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Red dwarfs and the nearest terrestrial planets

Detection and prospects for characterization of nearby potentially habitable planets

G. Anglada-Escudé[1,2,3]

[1] School of Physics and Astronomy – Queen Mary University of London, 327 Mile End Rd., E1 4NS London, United Kingdom
[2] Institut de Ciéncies de l'Espai – Consejo Superior Investigaciones Científicas – C/ Can Magrans s/n, Barcelona, Spain
[3] Institut d'Estudis Espacials de Catalunya – Gran Capità, 2-4, Edifici Nexus, despatx 201, 08034 Barcelona, Spain, e-mail: `anglada@ice.cat`

Abstract. Warm terrestrial planets is the most natural place where we can expect to find evidence for live similar to our own. Despite we would all like to study Earth-like planets around Sun-like stars, these remain elusive with our current capabilities. On the other hand, red-dwarf stars smaller than the sun are the most numerous in our Galaxy, and therefore in the Solar neighborhood. Also, due to their smaller size and mass, small terrestrial planets can now be routinely detected around them using the transit and the radial velocity techniques. Depending on the method used for the detection, different techniques can then be used for detection and characterization of their atmospheres. We review why the detection of very nearby red dwarf planets is so relevant nowadays, and the characterisation observational opportunities these planets can offer.

Key words. Stars – Extrasolar planets – Planetary Systems – Instrumentation – Red dwarfs – Astrobiology – Transits – Spectroscopy – Observational astronomy

1. Introduction

Detection and study of extrasolar planets is currently a mainstream research topic in astrophysics. The first well solid evidence of an exoplanet around a main sequence star was 51 Peg b, which is a hot Jupiter (Mayor & Queloz 1995). Soon after half a dozen detections where reported by the American counter part (Marcy & Butler 1996). After that, dedicated surveys started using a variety of techniques. Since then, more than 4100 exoplanet candidates have been reported[1].

There are essentially five major methods for exoplanets detection. These are the radial velocity method, the transit method, astrometry, microlensing, and direct imaging. The two most successful methods are the radial velocity and the transit methods, and they have shaped our understanding of planetary systems. What can be learned from a planet strongly depends

[1] The Exoplanet Encyclopedia `http://exoplanet.eu/`, *accessed Sep 1st, 2019*

on how it is detected. Before discussing these two methods, let us quickly review the other three. Microlensing has produced a few dozen detections at large orbital separations, which is a regime that the other methods cannot access. Although these detections are very useful for population studies and to constrain planet formation theories; microlensing are one-off events, so further characterization of individual systems is not feasible.

The astrometric method was the first one attempted. However, it has been broadly unsuccessful to the date, mostly due to the paucity of gas giants in long period orbits around low mass stars and difficulties in calibrating the measurements. However the Gaia/ESA space astrometry mission is accumulating very high precision astrometry (about 80 epochs each 100 μas) which will be released by 2022. Based on current population statistics, Gaia should reveal several thousands of new exoplanets (gas giants mostly). The direct imaging method would be the ideal one for further characterization. However, implementing it has been more technically challenging than initially anticipated, so detection of small planets using it remains elusive.

1.1. Radial velocity

A planet orbiting a star causes the star to also orbit the center of mass of the system. This counter-motion can be measured very precisely using Doppler spectroscopy at 1 ms^{-1} precision at optical wavelength by monitoring hundreds (to thousands) of spectral lines (Mayor & Queloz 1995). About 1000 planets have been reported using this technique. More massive short period planets are more easily detectable with radial velocities. As a reference, Jupiter moves the Sun at about 12 ms^{-1} over a period of 12 years. A Jupiter mass planet orbiting with a period of 4 days, causes a motion of $\sim$ 100 ms^{-1}. On the other hand, the Earth imprints a velocity of only 10 cms^{-1} on the Sun, and a detection using this technique is still not feasible today for technical and astrophysical reasons. The sensitivity of the technique improved significantly from the first detections in the 90's (precision $\sim$ 5 ms^{-1}) to the end of the 2000's. These increase led to the detection of smaller and smaller objects down to and few Earth masses in short orbital periods (<50 days). Population analyses based on the large Doppler surveys from the 2000's decade (Howard et al. 2010; Mayor et al. 2011) show that about 30% of the stars are orbited by compact planetary systems of 'super-Earth'–mass objects, which are absent in our Solar System. Another remarkable result of the technique is the determination that, at most, 5% of planetary systems have Solar-System like architectures, meaning contain at least one gas giant with an orbital period longer than 3–4 years.

