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Space based microlensing planet searches

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Abstract. The discovery of extrasolar planets is arguably the most exciting development in astrophysics during the past 15 years, rivalled only by the detection of dark energy. Two projects unite the communities of exoplanet scientists and cosmologists: the proposed ESA M class mission EUCLID and the large space mission WFIRST, top ranked by the Astronomy 2010 Decadal Survey report. The later states that: "Space-based microlensing is the optimal approach to providing a true statistical census of planetary systems in the Galaxy, over a range of likely semi-major axes". They also add: "This census, combined with that made by the Kepler mission, will determine how common Earth-like planets are over a wide range of orbital parameters" We will present a status report of the results obtained by microlensing on exoplanets, the new objectives of the next generation of ground based wide field imager networks. We will finally present the fantastic prospect offered by space based microlensing at the horizon 2020-2025.

1 Microlensing planet hunting : where are we in late 2012 ?

The number of exoplanets discovered during the last fifteen years is now above 850 (and about 2300 candidates from Kepler), with a sharp increase in the last years. These discoveries have already challenged and revolutionised our theories of planet formation and dynamical evolution. Several methods have been used to find exoplanets: radial velocity, stellar transits, direct imaging, pulsar timing, transit timing, astrometry and gravitational microlensing. Gravitational microlensing is based on Einstein's theory of general relativity (Gould & Loeb, 1992): a massive object (the lens) will bend the light of a bright background object (the source) for example located in the Galactic Bulge. This can generate multiple distorted, magnified, and brightened images of the background source. When the lens is a star these images are unresolved and the brightness of the background star is amplified. The source's apparent brightness varies as the alignment changes due to relative proper motion of the source with respect to the lens. This light curve is monitored to detect and study the event. Thus, a microlensing event is a transient phenomenon with a typical time scale of $\sim 20\sqrt{(M/M_\odot)}$ days. If the lens is not a single star (binary star or star with a planet), the companion will distort the gravitational

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lens creating regions of enhanced magnification (caustics), which introduce anomalies in the light curve, lasting for about a day for a Jupiter mass and less than two hours for an Earth mass planet.

Microlensing is a rare phenomenon (towards the Galactic Bulge the optical depth to microlensing is $10^{\breve{}6}$). Therefore a two-step approach has been adopted since the 1990s. First, wide field imagers are monitoring a very large number of stars in order to detect real time on going microlensing events and alert them publicly (OGLE and MOA collaborations). The second step is to have a network of telescopes (mainly PLANET, μFUN, RoboNET, Mindstep) doing a follow up of a selected sample of the events with the highest sensitivity to exoplanets. From a networks of few telescopes in 2002, we now have up to 50 telescopes available on alert, ranging from robotic 2m telescopes to amateur telescopes in a backyard. In some cases, more than 20 telescopes have been collecting scientifically useful data on a given microlensing event (Batista et al., 2009). Up to now, 19 exoplanets have been published with this method

This includes cold Neptunes (Gould et al., 2006, Sumi et al. 2010), cold super Earths (Muraki et al. 2011, Bennett et al. 2008, Kubas et al. 2012), Saturns (Bachelet et al. 2012, Miyake et al. 2012), Saturn in the Bulge (Janczak et al. 2010), and multiple planet systems (Gaudi et al. 2008, Han et al. 2012, Beaulieu et al. 2013). We also detected Brown dwarfs orbiting M dwarfs (Bachelet et al., 2012) and 4 massive Jupiters orbiting M dwarfs (Dong et al. 2009, Batista et al. 2011, Street et al., 2012, Yee et al. 2012) that are not predicted by the core accretion theory (Laughlin et al 2004, Ida & Lin 2005, Alibert et al. 2005). On the other hand, gravitational instability can form large planets around M dwarfs (Boss 2006), but typically farther out. Planets formed by such mechanism would have to migrate significantly.

