{\text{rel}}}{\theta_E} \mu_{\text{rel}},$$

where $\mu_{\text{rel}}$ is the vector relative lens–source proper motion
measured in a heliocentric frame. The impact parameter $u_0$ and
peak time $t_0$ of the event seen from Earth depend on $\pi_0$ as well
as the vector separation between the Earth and Kepler projected
on the plane normal to the event’s location on the sky. ($t_0, u_0$)
and ($t_{0,\text{Kep}}, u_{0,\text{Kep}}$) are related by

$$\begin{pmatrix} \Delta t_0 \\ \Delta u_0 \end{pmatrix} = \begin{pmatrix} t_{0,\text{Kep}} \\ t_{\text{E, Kep}} \end{pmatrix} \begin{pmatrix} \frac{D_s}{t_{\text{E}}} \\ \frac{D_l}{t_{\text{E}}} \end{pmatrix},$$

where the components of $D_s$ are defined to be in the direction
parallel and perpendicular to $\pi_0$, and $t_{\text{E}} = au_0/\pi_0$ is the
projected Einstein radius, i.e., the Einstein radius projected
onto the observer plane. We parameterize the effects of source
and blended light with a baseline magnitude, e.g., $I_0$, and the
fraction of this flux that is contributed by the source $f_s$, both of
which are different for each observatory and each filter.

2.2. Ground-based Observatories

To schedule observations, GULLS reads in a schedule script
that is repeated for the duration of the simulations. For ground-
based observations this is overridden and observations are not
taken if the elevation of an event falls below an elevation limit
(here optimistically set at 20°), or if the Sun’s elevation is
(again, rather optimistically) above –6°. The basic astronomical
functions used for these computations were based on code by
Ofek (2014). Observations are also not taken if the weather is
“bad”; we incorporate into the definition of bad weather
anything that might halt observations. A fixed weather calendar
is computed in advance with a site-by-site good weather
probability, that is tested against a uniform random deviate
every six hours. We adopted a good weather probability that
was 5% worse than measured clear sky fractions to account for
other sources of lost observing time such as high winds and
technical problems. For OGLE, we adopted a clear night
fraction of 80% from Las Campanas Observatory site testing
results (Thomas-Osip et al. 2010) and for MOA we adopted the
average of the 1992–2007 weather statistics presented in the
annual report of the Mt. John observatory.8 We removed by
hand the nights on each calendar where the moon would have
been too close to the survey fields for wide-field survey
observations (the night of minimum separation, and one night
either side of this, which approximately matches the actions of
the OGLE survey as seen in their Early Warning System
lightcurves; Udalski 2003).

The architecture of our code makes it difficult to simulate the
effect of variable seeing, so we simply opt to assume a single
value of seeing, the median, for each site. In each case we used
a Moffat (1969) point-spread function (PSF) with parameter
$\beta = 4$. We do, however, simulate the effect of variable sky
brightness and extinction as a function of filter, elevation, and
moon position using the model of Krisciunas & Schaefer
(1991). We also account for the increase of atmospheric
extinction with airmass through a filter-dependent extinction
coefficient. The adopted parameters for ground-based observa-
tories are described in 2.6.

2.3. Parallax and Orbits

To compute the effects of parallax on the lightcurve, we
begin by defining an inertial reference frame, which in this case

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6 The original name MABLS now only refers to a tool for computing
microlensing optical depth and event rates using the Besançon model
(Awiphan et al. 2016).

7 We have previously experimented with incorporating limb darkening
for bound Earth-mass exoplanet events, where it is likely to play a larger role
than here, and found that it did not significantly affect detection efficiencies.