Another factor that can help in the sensitivity towards small planets is the mass of the star. Red-dwarfs, are stars in the mass range between 0.6 to 0.09 $M_\odot$. Thanks to this, the Doppler technique has been able to reach the sensitivity to detect temperate $\sim$ 1 $M_\oplus$ planets. The method measures the minimum mass only. Only when transits are detected (the orbit must be edge on), or if direct imaged would be available (no success using this approach so far) the true mass of the planet can be unambiguously determined. The Doppler method would be insensitive to orbits that are completely face-on. However, one can show that the probability of an orbit being that way is rather small. For these reason, the sensitivity of the Doppler method is only mildly affected by the random orientation of the orbits (as opposed to the transit technique, which requires strictly edge-on orbits). The Doppler method requires bright stars. Nowadays, it is mostly used to either confirm or characterize transiting exoplanets, or to perform volume limited surveys of the solar neighborhood. The (initially) unexpected over-abundance of few Earth-mass planets in short period orbits rather than the improvements in the technique over the last 10 years is the most important factor why the Doppler technique has been so successful in detecting planets, and it is very competitive still today.

1.2. Transit method

If the orbit of a planet is aligned between our line of sight and the star, periodic occultation of the star light by the planet surface (so-called transits) will occur at each orbit. Transits of a Jupiter size planet in front of the Sun produce a dimming of the star-light of about 1% and can be detectable from the ground. The dimming is proportional to the planet-star area ratio, so smaller planets are much harder to detect. Transits typically last for a few hours, and it requires at least three or more transits measurements to ensure periodicity. To detect smaller planets (eg. Earth transiting the Sun causes a dimming of $5{\times}10^{-5}$) one has to work from space. Because the orbits are randomly oriented and that the transit probability is of the order of 1% (or smaller for Earth-like orbits), one needs to monitor many thousands of stars at a time to obtain statistically meaningful samples. These were the design requirements of the Kepler space-craft (3+ years, space photometry, $\sim$ 200 000 targets). The predictions estimated that it could detect 3–4 terrestrial analogues. Instead, and thanks to the unexpected over-abundance of short period small planets, Kepler detected about 3000 objects, featuring numerous compact multi–planet systems (e.g. six planets in the Kepler–11 system, Lissauer et al. 2011). Also, the high occurrence of compact multi–planet systems is not strongly dependent on the mass of the star. That is, smaller red–dwarfs are also hosts to compact systems. Earth size planet orbiting the smallest red-dwarfs would cause a dimming of $\sim$ 1%, and can be done from the ground. This is the goal of some ground based surveys such as MEarth (Ment et al. 2019) TRAPPIST+SPECULOOS (Gillon et al. 2017).

1.3. The M–dwarf advantage

The combination the following factors

- **Red dwarfs are fainter**. Therefore, the temperate orbits are much closer to the star, and corresponds to orbital periods between 5 - 50 days. Because the orbits are shorter, the signals repeat more often, so one can satisfy the repetition criteria much faster.
- **High abundance of small planets in compact planetary systems**, and combined with the fact that most stars are actually M-dwarfs.
- **Planets orbiting small stars are easier to detect**. Both transit and Doppler technique have more sensitivity to short period planets signals are larger ($\times$20–$\times$100 transit signals, $\times$5-$\times$20 for radial velocity signals).

is often called the M-dwarf advantage, and explains why most so-called potentially habitable planets have been reported around red-dwarfs. Among these systems, a few representative ones in terms of possible follow-up science are:

Proxima b. Detected via de Doppler technique using historical (VLT/UVES), and new precision measurements obtained with the HARPS spectrograph with an optimized observing strategy (Pale Red Dot project, Anglada-Escudé et al. 2016), is the exoplanet orbiting the nearest star to the Sun (Proxima Centauri). It has an orbital period of 11.2 days, a minimum mass of 1.3 $M_\oplus$ and an equilibrium temperature similar to Earth's. Space-based photometric searches determined that the planet does not transit (Kipping et al. 2017; Jenkins et al. 2019). Because of its proximity, its angular separation at its maximum elongation is about 40 mas, which may enable direct imaging with a combination of techniques (eg. Snellen et al. 2015), and phase resolved photometry of spectral features (Kreidberg & Loeb 2016; Snellen et al. 2017) using James Webb Space Telescope (JWST hereafter).

TRAPPIST 1. Three planet candidates where initially discovered from the ground using the 60cm diameter telescope TRAPPIST (in Chile). A long stare by the SPITZER space telescope revealed the presence of seven Earth-size planets orbiting it. The planetary system is very compact, and features three of the planets lie in temperate orbits. Since the planets transit, characterisation studies of their atmosphere can be readily done using HST (de Wit et al. 2018). TRAPPIST 1 is a small red-dwarf at 11 pc from the Sun, so it is a relatively faint target for HST. Large JWST programmes are being planned to perform direct detection of molecules in the putative atmospheres of several of these planets.