Although the number of microlensing planets is relatively modest compared with that discovered by the radial velocity method and by Kepler, this technique probes a part of the parameter space (host separation vs. planet mass) which is not accessible currently to other methods. The radial velocity and transit method favour the detection of close in and therefore hot planets with a current bias to large/massive planets. More recently it extended to hot super Earths such as GJ1214b, Kepler 10b, hot Earths Kepler 20e and 20f and the first large sample of terrestrial-sized exoplanets (Buchhave et al. 2012). Moreover, within the 2000 planetary systems discovered by Kepler (Batalha et al. 2012), 50 exoplanets are in the stellar habitable zone. Microlensing complements these detections because it is most sensitive to planets beyond the distance where water ice forms (the snow line), and to masses down to the Earth. Gould et al. (2010) have made the first measurement of the frequency of ice and gas beyond the snow line, and have shown that this is about 7 times higher than closer-in systems probed by the Doppler method (Cumming et al. 2010). This comparison provides strong evidence that most giant planets do not migrate inwards very far. Howard et al. (2011) has presented the first abundances of planets orbiting solar like star within 0.25 AU from Kepler, while Mayor et al. (2011) have measured the abundance of Neptune and super Earth using radial velocities. These studies show that 17-30 % of solar like stars have planets on short orbits. Cassan et al. (2012) finds that 17^{+6}_{-9} % of stars host Jupiter-mass planets ($0.3 - 10MJ$). Cool Neptunes ($10 - 30M_{\oplus}$) and super-Earths ($5 - 10M_{\oplus}$), however, are even more common: Their respective abundances per star are 52^{+22}_{-29} % and 62^{+35}_{-37} %. Planets around stars are the rule, rather than the exception.

The derived mass function is $\mathrm{dN/(d\log a\, d\log M)} = 10^{-0.62\pm0.22}\ \mathrm{(M/Msat)}^{-0.73\pm0.17}$ (where N is the average number of planets per star, a the semi-major axis and M the planet mass, and $Msat = 95M_{\oplus}$), appears steeper than results from the Doppler technique and abundances slightly larger. Differences can arise because the Doppler technique focuses mostly on solar-like stars, whereas microlensing a priori probes all types of host stars. Moreover, microlensing planets are located further away from their stars (closer to the locus of formation) and are cooler than Doppler planets (that have been almost certainly affected by migration). Bonfils et al., (2013) just released their statistics on the M dwarf sample monitored by HARPS on orbits between 1-100 days and concluded a high abundance of super Earth, in agreement with the microlensing result (although probing inner orbits).

Microlensing is roughly uniformly sensitive to planets orbiting all types of stars, as well as white dwarfs, neutron stars, and black holes, while other methods are most sensitive to FGK dwarfs and are now extending to M dwarfs. It is therefore an independent and complementary detection method for aiding a comprehensive understanding of the planet formation process. It is currently capable of detecting cool planets of super-Earth mass from the ground and, with a network of wide field telescopes strategically located around the world, could detect planets with mass as low as the Earth.

Exoplanets probed by microlensing are orbiting stars much further away than those probed with other methods, which are sensitive to planets orbiting stars in the Sun neighborhood. They provide an interesting comparison sample with nearby exoplanets, and allow us to study the extrasolar population throughout the Galaxy, in the Disk but also in the galactic Bulge (Janczak et al. 2010). In particular, the host stars with exoplanets appear to have higher metallicity (Fischer and Valenti, 2005). Since the metallicity is on average higher as one goes towards the Galactic Centre, the abundance of exoplanets may well be somewhat higher in microlensing surveys. Ground-based microlensing mostly probes exoplanets outside the snow line, where the favored core-accretion theory of planet formation predicts a larger number of low-mass exoplanets (Ida & Lin, 2005, Alibert el al. 2005).

Since microlensing can instantaneously detect planets without waiting for a full orbital period, it is immediately sensitive to planets with very long periods. Although the probability of detecting a planet decreases for planets with separations larger than the Einstein ring radius, it does not drop to zero. As a consequence, planets on very wide orbits, and free-floating planets (ejected during the formation process or formed as such) are detectable by microlensing. A significant population of free-floating planets is a generic prediction of most planet formation models, particular those that invoke strong dynamical interactions to explain the observed eccentricity distribution of planets (Goldreich et al., 2004 Juric & Tremaine, 2008, Ford & Rasio, 2006). An important population of free-floating Jupiters has also been unveiled (Sumi et al. 2011) and is raising questions about the importance of dynamical interactions after the formation of the planets (Morbidelli et al., 2012). In the coming years it is important to check their free-floating nature (not bound to a star), perform mass measurements when possible (thanks to terrestrial parallax, Gould et al. 2010), measure their abundance and try to detect lower mass ones.

Most planets in our Solar System are surrounded by satellites or moons, some of them being also part of a binary system (Pluto and Charon). The population of multiple-planetary systems containing many planets is increasing (e.g. Kepler 11, HD10180, Gliese 581). Although exomoons have not been published yet, various dedicated methods have been proposed for their detection, such as transit light curve, transit timing, direct imaging, microlensing (Bennett & Rhie 2002, Liebig & Wambsganss, 2010) and Doppler spectroscopy (Kipping et al. 2009, Simon et al. 2010, Sartoretti & Schneider 1999). Kepler's high precision has opened the possibility of detecting exomoons (Kipping et al., 2009). Steffen J.H., et al., (2013) is presenting the most up to date transit timing work by the Kepler team, while an independent survey using public Kepler data is underway, the Hunt for Exomoons with Kepler (HEK project, Kipping et al. 2012). Several analyses for exomoon detection have been published but none of them revealed any evidence for moon signature (Kipping et al. 2013, Nesvorny et al. 2012, Montalto et al. 2012).

