

The WFIRST Exoplanet Microlensing Survey

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1. Scientific Rationale

The Wide Field Infrared Survey Telescope (WFIRST) was the top ranked large space mission in the 2010 New Worlds, New Horizons decadal survey, and it was formed by merging the science programs of 3 different mission concepts, including the Microlensing Planet Finder (MPF) concept (Bennett et al. 2010). The WFIRST science program (Spergel et al. 2015) consists of a general observer program, a wavefront controlled technology program, and two targeted science programs: a program to study dark energy, and a statistical census of exoplanets with a microlensing survey, which uses nearly one quarter of WFIRST’s observing time in the current design reference mission. The New Worlds, New Horizons (decadal survey) midterm assessment summarizes the science case for the WFIRST exoplanet microlensing survey with this statement: “WFIRST’s microlensing census of planets beyond 1 AU will perfectly complement Kepler’s census of compact systems, and WFIRST will also be able to detect free-floating planets unbound from their parent stars.”

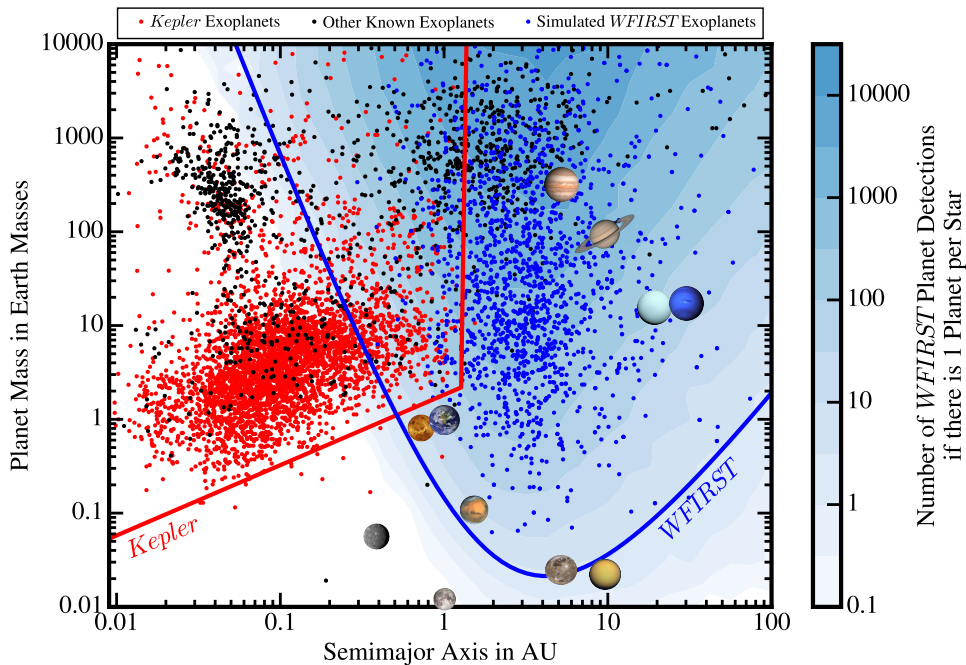


Fig. 1.— Comparison of the WFIRST design sensitivity to that of Kepler in the planet mass-semimajor axis plane (Penny et al., in preparation). The red line shows the approximate 50% completeness limit of Kepler (Burke et al. 2015). Blue shading shows the number of WFIRST planet detections during the mission if there is one planet per star at a given mass and semimajor axis. The thick blue line is the contour for 3 detections. Red dots show Kepler candidate and confirmed planets, black dots show all other known planets. Blue dots show a simulated realization of the planets detected by the WFIRST microlensing survey, assuming a fiducial planet mass function. Solar system bodies are shown by their images, including the moons Ganymede, Titan, and The Moon at the semi-major axis of their hosts.