Other nearby bright transiting planets with 'warm to temperate' small planets include LHS 1140b/c (Ment et al. 2019), GJ 357 (Luque et al. 2019), and a few more. **Other compact planetary systems with temperate planets detected with Radial velocities** that due to their proximity to the Sun –less than 5 pc– may be eventually followed up with direct imaging methods include Ross 128 (1 planet), Wolf 1061 (2 planets), GJ 1061 (3–4 planets), Teegarden's star (2 planets), and a few more. The number of planet detections in this category is expected to increase substantially within the next 2-3 years, at which point all very nearby red-dwarfs will have been observed with enough precision and cadence to complete the sample.

Stellar activity studies and intense theoretical work triggered by these exciting systems indicate that Earth-like planets around red dwarfs would unlikely be able to sustain an Earth-like atmosphere (Airapetian et al. 2017). However, planet formation simulations (Coleman et al. 2017), and preliminary determinations of the true masses in the TRAPPIST system (Ment et al. 2019) indicate that these planets likely formed beyond the ice-line of the system and later migrated to the current orbits. This would suggest volatile rich worlds ($\sim 5\%$ water content), and therefore may be able to retain and regenerate atmospheres over time, while keeping a substantial body of liquid water on their surfaces.

2. Volume limited sample of stars and characterization prospects

In order to assess which technique is more optimal to produce targets that can be characterized, it is clear that we want more photons (nearest stars), and have other observational advantages (favourable planet-star ratio properties). When all trade-offs are equated in, one finds that from and observational point of view, best targets are stars between 0.1 and 0.5 solar–masses provide best characterization chances. As an illustrative example of the local demographics, the list of all the known star systems within 5 pc contains: 1–A (Sirius), 1–F (Procyon), 3–G (Sun, Alpha Cen A & Tau Ceti), 7–K dwarfs, and 46– M-dwarfs and 6 brown-dwarfs and 5 white dwarfs. Looking at these numbers, it becomes apparent why most of the nearest planets have been found around red-dwarfs, even before accounting for the M-dwarf advantage discussed earlier.

For the sake of quantifying the relevance of each technique in terms of detection and future characterization of warm terrestrial planets, we now show some simple simulations assuming that all stars in the 5 pc list have a 1 $M_\oplus$ planet with a black-body equilibrium temperature equal to Earth's. The sensitivity of astrometry and microlensing methods to nearby temperate Earths is beyond the reach of the technology plans for the next decade, so they are not discussed further.

2.1. Transits applied to the 5 pc sample

Given a modest space photometer, such planets would be detectable around all spectral types. To visualize the expected yield of this technique on the nearby stellar sample, we estimate what would be the expected number of transiting Earth-analogues as a function of the distance (see Fig. 1). We find that the expected value reaches $\sim$1 at around 4.6 pc. Given that the number of targets grows quickly with distance (d^3), this is also the distance where we would expect to detect the nearest transiting Earth analogue in the most optimistic scenario. Assuming that only 1/3–rd of the stars likely contain such a planet (Dressing & Charbonneau 2015), the distance at which we would expect the first temperate Earth–analogue is about 6 pc. Finding these high profile targets are the primary goals of the TESS (Ricker et al. 2015) and SPECULOOS (Gillon et al. 2017) surveys. The number of temperate rocky planets around bright enough stars to allow characterization with JWST and giant ground based telescopes is likely to be limited to less than 10 objects.

