Formation, Detection, and Characterization of Extrasolar Habitable Planets
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Exploring the Cosmic Context of Earth

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Abstract. Studying the amazingly diverse planet zoo provides us with unprecedented opportunities for understanding planet Earth and ultimately ourselves. An assessment of a planet's "habitability" reflects our Earth-centric prejudice and can serve to prioritise targets to actually search for signatures of life similar to ours. The probability for life beyond Earth to exist however remains unknown, and studies on habitability or statistics of planetary systems do not change this. But we can leave speculation behind, and embark on a journey of exploration. A sample of detected cosmic habitats would provide us with insight on the conditions for life to emerge, develop, and sustain, but disentangling the biota fraction from the duration of the biotic era would depend particularly on our knowledge about the dynamics of planetary systems. Apart from the fact that planets usually do not come alone, we also must not forget that the minor bodies in the Solar system vastly outnumber the planets. A focus on just what we might consider "habitable" planets is too narrow to understand their formation and evolution. While uniqueness prevents understanding, we need to investigate the context and embrace diversity. A comprehensive picture of planet populations can only arise by exploiting a variety of different detection techniques, where not only Kepler but also gravitational microlensing can now enter hitherto uncharted territory below the mass or size of the Earth. There is actually no shortage of planets, the Milky Way alone may host hundreds of billions, and so far we have found only about 1000.

Keywords. Planetary systems, Astrobiology, Gravitational lensing: micro, Techniques: high angular resolution

1. Diversity vs uniqueness

From two decades of exploring planetary systems, we have learnt that planet Earth is a member of a planet zoo that is amazingly diverse. Exploring this diversity is key to understanding our home planet, - its past, present, and future. As we progress along our path of exploration, it is unlikely that the series of surprises that we have encountered so far has already come to an end.

However, on many aspects, we still have to consider Earth being unique in the cosmos. In fact, it is the only place known (to us) to harbour life. Uniqueness is a problem though, because something that is unique cannot be understood, - it requires context.

Many planets have been styled as "Earth-like", as we have found ones more and more closely resembling Earth. This is not too surprising, given that this attribute is always relative, and never absolute. We would need to define specific degrees of similarity for defining well-defined categories, such as "life-bearing planets". "Habitable planet" in particular does not constitute such a category, with habitability being intrinsically speculative rather than being a natural characteristic.†

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† The criteria that are actually used to define "habitable" however themselves can be used to define a category of planets.

Instead, habitability is a means for guiding exploration. With the choice of potential targets being large, and resources being limited, where to look is a most relevant question. Habitability can be seen as a proxy for the probability that life exists, where the latter is no more than a reflection of our Earth-centric prejudice, which sets prior assumptions. It thereby is a measure only of our expectations, while reality may be entirely different. Our rather patchy and fuzzy knowledge is not well mapped to a two-drawer system, which requires to draw a sharp line between planets that we may want to call habitable and those that we decide to call unhabitable. A smoother classification better addresses the fact that neither do we know that there is life on habitable planets, nor can we rule it out with certainty on those declared unhabitable.

We need to acknowledge the fact that the emergence of life is not understood at all. We neither know the necessary nor the sufficient conditions. We also do not know *where* life first emerged. Tracing life on Earth back to the origin is insufficient for understanding the road(s) to life. There are two ways forward: 1) Understanding the emergence from context (i.e. the before *and* the after), and/or 2) Finding other instances of life, from which we can read off the conditions.

On the other hand, detecting a habitable planet does not tell us *anything* about life beyond Earth. One would just replace speculation with speculation. Only with further exploration in mind, the assessment of habitability becomes useful.

2. An explorative view on the Drake equation

The concept of habitability actually shows in the Drake equation from 1961, which decomposes the number N of intelligent civilisations detectable from radio transmissions into 7 factors, namely 1) the formation rate $R_\star$ of suitable stars, 2) the fraction f_p of those with planetary systems, 3) the number n_e of planets per such system with conditions suitable for life, 4) the fraction f_l of such planets on which life actually develops, 5) the fraction f_i of life-bearing planets on which intelligent life emerges, 6) the fraction f_c of emerged civilisations that develop technology for propagating detectable signals, 7) and finally the time span L over which these civilisations disseminate such signals, so that

$$N = R_\star\, f_\mathrm{p}\, n_\mathrm{e}\, f_\mathrm{l}\, f_\mathrm{i}\, f_\mathrm{c}\, L\,. \tag{2.1}$$

These 7 factors formed the agenda of a 7-day meeting to which Frank Drake invited, - one day for each of the factors, and it is the factor n_e that corresponds to the search for explicitly *habitable* planets.