WFIRST is needed to detect low-mass planets at orbital separations $\gtrsim 1$ AU,

complementing Kepler’s sensitivity to short period planets. Fig. 1 shows that WFIRST is sensitive to planets in these orbits with masses two orders of magnitude smaller than what is achievable with other methods. It indicates that WFIRST will be sensitive to analogs to all the planets in our Solar System, except for Mercury, and its sensitivity reaches down to very low mass planets as indicated by the light curve from a WFIRST simulation shown in Fig. 2 (Penny et al. in preparation). Even very low mass planets can be detected with strong signals. WFIRST is also sensitive to free-floating planets down to the mass of Mars that have been ejected from the planetary systems of their birth, which should provide important clues the processes of planet formation.

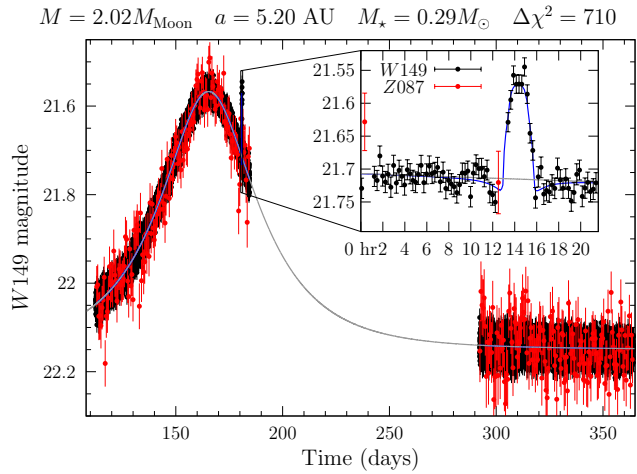


Fig. 2.— Example WFIRST lightcurve of a $0.025M_{\oplus}$ (2 lunar-mass) bound planet detection. Black and red data points are in the wide W149 and Z087 filters, respectively. The blue curve shows the underlying true lightcurve and the grey line shows the best fit single lens light curve.

The ultimate goal of NASA’s exoplanet program is to search for signs of life on other planets, but this requires an understanding of the planet formation process. Crucial details, such as the delivery of water to Earth, are likely to depend on the details of the planet formation process (Raymond et al. 2007). So, the presence of an Earth-size planet in the habitable zone may not be a sufficient condition to allow life to develop. On the other hand, our understanding of planetary habitability is currently rather primitive, so it could be that planets very different from Earth could have conditions that are suitable for life (Seager 2013). Thus, gaining a better understanding of the basic properties of exoplanets and their formation mechanisms is a critical part of NASA’s search for life outside the Solar System. It has proved to be quite challenging to develop a detailed understanding of planet formation process, as it seems to involve a wide range of physical processes operating over a huge range of length scales. It is fair to say that planet formation theory has yet to provide any detailed predictions that have been confirmed, and that progress in the theoretical understanding of planet formation must closely follow observational discoveries. Thus, WFIRST’s exoplanet microlensing survey is a crucial element of NASA’s exoplanet program.

Ground-based microlensing is already playing a crucial role in our understanding of planet populations. Suzuki et al. (2016) have found a break and likely peak in the exoplanet mass ratio function at a mass ratio of $q \sim 10^{-4}$, and other ongoing surveys promise substantially improved statistics. Fully characterizing the mass-ratio and mass functions can only be done from space. Ground-based microlensing rapidly runs out of sensitivity to

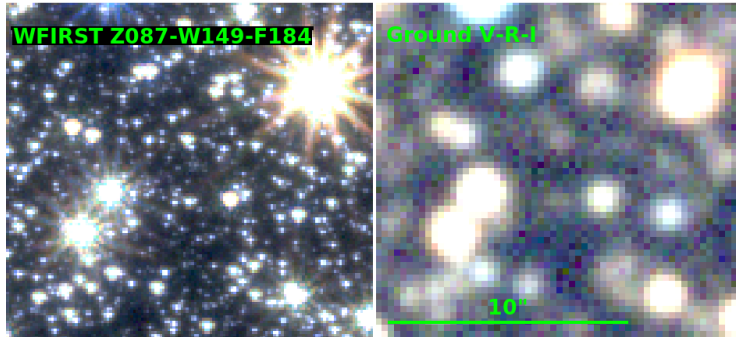


Fig. 3.— Simulated color images of a WFIRST microlensing survey field, as observed by WFIRST in the IR and a optical ground-based telescope. Only the blue foreground disk stars and bulge giants are resolvable in the ground-based images on the right, while the much more numerous main sequence stars are resolved in the WFIRST images.

planets below the observed break in the mass ratio function.