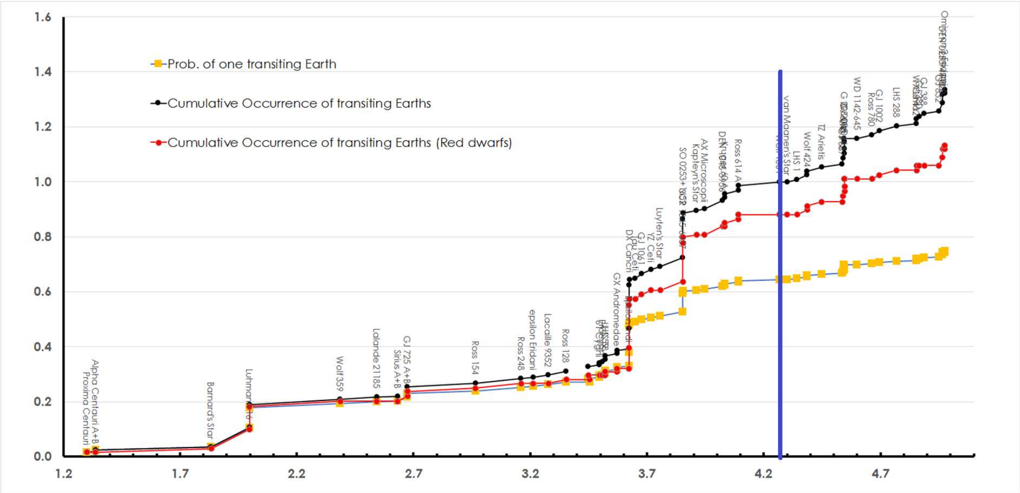

Fig. 1. Different ways to estimate the distance at which we can expect to detect the first transiting temperate terrestrial planet. The dots are computed using compound probabilities for each star. The resulting occurrence rate (or expected number) of transiting planets as a function of the distance is illustrated as a black line, the red line uses red-dwarfs only and the yellow line is the cumulative probability of finding a transiting planet. The blue vertical line marks the distance at which the expected value of transiting temperate planets reaches unity.

2.2. Radial velocity applied to the 5 pc sample

For the radial velocity method, we estimate the number of full telescope nights that we would need to detect the object (i.e. reach a signal–to–noise ratio of 5). The radial velocity method is less sensitive to inclination, so one can expect that almost all such planets can be detected after spending enough time on target. Adding all the stars in the 5 pc sample, we find that we would need ∼14000 nights (38–yrs). However, a closer inspection to Fig. 2 shows that most of the nights would be needed on very few expensive targets (A, G, F, and K stars). If the survey is limited to the M–dwarfs, then the required time falls to ∼140 nights meaning that a complete survey can be completed within a year. These red-dwarf sub-sample sample includes 37 objects, which actually contains 67% of all the systems. These explains why Doppler surveys such as HARPS M-dwarf programme (Bonfils et al. 2018), Red Dots (Anglada-Escudé et al. 2016), and CARMENES (Quirrenbach et al. 2012) have been so productive in detecting nearby terrestrial planet candidates in the past few years.

2.3. Direct imaging applied to the 5 pc sample

In terms of direct imaging, we now plot the angular separation of each planet in terms of the diffraction limit of a 8 m telescope observing the stars at 800 nm (ESO/VLT–SPHERE like instrument, Beuzit et al. 2006). All the stars that are prohibitively expensive using the radial velocity technique (AFGK types), now feature prominently as the most promising targets (see Fig. 3). For the α–Centauri System and Sirius, one should be able to resolve them with a 1–2m class space telescope.

2.4. Millimetric/radio imaging?

Characterization of nearby potentially habitable worlds is a world class endeavour, meaning some of the projects with good chances of being executed are in the tens to 1 billion cost level. Given the stakes, one could eas-