8 http://www.phys.canterbury.ac.nz/research/astronomy/docs/MIUCamrenp07v2.pdf
we choose to be the frame moving with *Kepler* at the time of the event’s peak magnification as seen by *Kepler*, $i_{0,\text{Kep}}$. We compute the orbits of observers using the formalism and ephemerides of Standish & Williams (2013, p 305). We approximate *Kepler*’s orbit by assuming its orbital elements to be the same as the Earth’, except for the semimajor axis $a_0 = 1.01319 \text{ au}$, mean longitude $L_0 = 164^\circ 72296$, and its rate of change $\dot{L} = 352^\circ 99329 \text{ yr}^{-1}$, which were chosen to place *Kepler* at the same position as the Earth on its launch date and to match its orbital period of 372.5 days. The accuracy of the orbit is more than sufficient for our purposes in simulating the mission, and reproduces the projected separation $D_i$ between Earth and *Kepler* as a function of time, which is shown in Figure 4 below. Ground-based observers were assumed to be at the center of the Earth as it orbits the Earth–Moon barycenter.\(^9\)

For each epoch of observation, we compute the position of the observer in the inertial reference frame and translate this into a 2D vector shift in the apparent location of the source star, parallel and perpendicular to its linear trajectory in the inertial frame, in units of the Einstein radius, $\theta_E$. The shift depends on the sky coordinates of the microlensing event and the microlensing parallax, $\pi_\ell$. A detailed description of satellite parallaxes in a heliocentric frame is given by Calchi Novati et al. (2015).

### 2.4. Fisher Matrix Parameter Estimates

For each simulated event, in addition to assessing whether the event will be detected or not, we would like to estimate what the measurement uncertainties of the event’s parameters would be. We do this using a Fisher matrix analysis (see, e.g., Gould 2003), by assuming that the input lightcurve model is the best fit to the data and that the distribution of $\chi^2$ is quadratic in each parameter. Even when this assumption breaks down, a large value of a Fisher matrix parameter uncertainty estimate will indicate that a parameter is unconstrained by the data. To compute the uncertainty on the magnitude of the parallax vector $\pi_\ell$ from the covariance matrix of the lightcurve parameters, we multiply the covariance matrix by the Jacobian of the equation $\pi_\ell = (\pi_{\ell,E}^2 + \pi_{\ell,N}^2)^{1/2}$.

### 2.5. Galactic Model

In contrast to Penny et al. (2013), we use the public version of the Besançon model as our input Galactic model (Robin et al. 2003). We found it necessary to make the following changes to the star catalogs that are the output by the model’s web interface.\(^10\) First, we computed a larger range of stellar magnitudes than provided by the model, by converting unreddened MegaCam ugriz magnitudes to SDSS ugriz magnitudes using the transformations of Gwyn (2008). Extinction was then applied to each magnitude using the Marshall et al. (2006) 3D extinction model in the $K$-band. $K$-band extinctions were converted to other bands by assuming a ratio of total to selective extinction $R_V = 2.5$ (Nataf et al. 2013) and a Cardelli et al. (1989) reddening law. After applying extinction, we computed Johnson–Cousins magnitudes using the “Lupton (2005)” transformations\(^11\)

\[
V = g - 0.5784(g - r) - 0.0038, \quad (4)
\]

\[
R = r - 0.2936(r - i) - 0.1439, \quad (5)
\]

\[
i = i - 0.3780(i - z) - 0.3974, \quad (6)
\]

and *Kepler* magnitudes using the transformation from $g$ and $r$ magnitudes of Brown et al. (2011). In hindsight it would have been preferable to perform all the magnitude transformations before applying extinction, but the effect on the resultant magnitudes is negligible (e.g., for $V$ it results in a 0.3 percent change in the $V$-to-$K$ extinction ratio $A_V/A_K$).

The second change corrects an error in the $V$-component of stellar UVW velocities that affects stars beyond the position of the Galactic center ($X > 8 \text{ kpc}$ in the standard heliocentric Cartesian system). The error was propagated to proper motions and so would affect our event rates if left uncorrected. We applied the correction (A. Robin 2015, private communication)

\[
V \rightarrow -2V_{\text{LSR}} - V \quad \text{if} \quad X > 8 \text{ kpc}, \quad (7)
\]

where $V_{\text{LSR}} = 226.4 \text{ km s}^{-1}$ is the local standard of rest, and recomputed proper motions (Johnson & Soderblom 1987).