Only the last 3 factors of the Drake equation are specific to intelligent life or its detection by means of electromagnetic signals. So if we do not demand intelligence or technology, and consider the duration Λ of a biotic era, we find a shortened equation for number H of the habitats of life, namely

$$H = R_\star\, f_\mathrm{p}\, n_\mathrm{e}\, f_\mathrm{l}\, \Lambda\,. \tag{2.2}$$

Given that we do not know the road to life, it makes sense to move the division line between the factors. In fact, the factor n_e can be split into the number of planets n_p, and a habitability fraction f_h, i.e. $n_\mathrm{e} = n_\mathrm{p}\, f_\mathrm{h}$. Moreover, the habitability fraction f_h immediately recombines with the life ignition factor f_l to the biota fraction $f_\mathrm{b} = f_\mathrm{h}\, f_\mathrm{l}$. Thereby, habitability is being eliminated in favour of factors that are directly related to observations rather than speculations, yielding

$$H = R_\star\, f_\mathrm{p}\, n_\mathrm{p}\, f_\mathrm{b}\, \Lambda\,. \tag{2.3}$$

No form of the Drake equation will ever tell us something about the abundance of life beyond Earth. The factors on the right remain the unknowns. Similarly, no planet population statistics, how advanced they ever might be, will tell. The challenge is in finding the signatures of life. Once this has been achieved, with an explorative view on the Drake equation (Dominik 2012), one can solve for the unknowns that hold the information about the emergence and sustainability of life, which gives

$$f_\mathrm{b}\,\Lambda = \frac{H}{R_\star\,f_\mathrm{p}\,n_\mathrm{p}}\,. \tag{2.4}$$

However, with only the product of the biota fraction f_b and the duration Λ of the biotic era being delivered, we do not learn whether there are *many* planets with life that sustains for a *short* period, or whether there are *few* planets with life that sustains for a *long* period.

Formally, we can solve for the biota fraction

$$f_\mathrm{b} = \frac{H}{R_\star\,f_\mathrm{p}\,n_\mathrm{p}\,\Lambda(\tau_\star)}\,, \tag{2.5}$$

and obtain a lower limit by setting the stellar life-time $\tau_\star$ for the duration $\Lambda(\tau_\star) \leqslant \tau_\star$ of the biotic era. It might actually be a fair fraction of the stellar life-time $\tau_\star$, where detailed planetary dynamics and understanding of the role of the small bodies could provide better estimates, – while the detection of habitats will give us the opportunity to really find out what the necessary and sufficient conditions are.

3. Planet populations beyond Earth mass

Popular diagrams of the Solar System show the Sun and its planets, but there are the planet's satellites as well, and moreover the smaller bodies, which hold the overwhelming majority. However, for stars other than the Sun it is only the planets we are discussing so far. Exploration must not end at Earth size or Earth mass, but go beyond.

Kepler has already provided us with some candidates for quite small planets with orbital periods $P \lesssim 100$ d, closing the gap between Earth and Mars (Fressin *et al.* 2012; Gautier *et al.* 2012; Muirhead *et al.* 2012).

Meanwhile, gravitational microlensing (Einstein 1936; Paczyński 1986; Mao & Paczyński 1991) has demonstrated its sensitivity to cool Super-Earths already in 2006, with a one-night blip of 20 % revealing 5 Earth-mass planet OGLE-2005-BLG-390Lb (Beaulieu *et al.* 2006). As Fig. 1 illustrates, this was far from the sensitivity limits. Had an Earth-mass planet been in the same spot, it would have led to a 3 % signal lasting about 12 hours, detectable with dense observations after prompt triggering (Dominik *et al.* 2007).

Now, it is the finite size of the observed source star that limits the observed signal amplitude, smearing out pronounced but short signals. The characteristic scale of planetary microlensing is given by the angular Einstein radius

$$\theta_\mathrm{E,p} = \sqrt{\frac{4Gm_\mathrm{p}}{c^2}\,\left(D_\mathrm{L}^{-1} - D_\mathrm{S}^{-1}\right)}\,, \tag{3.1}$$

where m_p denotes the mass of the planet, and $D_\mathrm{S} \sim 8.5$ kpc and $D_\mathrm{L} \sim 6.5$ kpc are the distances of the source star or the lens star from the observer, respectively. For an observed source star of angular radius $\theta_\star$, the planetary excess magnification A_p becomes a function of $\theta_\star/\theta_\mathrm{E,p}$, i.e. $A_\mathrm{p} = A_\mathrm{p}(\theta_\star/\theta_\mathrm{E,p})$. Consequently, if we take account of the fact that in the case of OGLE-2005-BLG-390, the source star was 10 times larger than the Sun, one finds that with a star of Solar radius one can get a 3 % signal still for a companion