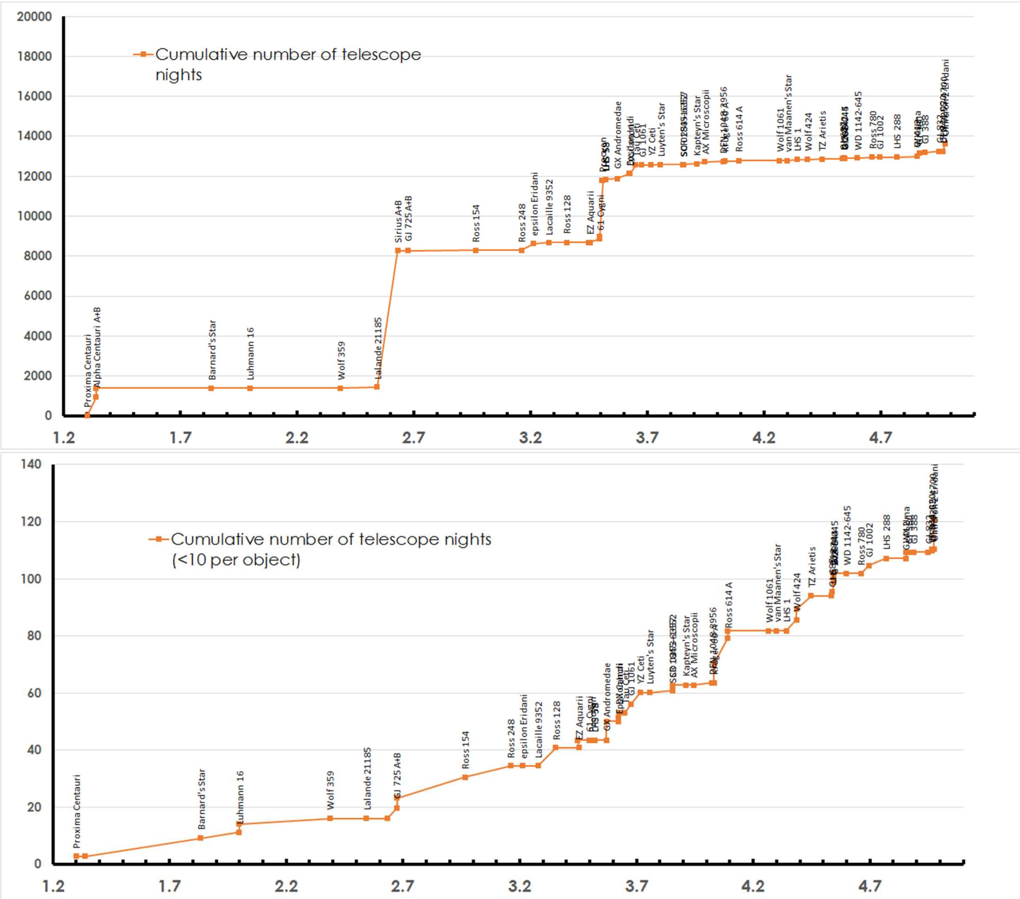

Fig. 2. Estimated number of full telescope nights (8 hours/night on a 4 m telescope) that would take to execute a full survey with the sensitivity to detect (and rule out) all temperate terrestrial planets within 5 pc from the Sun. (Left) When looking at all the stars, it would take of the order of 40 years. (Right) When the most massive AFGK spectral types are excluded, a survey on ~ 70% of the sample can be completed in much shorter time (~ 140 nights).

ily justify high risk proposals and alternative methods leveraging on a number of non-main stream techniques in exoplanet (mostly limited to optical and near infrared observations). Just as an example, when an exoplanet is observed in the sub-mm and radio domains, the planet-star contrast ratio becomes maximally favourable. Assuming that both star and planet thermally emit as black bodies in the Rayleigh-Jeans regime, the contrast ratio becomes independent of the wavelengths and it becomes

$$C_{\mathrm{RJ}} = \frac{T_p}{T_*}\frac{R_p^2}{R_*^2} \tag{1}$$

where T_p and T_* are the temperature of the planet and the star respectively, and R_p and R_* are the corresponding radii. For a Sun-like star, these contrast ratio is about 0.5×10^{-6}, but for a red-dwarf (Proxima Centauri) is 10^{-3}. Other

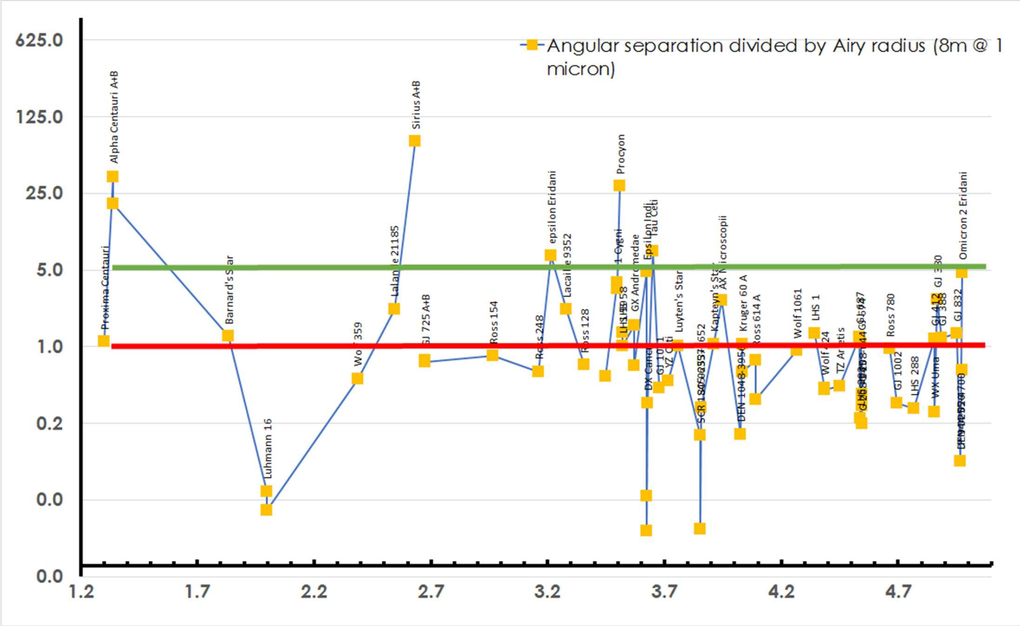

Fig. 3. Sensitivity of direct imaging methods to nearby terrestrial planets. The angular separation normalized to the diffraction limit of an 8 m telescope at 800 nm (y-axis) is plotted against each target sorted by distance (x-axis). The targets above the green line are above 5 times this diffraction limit and should be achievable with upgrades to current instruments or near future dedicated experiments. Those above the red line are above one diffraction limit threshold. These, in principle, could be imaged by combining high contrast, high spatial resolution and high spectral resolution techniques. More than for direct detection, the advantage of direct imaging is in terms of characterization. The method would greatly benefit from knowing the approximate orbit and characteristics of the planets (e.g. attempt imaging of planets detected by radial velocities or astrometry).