In the Besançon model, each stellar population (thin disk, bulge, etc.) was allowed its own stellar IMF. As the low-mass end of the bulge IMF was poorly constrained at the time (Robin et al. 2003), it was chosen to be a continuous Salpeter (1955) mass function with slope $-2.35$. This over-produces low-mass stars in the bulge if the bulge IMF is similar to that of Kroupa (2001) or Chabrier (2003) which, while this barely affects star counts measurable from the ground, causes a microlensing event rate that is too high by a factor of $\sim 3$ relative to a Kroupa IMF. To correct for this, we weighted events involving bulge stars with masses below $0.5 M_\odot$ by a factor $(M/0.5 M_\odot)^{2}$, effectively giving the bulge an IMF similar to that of the other populations in the model, with a low-mass slope of $-1.35$. The weighting was applied twice if both the source and lens stars had masses below $0.5 M_\odot$.

Even after adjusting the mass function in the bulge, the number of bulge main sequence stars was still too high, as has been recognized by Kerins et al. (2009). Our final change to the model was to further weight events involving bulge stars by a factor, $f$, to match the overprediction of main sequence bulge stars in the Besançon model to the number measured by Calamida et al. (2015) using *HST* data at $(\ell, b) = (1^\circ 25, -2^\circ 65)$. This factor was $f = 1/3.16$. Again, if both source and lens stars belonged to the bulge, this down-weighting was applied twice.

The above corrections were applied in turn, instead of simply computing a single overall event rate scaling factor, in order to make sure that the distance distribution of lenses would remain as realistic as possible. After making the above corrections, we tested the event rates of the adjusted model by simulating in detail the MOA-II survey conducted in 2006 and 2007 (Sumi et al. 2011, 2013), matching the weather patterns and detection cuts in order to predict the number of events that will actually enter the sample. A full description of this simulation will be presented in a future paper. The simulation predicted a factor of 0.59 fewer detections than actually passed all the detection cuts in the MOA survey. The timescale distribution of the simulation was a largely consistent with that of the data. We

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\(^9\) We therefore do not consider the small probability of measuring terrestrial parallax.

\(^10\) http://model.obs-besancon.fr/

\(^11\) See https://www.sdss3.org/dr8/algorithms/sdssUBVRITransform.php.
therefore multiplied the results of our simulations by $1/0.59$ to match the MOA results. Note that the recent downward revision of the optical depth and event rate per star measurements from this survey (Sumi & Penny 2016) does not affect our event rate per area results.

2.6. Simulating K2C9 Observations of a Population of Free-floating Planets

We simulate the combination of the ongoing high-cadence microlensing surveys of OGLE ( Udalski et al. 2015a) and MOA (Sako et al. 2007) with the K2 C9 survey, using the latest and final definition of the 3.74 deg$^2$ superstamp (Henderson et al. 2016) chosen using the method of Poleski (2015) and shown in Figure 1. At the time when we ran the simulations, the status of the KMTNet survey (Kim et al. 2010; Henderson et al. 2014) for the 2016 season was uncertain, so we did not simulate it. We therefore expect the ground-based sensitivity of our simulation to be very conservative. Figure 2 shows an example lightcurve. The simulation parameters of the surveys and their detectors are listed in Table 1. Most of the parameters for K2 were taken from the Kepler Instrument Handbook (Van Cleve & Caldwell 2009). As the photometric precision it is possible to achieve with crowded field Kepler data is uncertain, we have simulated an optimistic and pessimistic scenario for a systematic noise floor in the K2 data. For the optimistic case, we simply add a 0.001 fractional error in quadrature with the noise that is computed through our usual calculations that simulate CCD photometry (Penny et al. 2013). For the pessimistic case, we set an absolute noise floor of 45 $e^-$ s$^{-1}$ independent of magnitude, which has been demonstrated in the crowded field of NGC 2158 in K2 Campaign 0 data (M. T. Penny & K. Z. Stanek 2017, in preparation). In both cases we assume that the associated systematic noise terms account for any imperfect detrending. See Section 4 for an assessment of the relative likelihood of each scenario.