The statistics provided by microlensing, combined with those from other methods, will thus enable a critical test of planetary formation models (Ida & Lin 2005, Mordasini et al., 2009). Microlensing can provide a census of cold planets that matches in sensitivity and extends the parameter space of other large surveys conducted using transits and radial velocities. Astrometry (with GAIA, PRIMA) will allow the detection of massive planets on wide orbits for the coming years, whereas direct detection will probe massive and young stars (SPHERE, PALM-3000, GEMINI planet finder).

2 The network of wide field imagers network era (2012-2020)

The existing structure of a network of telescopes controlled by PLANET, μFUN, OGLE, MOA, RoboNET and MINDSTEP was netting 5-7 planets per year in the period 2007-2011. In 2012, 22 planets have discovered. Contrary to the previous years, the wide field imager contribution from OGLE-IV, MOA-II and WISE is entirely dominant over the contribution of the fleet of the follow up telescopes for most of the planets. We are very clearly at a turning point, as it has been anticipated years ago. Moreover, other wide field imager will join the worldwide effort from 2013. The first ones will be the new Harlingten 1.3m telescope at the Greenhill observatory (Bies Die Tier, Tasmania), the SkyMapper from Mount Stromlo to be operated as part of the EARTH-HUNTER collaboration. In the period 2014-2016, the 3 telescopes from the KMTNet will come online at CTIO, SAAO and Siding Spring. Each node will be a 1.6m telescope equiped with 4 square degrees camera. Moreover, there are also plans to install a wide field imager in Namibia. Meanwhile, the LCOGT telescopes is deploying 1m and 40 cm telescopes around the world. They could be interesting addition to the wide field imager network by performing simultaneous observations from different latittutde/longitude to allow for detection of terrestrial parallax that will help mass measurements. In addition to the wide field imager photometry, there is a need to perform the coordination of targeted observations with Adaptive Optics systems on KECK, SUBARU, VLT, HST in order to constraint on light from lens to better constrain the parameters of the system. Observations few year apart will also permit to measure the direction and amplitude of the proper motion lens-source, allowing to nail down the parameters accurately.

With this worldwide effort, at the horizon 2018, the following objectives will be reached :
1) Measure the frequency of Earth-mass planets beyond the snow line
2) Measure the frequency of free-floating (i.e., ejected) gazeous planets
3) Measure the frequency of giant planets beyond the snow line as a function of planet-host mass and separation
4) First constrains the frequency of exomoons via microlensing

Given the expertise of the microlensing community, we can say that there are no technical/software hard points to reach these objectives in this time frame.

3 The ultimate planet hunting machines, EUCLID and WFIRST

At the horizon 2020+, a wide field imager in space will obtain a comprehensive census from free-floating small mass telluric planets to frozen Mars and habitable Earth orbiting solar like stars. The concept initiated with a dedicated mission (Bennett and Rhie 2002), the Microlensing Planet Finder (MPF), which has been proposed to NASA's Discovery program but not selected. The objective is to be able to monitor turn off stars in the galactic bulge as microlensing sources. Bennett and Rhie (1996) had shown that the detectability of exoplanets via microlensing depends strongly on the size of the source star. As an example, the $\sim 5.5 M_\oplus$ super Earth detected by Beaulieu et al. (2006) with a bulge giant has a source star was close to the limit of detection. Lower mass planets are detectable only with small source star, unresolved from the ground. Given the extinction of the fields and the temperature of the source stars, the monitoring is better done in the IR. Moreover, about $\sim 2\mathrm{deg}^2$ towards the galactic Bulge have a very high optical depth to microlensing. The ideal microlensing planet hunting machine is a 1m class telescope, with a wide field imager (about $\sim 0.5\text{deg}^2$ and high angular resolution (0.1 – 0.3arcsec/pix), to observe the galactic bulge with a sampling rate better than 20 min. Despite the fact that the designs were completely independent, there is a remarkable similarity between the requirements for missions aimed at probing Dark Energy via cosmic shear, baryonic acoustic oscillations and a microlensing planet hunting mission. The requirements of the designs are stronger for the cosmic shear compared to the microlensing.