sources of radiation (cyclotron, line emission, etc) will also scale favourably and these are very nearby objects (1.2 pc for Proxima Centauri), when compared to the more typical targets observed at such wavelengths (star forming regions at > 100 pc). These means that high spatial resolution can be achieved (1 % of an AU is ~10 mas) with current facilities, and the involved fluxes might not be negligible. Despite a priory chances of detecting something may seem low; theoretical predictions of exoplanet observations have proven to be rather inaccurate in the past, and an investment of a few tens of nights of large radio telescopes can be worth the risk. In addition to attempting direct characterization of the exoplanets, other features of the planetary systems (asteroid and Kuiper belt analogues) should also produce *easily* detectable signatures (ϵ Eridani with LMT, Chavez-Dagostino et al. 2016). It is also worth mentioning that planets with Saturn-like ring systems would have a greatly enhanced thermal emission cross-section further boosting signals.

3. Characterization prospects for the next ten years

As mentioned earlier, the nature of the information that can be obtained from a planet critically depends on the detection method, and other features of the star (i.e. its distance to the Sun). The planets where additional information can be obtained in a more straightforward way are the transiting ones. However, there will not be many of these orbiting bright nearby stars, and alternative techniques are in development. Here is a summary of the most common techniques being used to obtain more information once the presence of a planet has been established. For each follow-up technique, we indicate on which kind of planets this is technically possible today, and what are the expectations for the next decade.

– **Combining transits and radial velocities.** The transit method only provides relative size to the star. Measuring the mass of the exoplanet can then be performed using complementary follow-up Doppler observations. Since the orbital period is not an unknown parameter, a much smaller number of Doppler measurements are sufficient to provide a robust estimate of the mass of the planet. *Now applies to*: Hot to temperate Jupiters that transit (all spectral types), hot Neptunes and super-Earths (all sp. types), and hot to warm terrestrial planets around red dwarfs. *Will apply to*: mass upper limit to transiting terrestrial planets around sun-like stars. Mass measurements to transiting terrestrial planets around K and M dwarf

– **Precision radial velocities during transits.** By observing and measuring Doppler shifts and spectral-line profile changes, one can also measure the orientation of the orbit of the planet with respect the rotation of the star. The measurement of this effect -often called Rossiter-McGaughlin effect- has confirmed that planetary systems are "generally" aligned with the rotation plane of the star, but only for stars cooler than 6000K. Above that temperature, stars the orbital plane of the planets seem to be more random, including counter rotating objects, which is, in principle, explained by a less efficient tidal star-planet interaction and the presence of perturbing bodies (longer period planet or a stellar binary). High precision RM measurements are mostly limited to hot Jupiter systems, so it is not entirely clear if this also applies to compact planetary system with smaller planets. *Now applies to*: Hot to temperate Jupiters that transit (all spectral types and age), transiting hot Neptunes and super-Earths for young/fast rotating stars ($P_{\rm rot} < 10$ days). *Will apply to:* Transiting terrestrial planets around young/fast rotating stars.

– **Spectro–photometry of secondary eclipses.** Hot to warm planets have temperatures in the range of 2000 K down to a few hundred Kelvins. Under this situation their black body emission peak can be anywhere between 1 micron and 10 microns. As mentioned earlier, as long as the star planet are observed in (close to) the Rayleigh-Jean regime, the contrast ratio is more favourable for the detection of light of the planet than at optical wavelengths. When the planet goes behind the star, a shallower dip in the light curve can be measured. Under simple assumptions and with 2 or more measured bands, the equilibrium temperature of the planet can be then inferred. This observation also provides a reasonable measurement of the bolometric luminosity of the planet. When three or more bands are available, a low–resolution spectrum can be obtained using this approach, providing first hints of possible molecular absorption bands in the atmosphere of the planet. Note that the signal of this secondary transit is rather small already (~0.001 relative flux even at IR bands), so detecting perturbations over that at different wavelengths can be rather challenging and often contaminated by systematic uncertainties coming from the instrument but also from the star (spots, variability, flaring, non-thermal emission, etc). *Now applies to:* Hot Jupiters that transit (all spectral types), transiting hot Neptunes/super-Earths around red dwarfs. A few on very hot terrestrial planets. *Will apply to:* Transiting hot super-Earths, warm terrestrial planets around latest stellar types