Signals from the smallest planets (mass $\lesssim 1M_{\oplus}$) are largely washed out by finite-source effects (Bennett & Rhie 1996), especially if they orbit inside the Einstein radius, which is typically 2-3 AU. These effects are minimized for dwarf source stars, but the bulge main sequence stars that comprise the vast majority of microlensing source stars are not resolved in the ground-based images. This means that the ground-based photometry of these stars is imprecise due to blending with other unresolved stars and that the microlensing signal is diluted. WFIRST’s vastly improved resolution (Fig. 3) will resolve these issues.

This improved resolution will also enable the characterization of the host stars by allowing direct measurements of their flux and the vector lens-source relative proper motion, μ_{rel} (Bennett et al. 2006, 2015) WFIRST will also combine relative proper motion measurements with partial microlensing parallax measurements to measure masses more directly (Gould 2014). Combining the mass-distance relationships from microlens parallax and flux measurements also determines the mass of the lens (Yee 2015). Measurements of μ_{rel} also ensure the the measured light can be correctly identified with the exoplanet host star (Bhattacharya et al. 2017; Koshimoto et al. 2017).

Fig. 4 shows HST images that reveal the lens (and planet host) star separating from the source star at the predicted μ_{rel} value for planetary microlensing event OGLE-2005-BLG-169. High angular resolution follow-up observations from space or narrow field adaptive optics systems are needed to measure such effects for events found from the ground, but WFIRST will measure such effects directly. With $\sim 40,000$ images per star, WFIRST will have the S/N to measure lens-source separations much smaller than seen in Fig. 4.

2. Developments Since the Decadal Survey

The WFIRST mission has undergone some changes since the Decadal Survey. The main change has been the move from a 1.3-1.5m telescope to a 2.4m aperture telescope that was gifted to NASA from another government agency. This has opened up some opportunities for WFIRST. It has enabled a technology demonstration wavefront controlled coronagraph to be added to WFIRST, and it allows the dark energy studies to go much deeper in contrast to ESA’s Euclid mission. The improvements for the exoplanet microlensing survey have been

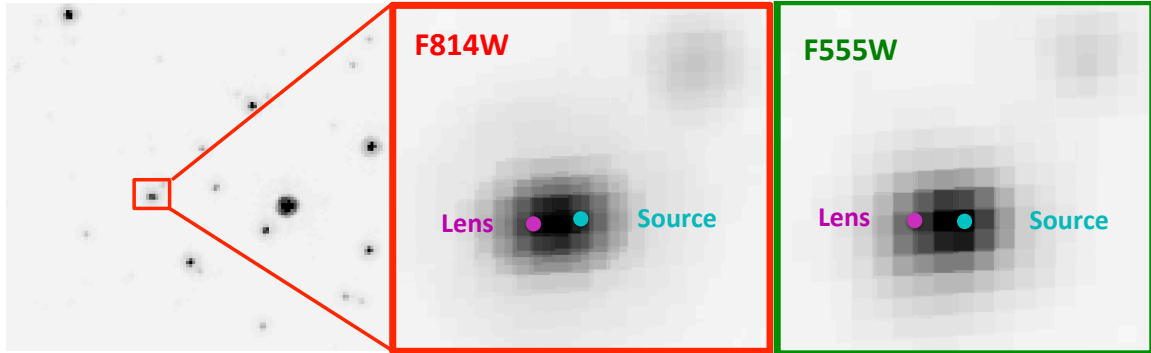


Fig. 4.— Stacked, dithered HST/WFC3 images of the OGLE-2005-BLG-169 source and lens star, separated by 50 mas in images taken 6.5 years after the microlensing event. The fit to microlensing light curve constraints and mass-magnitude relations yields the masses of the host (or lens) star and its planet of $M_L = 0.69 \pm 0.02 M_\odot$ and $m_p = 14.1 \pm 0.9 M_\oplus$ (Bennett et al. 2015).

more modest, because the smaller field-of-view and larger slew times than previous designs counteract some of the gains in photometric precision. However, the significant improvement in angular resolution adds a great deal of margin to the lens-source relative proper motion (μ_{rel}) measurements that are part of the primary WFIRST mass measurement method, illustrated in Fig. 4.