Parameters for OGLE were taken from Udalski et al. (2015a) or the OGLE website. The OGLE cadence was set by

\[ u_{0,K_{\text{ep}}} = -0.11 \quad u_0 = -1.24 \quad (t_0 - t_{0,K_{\text{ep}}})/t_E = 0.97 \]

Figure 2. Example of a simulated lightcurve. Gray and black points, plotted against the left axis, show pessimistic and optimistic K2 photometry, respectively (see the text for details). Purple, blue, and red points, plotted against the right axis, show MOA and OGLE V and I photometry, respectively. Note that the y-scales and the baseline magnitudes are very different for the K2 and ground-based photometry, and that the event as seen from K2 is highly magnified but severely blended.

Table 1

| Parameter          | K2   | OGLE | OGLE | MOA |
|--------------------|------|------|------|------|
| Filter             | $K_{\text{p}}$ | $V$  | $I$  | MOA-R |
| Cadence (min)      | 30   | 45.5 | 45.5 | 10   |
| Exposure time      | $270 \times 6$ s | $150$ s | $100$ s | $60$ s |
| Start observing    | Apr 6 | ... | full 2016 season | ... |
| End observing      | Jun 29 | ... | ... | ... |
| Pixel size ($\mu$) | 3.98 | 0.26 | 0.26 | 0.58 |
| PSF size           | ...  | 0.9 | 0.9 | 2 | |
| Gain ($e^-$/ADU)   | 110  | 1.6 | 1.6 | 2.2 |
| Readout noise ($e^-$) | 120 | 7.5 | 7.5 | 6 |
| Full well ($10^7$ $e^-$) | 10 | 2.0 | 2.0 | 2.0 |
| Bits pixel$^{-1}$  | 14   | 16  | 16  | 16  |
| $m_{\text{zero}}$  | 12   | 22  | 22  | 22  |
| Flux at $m_{\text{zero}}$ ($e^-$ s$^{-1}$) | $1.83 \times 10^5$ | 9.577 | 5.475 | 22.65 |
| Systematic error$^a$ | 0.1% | 0.4% | 0.4% | 0.4% |
| Aperture radius ($\mu$) | $45 \times 3$ pixels | $0.9$ | $0.9$ | 2 | |
| Sky$^b$            | 21.5 | 21.8 | 19.9 | 20.2 |
| Extinction coefficient (mag arcsec$^{-2}$) | ... | 0.14 | 0.069 | 0.075 |
| Good-weather probability | ... | 0.75 | 0.75 | 0.60 |

Notes. Simulation parameters for each of the observatories.

$^a$ For the Kepler PSF we use the numerical PSF from detector 10 in module 4 at the edge of the focal plane (Bryson et al. 2010), which should be very similar to the PSFs in the superstamp.

$^b$ Magnitude at which flux per second is defined.

$^c$ For K2 we simulate two scenarios for a systematic noise floor, optimistic (labeled O above) and pessimistic (labeled P).

$^d$ Adopted from Henderson et al. (2014).

$^e$ Sky background at zenith with no moonlight.

$^f$ For all observers we include a model of the zodiacal light (Leinert et al. 1998), but for Kepler we mistakenly double counted and added a constant background of the roughly the same brightness; the impact should be minimal however as stars will bring every pixel “above sky.”
assuming OGLE would spend 50 percent of its time observing the superstamp, alternating between V and I filters. The $\sim$20 minute combined cadence of OGLE V and I is similar to the actual OGLE cadence that will be used during the campaign, but the ratio of V to I exposures will be significantly reduced (R. Poleski 2016, private communication). Parameters for MOA were taken from Sako et al. (2007). We assumed that MOA-R magnitudes (a wide bandpass covering R and I) were equal to I-band magnitudes. Values for sky brightness, extinction coefficients and weather probabilities were taken from various appropriate observatory webpages.