– **Spectro–photometry of the primary transit**. Since optical instruments can achieve higher precision and are often more stable, higher resolution spectro–photometry can be obtained at ultraviolet, optical and near infrared wavelengths when observing the primary transit. If molecular species are present in the atmosphere of a planet, the effective cross section of the atmosphere varies with wavelength, which makes the transit depth dependent with wavelength. This is done primarily from space (using HST), but since it is a differential measure, it can also be done from the ground using large apperture telescopes in sites with very good observing conditions (seeing $< 1''$, low water vapour column). This technique has yield the detection of several molecular and some atomic features in hot Jupiter and a handful of hot Neptune systems. The method has also been applied to planet in the super-Earth and Earth size regime targets putting stringent upper limit to the existence of atmospheres with low molecular weights in terrestrial planets as well (eg. H_2 rich atmosphere ruled out in the TRAPPIST-1 system). This is a relatively mature technique and the literature of the method is extense. We refer the reader to Manjavacas et al. (2019) for a review of the technique, and its discoveries *Now applies to:* Hot Jupiters that transit (all spectral types), transiting hot Neptunes/super-Earths around red dwarfs. Some attempts on terrestrial planets (eg. TRAPPIST 1, upper limits). *Will apply to:* Transiting temperate planets around latest stellar types ($\lesssim$0.3 $M_\odot$) within next 3-4 year, maybe better.

– **Optical High–resolution spectroscopy of primary**. For planets orbiting bright stars, one can also obtain high resolution spectroscopic measurements during the transit and hope to be able to see line depths changing in phase with the transit, indicating that the atmosphere of a planet has a larger cross-section at very precise wavelengths indicative of atomic or molecular species. The method has been used successfully on chromospheric lines such as Ca H+K doublet (396 nm), and Na D1+D2 doublet (588 nm), and more recently He I triplet at 1084nm, which have large cross-sections in low density gases (upper layers on the atmosphere of some planets). *Now applies to:* Hot Jupiters that transit (all spectral types), *Will apply to:* Transiting temperate planets around latest stellar types (<0.3 $M_\odot$) when efficient high-resolution infrared spectrometers become available in large telescopes.

– **Phase resolved near–infrared high resolution spectroscopy.** Similar to the previous method, this one observes the thermal emission of hot planets. Because the planets have a spectrum very different from the star (eg. presence of CO), molecular bands moving at orbital velocities (tens to hundreds of kms^{-1}) can be detected by cross-correlating residual spectra to masks with weighted line positions. Molecular species (such as CH_4, CO, and others), can have hundreds of these spectral lines, so the joint signal of all of them can be detected in the co-added cross-correlation profile. A similar method consisting on cross-correlating the residual spectrum with the spectrum of the star itself has been attempted to try to detect reflected light (eg. 51 Peg b, Martins et al. 2015). *Now applies to :* Hot Jupiters (all spectral types), no transit needed. *Will apply to:* Temperate planets around latest stellar types ($\lesssim$0.3 $M_\odot$) when efficient high resolution NIR spectrometers become available in large apperture telescopes.

– **Phase resolved spectro–photometry.** Similar to the transit photometry, one should be able to detect changes in the light received from a star with a planet due to the orbital phase of the planet over time. The method has been used on systems where the planet is known to transit (interpretation of the modulation is more straightforward). When doing this measurements on molecular bands that the atmosphere of the exoplanet might have, one can also obtain a measurement of the presence of certain molecules (or their absence) in the atmosphere. *Now applies to:* Hot Jupiters (first claims). *Will apply to:* very nearby terrestrial planet candidates when combined with high contrast imaging (see below).

4. Direct imaging and high contrast methods

For many reasons, being able to actually "see" the exoplanet as an independent object from the star is highly desirable. First it provides unambiguous confirmation that the object is a planet indeed. Just from the very first images, one can then derive important properties such as orbital parameters, estimate its luminosity and mass (model dependent). Second, with a little colour information the effective temperature can be obtained; and with repeated observations over time, the characteristics of the orbit can also be estimated. Imaging exoplanets directly usually requires an adaptive optics system to correct from atmospheric perturbations, a physical occulter to remove as much light of the star as possible (devices generally called coronographs), and intense signal processing to mitigate false-positives from diffracting speckles caused by residual uncorrected effects. Speckle noise is currently the major limitation in increasing sensitivities towards higher contrast, and will also be a problem for very high contrast imaging missing from space.