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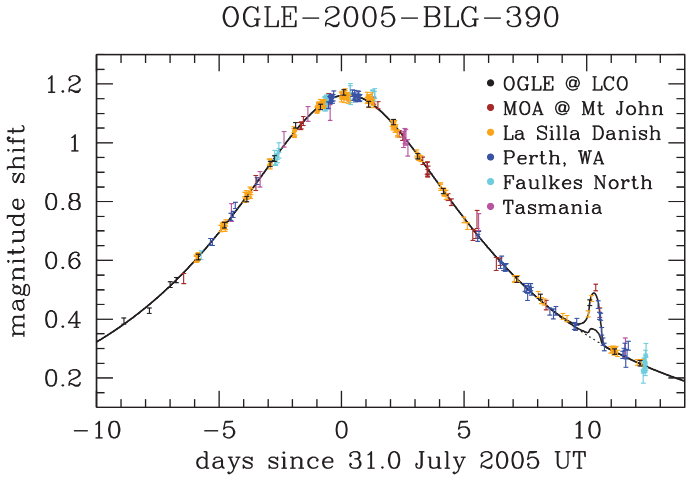

Figure 1. Data from different observatories and model light curve for microlensing event OGLE-2005-BLG-390, harbouring the signature of 5-Earth-mass planet OGLE-2005-BLG-390Lb. For comparison, the signature of a hypothetical Earth-mass planet in the same spot is shown as well.

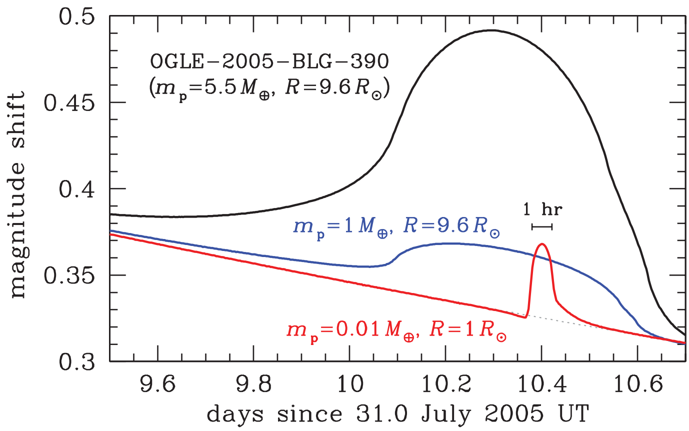

Figure 2. Observed planetary signature of OGLE-2005-BLG-390Lb compared to that of a hypothetical Earth-mass planet in the same spot, and that of a companion of Lunar mass with an observed source star of Solar radius rather than the giant of microlensing event OGLE-2005-BLG-390.

that is 100 times less massive than Earth, but it is 10 times shorter (about an hour) and 10 times less probably to occur (as illustrated in Fig. 2).

Moreover, for low-mass planets, the duration of the planetary signature relates to the source passing by its diameter rather than the planet mass, so that with a typical proper motion $\mu \sim 15\ \mu\mathrm{as\,d}^{-1}$ of the source star relative to the lens star, the duration becomes $2t_\star = 2R_\star/(D_\mathrm{s}\,\mu) \sim 2\ \mathrm{h}\,(R_\star/R_\odot)$, which means that one does not have to take care of time-scales shorter than about an hour.

Explicitly, one also finds the magnification due to a centrally hit isolated planet as

$$A_\mathrm{max} = \sqrt{1 + 4\left(\frac{\theta_\mathrm{E,p}}{\theta_\star}\right)^2}\,, \tag{3.2}$$

so that a 5 % deviation ($A_\mathrm{max} = 1.05$) implies a mass limit $m_\mathrm{p} \gtrsim 2\times10^{-8}\ M_\odot\,(R_\star/R_\odot)^2$.

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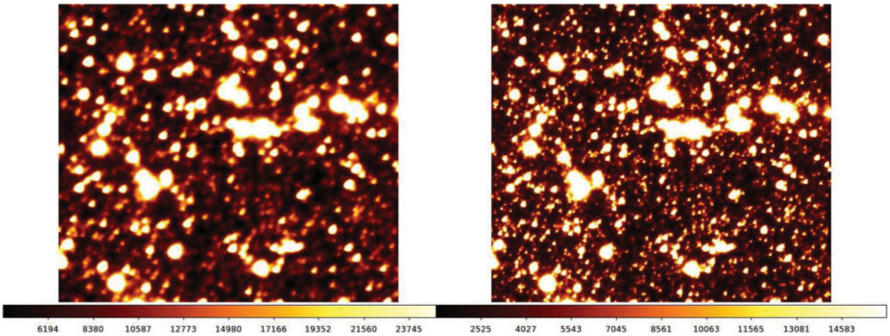

Figure 3. Illustrative example of higher resolution achieved by lucky imaging with the Danish 1.54m at ESO La Silla for a test field towards ω Cen with a width of 45" (courtesy of Kennet Harpsøe). Unlike the modern 1m robotic telescopes currently under deployment, this telescope is limited to an angular resolution of about 0.3" by its support structures, significantly above the diffraction limit.