We assumed that the population of FFPs is the same as that measured by Sumi et al. (2011), namely that there are 1.9 free-floating 1 Jupiter mass planets per main sequence star. To implement this in our simulation, we replaced each of the lens stars in our simulation (including white dwarfs) with an FFP (adjusting the event rate weighting proportional to $\sqrt{M}$). We then multiplied the number of detections by 1.9/(1 + 0.18), where the denominator is the sum of main sequence and white dwarf stars in the Sumi et al. (2011) model. We drew the impact parameter $u_{0, Kep}$ from a uniform distribution in the range $-u_{\text{max}} \leq u_{0, Kep} < u_{\text{max}}$, where $u_{\text{max}} = \max(1, 2\rho)$ in order to include detectable events where the source is comparable to or larger than the angular Einstein ring. This input range does not include events where both $u_{0, Kep} > 1$ but $u_0 < 1$ (the impact parameter for Earth-bound observers), which would potentially increase the number of characterizable events if a dispositive null detection (Wang et al. 2012) is possible from the K2 data. See Section 4 for a discussion of the value of such events.

2.7. Detection Criteria

To determine if an event is detectable in K2 data, we require an event to cause a $\Delta \chi^2 > 200$ deviation from a flat lightcurve, and that three or more consecutive data points deviate from the flat lightcurve by at least $3\sigma$. We consider an event to be detectable in ground-based data if it causes a $\Delta \chi^2 > 200$ deviation from a flat lightcurve. For the Fisher matrix parameter uncertainty estimates, we consider a parameter to be “measured” if its fractional uncertainty is less than 1/3 (i.e., $3\sigma$). Note that for parallax, for which there is a two-fold degeneracy in the magnitude of $\pi_e$ (Refsdal 1966; Gould 1994), the Fisher matrix estimate only characterizes one of the solutions. We discuss the impact of this degeneracy in Section 4.3.

3. Results

In contrast to the lengthy description of the simulations, the results can be presented much more concisely, and are summarized in Table 2. For the optimistic K2 photometry case, if the FFP population is as described by Sumi et al. (2011) (1.9 Jupiter mass planets per main sequence star), we expect that 7.9 FFPs will be detected during Campaign 9. Seventeen percent of these have $\Delta \chi^2$ values between 200 and 500, with the rest having higher-significance detections. For the pessimistic systematic noise scenario we expect 1.4 K2 detections, with 30 percent between $\Delta \chi^2 = 200$ and 500. The probability of no K2 detections in the campaign is 0.00038 for the optimistic simulation and 0.24 for the pessimistic simulation. The mean ratio of $\Delta \chi^2$ between the optimistic and pessimistic simulations is 77, implying that there is significant room for improvement in photometry relative to that achieved by M. T. Penny & K. Z. Stanek (2017, in preparation). The median V and I source magnitudes in the optimistic and pessimistic scenarios are $(V, I) = (22.5, 20.4)$ and $(V, I) = (21.0, 19.1)$, respectively. These show that even with its large pixels, the Kepler spacecraft is extremely sensitive to microlensing events.

In the optimistic scenario, we predict that 5.1 of K2’s events will be detected in ground-based data as well, and in 3.9 of these it should be possible to make a $3\sigma$ (or better) parallax measurement, up to the intrinsic four-fold degeneracy, which we discuss in Section 4.3. Measurements of the angular Einstein radius will be more rare, with only 1.1 predicted to have measurements of $\rho$. This is not particularly surprising, since the typical $\theta_0$ is roughly an order of magnitude smaller than the typical $\theta_E$ for Jovian mass lenses. About 30 percent of the $\rho$ measurements arise from events with sources smaller than 1 solar radius. The mass and relative parallax of the lens can be measured by combining the microlensing parallax and angular Einstein radius as

$$M = \frac{\theta_E}{K_{\rho E}}; \quad \pi_{\text{rel}} = \pi_E \theta_E.$$ (8)

We find that in nearly all cases where $\rho$ is measured (to at least $3\sigma$), parallax will also be measured to at least $3\sigma$. So, if we assume that measurement of $\rho$ and $\pi_E$ is sufficient for a mass measurement (see Henderson et al. 2016, and references therein for an overview of the method), our final expectation for the number of FFP mass measurements in the optimistic scenario is 0.98, or a $\sim$60 percent chance of at least one FFP mass measurement assuming Poisson statistics.