3. Simultaneous Ground-based Surveys

The primary WFIRST exoplanet host star and planet mass measurement method involves measuring the brightness and relative proper motion of the host star, so this method does not apply to planets without a host star. The same is true for planets hosted by brown dwarfs or white dwarfs. Fortunately, for events caused by low-mass free-floating or bound planets, there is a method that can determine the lens masses for events that can be observed from the ground. This method uses finite source effects (which yield the angular Einstein radius, θ_E) combined with a measurement of the microlensing parallax effect (as seen in Fig. 5) between Earth and WFIRST’s L2 orbit. This combination yields the lens mass (Yee 2013), and this is the only method to determine the masses of free-floating planets. This method is only expected to yield mass measurements for a fraction of free-floating planets, but this will be important, since it will be our only method to check if our statistical methods to estimate the mass distribution of free-floating planets might be subject to systematic errors due to uncertainties in their spatial or velocity distribution.

These parallax observations can only be obtained through simultaneous observations of free-floating planets from the ground and WFIRST, because the WFIRST data are not transmitted to the Earth in time for prompt alerts to observe with follow-up telescopes. There are several planned or existing ground-based telescopes that could be used for such a ground-based survey, and they would mostly make microlensing parallax measurements of different events. So, it would be beneficial to have several of these simultaneous ground-based surveys. The Large Synoptic Survey Telescope (LSST) is one option that could detect

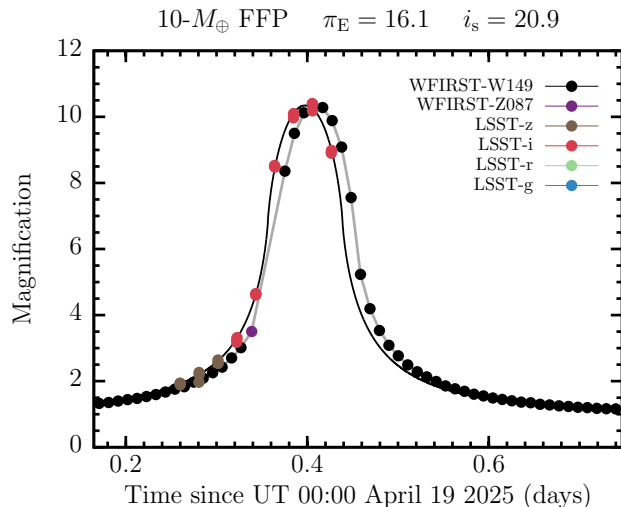


Fig. 5.— Simulated light curve of a free-floating planet of $10M_{\oplus}$ observed simultaneously by WFIRST and LSST. The shift in the time of peak magnification between the two light curves is due to the microlensing parallax effect. When combined with the source radius crossing time, t_* , that is also measured from this light curve, the microlensing parallax measurement will yield the host star mass.

relatively faint events (Marshall et al. 2017). The Japanese-American-South African PRIME infrared telescope that is now being developed for deployment in South Africa for WFIRST precursor observations (Bennett et al. 2018) would cover a different longitude and would be less affected by high extinction. Another attractive option would be the Korean Microlensing Telescope Network (KMTNet) (Kim et al. 2016) with telescopes on 3 Southern continents. A simultaneous WFIRST-KMTNet survey might serve as a possible Korean contribution to join the WFIRST Project.

4. Conclusion

The WFIRST exoplanet microlensing survey is the unique program that can extend the Kepler census of short period planets to the cooler, long period planets, like seven of the eight planets in our own Solar System. It will provide fundamental information on the properties of exoplanet systems that will be crucial for understanding planet formation and ultimately the search for life outside the Solar System.

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