Therefore, Paczyński (1996) already concluded that "it should be possible to extend the searches down to masses as small as that of our moon". Despite the decreasing detection probability $\propto \sqrt{m_\mathrm{p}}$, the prospects could be pushed by an increase in the abundance towards lower masses. On the other hand, the absence of detections would be a strong sign of the planetary mass function not continuing its currently estimated trend.

But efforts to advance even into the Lunar-mass regime suffer from crowding of the dense stellar fields towards the Galactic bulge. Resolving main-sequence stars from their brighter neighbours would require angular resolutions of 0.4" or below (Bennett & Rhie 2002), which could straightforwardly be achieved by space-based telescopes. However, attempts have already been made to exploit the technique of lucky imaging (Fried 1978, Tubbs *et al.* 2002) in order to obtain better photometry on microlensing events with 1-2m ground-based telescopes (Harpsøe *et al.* 2012), where Fig. 3 shows images obtained with the Danish 1.54m at ESO La Silla. It will play a key role in upcoming microlensing follow-up efforts with robotic 1m telescopes that are currently under deployment, forming part of the Las Cumbres Observatory Global Telescope (LCOGT) network, including three Scottish funded "SUPAscopes", or the Stellar Observations Network Group (SONG) network (Jørgensen 2008).

Several techniques have been suggested for the detection of satellites of extra-solar planets (e.g. Sartoretti & Schneider 1999, Han & Han 2002, Cabrera & Schneider 2007, Lewis *et al.* 2008, Liebig & Wambsganss 2010), where variations of transit timing or durations are likely to deliver first (Kipping 2009a, Kipping 2009b, Kipping *et al.* 2009).

4. Outlook

At the end, both the driver for and the ultimate benefit of studying extra-solar planets is to improve the understanding of ourselves. This cannot be done without exploring context, and differentiating amongst diverse data. Thereby, we can determine our own position within the wider picture. We therefore need to widen up our view rather than narrowing it down. In fact, this is what astronomy is all about, looking out, in order to be able to look back. This is possible only because the Heavens and the Earth are governed by the same laws of Nature. We now take this for granted, and this concept of cosmic unity was the ever prevalent one in China since ancient times.† In Europe however, it was a revolutionary postulate at Tycho Brahe's time, and famously reflected in the pair of enblems over the doors of his castle on the island of Ven: "Despiciendo suspicio – Suspiciendo despicio" ("By looking down, I look up – By looking up, I look down").

We are now being given unprecedented opportunities to leave an era of speculation behind. Only 20 years ago, we found first evidence showing that planets beyond the Solar System actually do exist (Wolszczan & Frail 1992, Mayor & Queloz 1995). From adopting the suggested planet mass function arising from 6 years of microlensing observations (Cassan *et al.* 2012), one infers that there are *at least* half as many planets as stars at 98% confidence, where only planets in the sensitivity window (orbital separations between 0.5 and 10 AU and masses between 5 $M_{\oplus}$ and 10 $M_{\rm jup}$) have been considered, and this estimate strictly refers to a sample average of stars as probed by the microlensing events (c.f. Dominik 2011). Moreover, small planets are found to be far more abundant than larger ones. Similarly, Bonfils *et al.* (2013) report abundances for hot Super-Earths ($1~M_{\odot} \leqslant m_{\rm p}\sin i \leqslant 10~M_{\odot}$, $1~{\rm d} \leqslant P \leqslant 10$ d or $10~{\rm d} \leqslant P \leqslant 100$ d) orbiting M-dwarfs of $f = 0.36^{+0.25}_{-0.10}$ or $f = 0.35^{+0.45}_{-0.11}$, respectively, arising from the HARPS (High Accuracy Radial velocity Planet Searcher) sample.

Clearly, there is no shortage of planets, and a number of more than 100 billion in the Milky Way alone appears to be realistic. So far, we know some thousand. Or in other words, we know next to nothing; there is a lot more left to explore.

Even the detection of life beyond Earth is not the ultimate goal (c.f. Dominik & Zarnecki 2011), it would rather mark the beginning of breaking into hitherto uncharted and maybe yet unimaginable territory.

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