Thankfully the attrition in the pessimistic scenario is a little less severe than in the optimistic scenario, principally because of the brighter sources to which K2 would be sensitive. Out of 1.4 K2 detections, we expect 1.0 to yield a parallax and 0.40 to yield a finite-source measurement. We expect that 0.42 would yield a full mass measurement, or that there is a 34% chance of at least one full mass measurement in the pessimistic scenario.

4. Discussion

4.1. Optimism versus Pessimism

When examining the flow-down of detections to mass measurements in Table 2, one could be forgiven for being gloomy. Before dispelling such gloom in the following subsections, however, we should address the relative levels of optimism and pessimism in our simulations. The pessimistic noise floor we assume is equivalent to a 0.067 mag uncertainty at $K_p = 18$, which one should recall is for a 30 min integration on a 1 m class space telescope. The photon noise contribution for such an integration at this magnitude, when also accounting

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13 We did not separate the contributions of OGLE and MOA.
for the expected ~17 magnitudes per aperture of blended light, is 1.7 mmag. So, the pessimistic noise floor is a factor of ~40 higher than the photon noise at $K_p = 18$. This is not too surprising considering that M. T. Penny & K. Z. Stanek (2017, in preparation) first convolved the $K2$ data to give it a ~8" PSF before performing difference imaging, and then measured the noise floor as the lower envelope of the lightcurve rms when many lightcurves in the cluster core displayed blended variability. Even if blending of variability is an issue in the Campaign 9 field, it will be possible to build an empirical model of it from ground-based data or, if the variable is periodic, remove it by folding (see, e.g., Wyrzykowski et al. 2006). Additionally, various techniques for extracting crowded field photometry are being explored by the K2C9 microlensing science team and others (e.g., Libralato et al. 2015, who have achieved a noise floor of ~2 mmag in crowded regions of NGC 2158). We therefore expect that the final K2C9 photometry will be much closer to our optimistic limit than our pessimistic limit.

4.2. Characterization of the Free-floating Planet Population

So, given that we can expect multiple detections of short-timescale microlensing events, what can we learn from them? With high-resolution adaptive-optics (AO) imaging, it will be possible to detect a possible stellar host of a putative FFP, or in the absence of a detection place limits on the mass of a potential host. Gould (2016) estimate that with current AO systems, one must wait 25–50 years for the source star to separate sufficiently from the potential host star in order to fully resolve both source and host. For the less patient, Henderson & Shvartzvald (2016) investigated theoretically a similar flow-down of detections to characterization of FFPs in K2C9 as we have here, with an additional ingredient of a search for a possible stellar host to the lens. They concluded that it was unlikely to be possible to both measure the combination of parallax and angular Einstein ring radius as well as rule out all possible stellar hosts down to the bottom of the main sequence in any single event. In other words, in all likelihood, it will not be possible to conclusively prove that any single candidate FFP event is both planetary and free-floating. Our results agree with this assessment, but we feel that Henderson & Shvartzvald (2016) missed an important opportunity to consider what one can learn from partial information for many FFP candidate events. Without doing so, one could be forgiven for drawing a pessimistic conclusion from the discussion in Henderson & Shvartzvald (2016). The conclusions we draw from our simulations is much more optimistic.

We have shown that, with reasonable assumptions about the achievable $K2$ precision, FFP events will be detectable in the $K2$ data. Should the short-timescale events all be caused by Jupiter mass planets (bound or unbound), it will be possible to measure parallaxes in over half of the detected events. In the remainder of FFP events, the microlensing event will not be seen from the ground, sometimes due to poor weather, but other times because the large parallax has caused the impact parameter from the ground to be too large for an event to be detected. For the latter scenario then, it will be possible to place a lower limit on the parallax, which, with a reasonable assumption of the kinematics and density distribution of the Galaxy, can be translated into a statistical upper limit on the mass. However, if the short-timescale events are caused by stellar-mass objects, it will be possible to measure parallaxes in all events, weather allowing.