EUCLID is an ESA medium size mission schedule for launch in late 2020. As core science, it will measure parameters of dark energy using weak gravitational lensing and baryonic acoustic oscillation, test the general relativity and the Cold Dark Matter paradigm for structure formation. Since its original submission (under the brand DUNE) in 2007 to ESA, a microlensing planet hunting program has been listed as part of the Legacy science (Beaulieu et al. 2007, 2008).

The vision adopted by the Europeans of a joint mission with Dark Energy probes and microlensing has been promoted and adopted by the Astro 2010 Decadal Survey when it created and ranked as top priority the WFIRST mission. The report stated : "Space-based microlensing is the optimal approach to providing a true statistical census of planetary systems in the Galaxy, over a range of likely semi-major axes". They also added: "This census, combined with that made by the Kepler mission, will determine how common Earth-like planets are over a wide range of orbital parameters". Some characteristics of EUCLID and WFIRST are summarized in table 1, and we will discuss the microlensing capability of these missions in the forecoming two sections.

3.1 EUCLID

summary of the results of the Penny et al. survey : please write it down :-)

3.2 WFIRST

Two reference designs have been originally considered for WFIRST (Green et al. 2012) to meet the requirements from the decadal survey as summarized in table 1. DRM1 is the first design to address all the science goals as a stand alone mission. DRM2 is non-duplicative of EUCLID and it is a cheaper version (1 billion versus 1.6 billions) using 4k chips H4RG instead of the 2k version. It is a pure imaging mission with a wider field of view of $\sim 0.56\text{deg}^2$. DRM1 has a smaller field of view, but two spectroscopic modes using a prism and a grating. The microlensing capability of WFIRST has been investigated first by Barry et al., (2011) and a thorough study is underway by Penny et al. (2013b). The later will apply exactly the same codes and hypothesis as done by Penny et al. (2013a).

NASA has acquired two complete 2.4m telescope from the National Reconnaissance Organization (NRO) of the US Department of Defense. They are wide field versions of the Hubble Space Telescope. Dressler et al., (2012) has studied the opportunity to use one of these telescopes to meet the Astro 2010 Decadal survey goals, and called it the NEW WFIRST project. Provided that existing hardware would be used, it is envisionned it would both fit in the DRM1 cost cap, while addressing all the objectives from the Decadal survey in a shorter time scale compared to the DRM1 implementation. Neverthless, althought it is promissing, more studies are needed to confirm that indeed it is possible.

For microlensing, the planet catch with NEW-WFIRST is estimated to be ~ 1.6 times larger than DRM1 design, with a higher efficiency in particular towards the low mass planets ($\sim$3 times more Mars mass planets). These estimates (not yet a full simulation) have been done with a survey of the same duration, with a IR focal plane of the same size, but smaller pixels for the NEW-WFIRST version.

Table 1. A short summary of EUCLID and WFIRST. Please note that although the design of EUCLID is definite, the design from WFIRST is under development. We discuss the opportunity of using 2.4m NRO telescope for WFIRST in the text.

EUCLID	WFIRST, DRM1 and DRM2
ESA M2 mission launch 2020 1.2m Korsch telescope	NASA mission, launch 2025+? 1.3m off axis, three-miror anastigmat telescope
Optical, 0.1 arcsec/pix, FOW 0.54 deg^2 IR bands : Y, J, H, 0.3 arcsec/pix, FOW 0.58 deg^2	$0.7 - 2.4\mu m$ IR bands : Z, Y, J, H, K, W bands, 0.18 arcsec/pix, FOW 0.375 deg^2 (DRM1) or ~ 0.56 deg^2 (DRM2)
Core science : Dark Energy. Legacy science : Exoplanets, SNIa, Galactic science	Core science : Dark Energy, exoplanets, Galactic science and general observatory.
4-6 months microlensing program (2020-2026) followed by 6 months after 2027 ? To be decided in 2014-2015	500 days microlensing program but when ? launch date depending on budget after JWST launch. 2025+ ?

Even if the European time scales are known to be rather slow, WFIRST will most likely be launched when EUCLID will be finishing his 6 years core survey. Indeed, it is only after JWST launch that WFIRST will be implemented.

4 Conclusion

Microlensing is at its golden age. It has a specific niche to address scientific questions that can only be answered by this approach. The different consortium involved in the ground base studies have evolved from competitive teams, to a global worldwide super consortium that goes beyond the standard approach. This cooperation/competition has been the key of the success and should be taken as a model by the other planet hunting techniques. The road is clear, with statistics of frozen Earth (among the objectives) to be obtained in the coming five years.

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