4.1. Orbits and spectrophotometry of young massive planets

Most of the planets detected directly via direct imaging are orbiting young and relatively massive stars ($1-2$ $M_{\odot}$). This is because young planets are still hot and self–luminous and bright at near infrared wavelengths due to on–going gravitational contraction. The presence long period planets around slightly supersolar mass stars seems to be related to more massive disks and are important observational probes for planet formation theories.

Low resolution spectro–photometry has been obtained on a number of these young planetary systems now. These provide information on the possible molecular bands present in their atmospheres, and can also be studied to measure variability in the presence of clouds or other surface features (e.g. evidence of clouds in HR8799b, Barman et al. 2011). Apart from direct imaging of the planets themselves, high–contrast imagers are being used in tandem with sub-millimiter observations to characterize young planetary systems in formation (e.g. see ALMA and SPHERE observations of TW Hya disk in Andrews et al. 2016; van Boekel et al. 2017, respectively). There is a small but growing number of systems with strong evidence of young massive planets being caught in formation (disk perturbations, and hot blobs moving embedded in disks). *Now applies to:* Young/self luminous giant planets and proto-planetary systems around young stars. *Will apply to:* young super-Earth/terrestrial planets around young stars? (see below). Direct imaging on nearby terrestrial planets in significant numbers will require a 10m+ class telescope from space.

4.2. Reflected light?

No planet has yet been imaged in reflected light. Planets in reflected light are very faint compared to the star ($< 10^{-6}$), even gas giant planets at the angular separations where current technology can produce high contrast ratios (>100 mas). Apart from confirming the presence of the planet and fully constrain the orbit, spectrophotometric measurements would provide albedo measurements as a function of wavelength which should be able to distinguish between different kinds of atmopheres, clouds and even 'biomarking' molecules for the case of terrestrial planets.

4.3. Spectrally enhanced high contrast imaging

A new set of techniques and instrument concepts are now emerging which aim at combining state of the art high contrast imaging (10^5) with cross correlation spectral methods (10^3-10^4). That is, light from the star is concentrated and removed by a high-performance adaptive optics+coronograph system, and then the light surrounding it is sent to *arrays* of high-resolution spectrometers. The residual light of the star can then be removed from the high-resolution spectra, and a cross correlation mask is run on the residuals thus achieving possible contrasts beyond $10^7 - 10^8$. As a reference, the contrast ratio at optical wavelength between the exoplanet Proxima b and its parent star Proxima Centauri is at the 10^7 level. A few demonstration experiments have been obtained. These includes observations of reflected light from hot Jupiter systems to demonstrate the spectral enhancement methods, and combination of high resolution spectroscopy with moderate performing adaptive optics (CRIRES, Snellen et al. Beta pic b). Instrument proposals are being developed and hardware implementation of dedicated instruments and demonstrators are expected within the next few years. According to Snellen et al. (2015), an E-ELT class telescope equiped with such a system should be able to image Proxima b in a matter of hours. *Now applies to:* Young and nearby massive giant planets, orbiting very bright stars. *Will apply to:* direct imaging of very nearby terrestrial planet candidates around red dwarfs.

5. Summary and conclusions

Detection of exoplanets is happening now with a wide range of techniques and planetary types. Among all the discovered exoplanets, the best targets to obtain more detailed information immediately are hot/warm planets transiting bright nearby stars. JWST will push current techniques (mostly developed for HST) so initial characterization of nearby transiting terrestrial planets can be achieved within the next few years. Detecting this more advantageous targets is the primary goal of NASA/TESS mission and other ground based surveys.

If one wants to obtain volume limited samples of exoplanets, especially around red-dwarf stars, the Doppler technique remains the most optimal one. A dedicated radial velocity instrument could finish the job within a year, and identify the most nearby terrestrial planet candidates amenable to possible direct imaging follow-up. Several programmes are working towards these goal (e.g. HARPS, RedDots, CARMENES).

Direct imaging is evolving quickly, but by itself it is currently limited to young massive planets. To detect the true Earth analogues around sun-like stars, direct imaging methods are possibly the most promising ones, but only for a few tens of stars.

For the characterization of the sample of nearby non-transiting terrestrial planets, spectral methods combined with high-contrast imaging offer the best promise. For very inactive stars, phase resolved curves should also be possible, but test experiments are needed to understand the fundamental limits imposed by stellar variability.

Finally, we want to remark that any bit of information on these systems is priceless. Leveraging on the huge costs that dedicated characterization space missions will have; and given the low success rate in the theoretical models anticipating observational features, small scale experiments of a few nights (e.g. high resolution imaging of nearby planetary systems in radio, sub-mm) have a high gain potential.

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