In Figure 3 we show the distribution of projected Einstein radii, $\tilde{r}_E = au/\pi_D$, for FFPs relative to the range of projected Earth–$K2$ baselines $D_*$ that are possible during the campaign. It can be seen that in many events $\tilde{r}_E$ will be smaller than $D_*$, meaning that it is probable for those events (though not certain) that the event will only be detectable from one location. However, we also plot the distribution of $\tilde{r}_E$ for stellar-mass lenses with timescales less than 2 days (i.e., FFP impostors). For these events, $\tilde{r}_E$ is always larger than the baseline, so it should always be possible to detect an event that $Kepler$ sees from the ground as well, provided that the weather is good. Therefore, for all events with suitable ground-based coverage that are detectable from $K2$ it will be possible to statistically infer with a high degree of confidence whether the mass of the lensing object is roughly planetary or roughly stellar. Angular Einstein ring radius measurements are not required for this inference. Note also that the normalization of the stellar distribution in Figure 3 was multiplied by 10 in order for the distribution to be visible, so that even without a parallax measurement or lower limit, a short timescale, $\tilde{r}_E < 2$ days, already strongly implies a planetary mass (Sumi et al. 2011).

So, following analysis of K2C9 we can expect know to a reasonable degree of accuracy the fraction of short-timescale events that are caused by planetary-mass objects. Can we also infer whether the population is truly free-floating or is just loosely bound to stars unseen through lensing? Henderson & Shvartzvald (2016) considered success as the ability to exclude all stellar hosts down to the hydrogen-burning limit with prompt AO imaging of events while the source and lens are still unresolved and argued that it was only possible for nearby events, within 2 kpc. These events would have the smallest $\tilde{r}_E$ and so could only have a parallax measurement in the early part of $K2$ C9 when the Earth–$K2$ baseline was also small; such events are also intrinsically rare (see, e.g., Penny et al. 2016 for
Figure 4. Distribution of event peak times $t_{0,Kep}$ for events detectable in only K2 data (solid black line) and in both K2 and ground-based data (dotted black line). Purple and green lines show the distribution of 3σ parallax measurements and parallax plus finite source measurements, respectively. The gray swath shaped like a check mark, and plotted against the right axis, is the distribution of projected separations between K2 and Earth for simulated events: the vertical spread is caused by events with a range of ecliptic latitudes. Even at the end of the campaign when the projected separation is larger than the typical FFP projected Einstein radius, a significant fraction of events seen by K2 can be detected from Earth, after accounting for the three dips in ground-based detections that occur when the moon is near the bulge fields and no observations are simulated.

4.3. Four-fold Degeneracy

So far, we have not paid much attention to the four-fold degeneracy that affects satellite parallax measurements from just two locations. In this section we consider how it affects our conclusions. The degeneracy arises from the inability to tell upon which side of the lens the source passes when observed from each observatory (Refsdal 1966; Gould 1994). This means that $\Delta u_0$ in Equation (3) can take one of two values, and the sign of each of these is also undetermined. The sign only affects the direction of the parallax vector and not its magnitude, so is not relevant to the estimation of the lens mass, but the magnitude of $\Delta u_0$ is.

In the case of a full solution of the lensing event, with both finite-source effects and parallax measured, the magnitude of $\pi_E$ will be approximately the same for the two degenerate solutions, because either $u_0$ or $u_{0,Kep}$ will be close to zero, and the difference between the degenerate values of $\Delta u_0$ will be of the same order of magnitude as the uncertainty on $u_0$ or $u_{0,Kep}$, which will be of the order of the source size.

In the case where the event is only detected from Kepler, and assuming that there is sufficient coverage from the ground, it will only be possible to place a lower limit on $|u_0|$, which will imply a lower limit on $|\Delta u_0|$ equal to the lower limit on $|u_0|$ minus $|u_{0,Kep}|$. This assumes the case where the source passes on the same side of the lens for both Kepler and Earth; the degenerate case with the source passing on opposite sides, and which holds 50% probability, has a larger lower limit on $\Delta u_0$ and $\pi_E$. For 75% of the events Kepler detects, $u_{0,Kep} < 0.5$, and we found in the simulations that ground-based observatories maintain detection efficiency to beyond $|u_0| > 1$, so for most such events it will be possible rule out $u_0 \sim u_{0,Kep}$. As stellar-mass lenses will always have small values of $\Delta u_0$ (the 99th percentile of $\Delta u_0$ for stellar-mass lenses with $t_u < 2$ days is 0.17), this means that for virtually all events that Kepler detects but are not seen from Earth, it will be possible to conclusively
rule out stellar-mass lenses, regardless of the parallax degeneracy.

Finally, we are left to consider the cases without finite-source effects and with a detection of the event from both Kepler and Earth. For events genuinely caused by FFPs, many will have values of $\Delta \theta_0 / \theta_{E,Kep}$ large enough to render the degeneracy moot in the separation of stellar-mass from planetary-mass lenses. If $\Delta \theta_0 / \theta_{E,Kep} \lesssim 0.17$ though, we must consider the degeneracy. For genuine FFP events where $\Delta \theta_0 / \theta_{E,Kep}$ is small compared to $\tau_D D_u$ au$^{-1}$, then $\Delta \theta_0 \approx \tau_D D_u$ au$^{-1}$, which will be guaranteed to cause a large difference in $\Delta \theta_0$ if the source passes on the same side of the lens, and in almost all cases when the source passes on the opposite side of the lens. The chance that both $\Delta \theta_0 / \theta_{E,Kep} \sim 0$ and $\Delta \theta_0 \approx 2|\theta_{0,E,Kep}|$ is very small if the lens is an FFP. However, if the lens is a star, $\tau_D$ will be small and so too $\Delta \theta_0$ will always be small, so we would conclude that an event with both $\Delta \theta_0 / \theta_{E,Kep} \sim 0$ and $\Delta \theta_0 \approx 2|\theta_{0,E,Kep}|$ is likely to be caused by a stellar mass. This is essentially a restatement of the “Rich argument,” that fine tuning is required in order for an event with large parallax to have both small $\Delta \theta_0 / \theta_{E,Kep}$ and $\Delta \theta_0$ (see Calchi Novati et al. 2015, for a full description and quantification of the probabilities), but in the context of constraining the lenses’ mass regime rather than its Galactic location.

4.4. Impact of Kepler’s Emergency Mode

The simulations we present were performed assuming a continuous 84 day K2 campaign with no mid-campaign break. The loss of the beginning of K2C9 due to a spacecraft emergency mode will obviously reduce the number of FFP events we can expect to detect. Kepler began observing again on April 22,14 which reduces the data-collecting duration of K2C9 by 67 days, or 80% of the duration we simulated. As can be seen from Figure 4, Kepler detects events uniformly in time, and the rate of characterizable events behaves in the same way, so all the predictions in Table 2 can be reduced by 20%, except the second line, which would be reduced by a slightly larger amount.

5. Conclusions

We have performed detailed simulations of K2 Campaign 9 and the accompanying ground-based observations to predict the yield of FFP detections if a population of 1 $M_{Jupiter}$ FFPs as inferred by Sumi et al. (2011) exists. We expect that the nominal K2 campaign would have detected $\sim$7.9 FFP events (under our optimistic, but more likely realistic assumptions), with most of them also being detected in ground-based observations, enabling parallax measurements. Even for the events not detected from the ground it should be possible to place upper limits on the mass of the FFP candidate given sufficient ground-based coverage and a reasonable assumption of Galactic model. We argue that prompt AO observations of a large sample of short-timescale events, combined with the parallax results of K2C9 should be able to conclusively show that the population of short-timescale events discovered by Sumi et al. (2011) is a population of genuinely free-floating, genuinely planetary-mass objects, or prove that this is not the case.

14 https://www.nasa.gov/feature/ames/kepler/mission-manager-update-kepler-recovered-andreturned-to-the-k2-mission

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