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Extrasolar planets: the final frontier

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Abstract. Roughly 500 planets orbiting other stars–extrasolar planets or "exoplanets" are known to exist, and there are over 1000 additional candidates identified, at the time of this writing. The techniques for detecting and characterizing exoplanets are multiple, and interesting in their own right as applications of basic physical principles refined to a very high level of accuracy or sensitivity. The variety of planets found to date exceeds what is found in our own solar system, as is to be expected, both in terms of the planets themselves and the properties of their orbits. The detection and characterization of an Earth around a nearby solar-type star is perhaps to be considered the ultimate goal of exoplanet research. Its success may depend upon our understanding of typical levels of dust emission from planetary systems around solar type stars, a problem that connects to Schiaparelli's pioneering work on the relationship between meteor streams and comets.

Key words. planets and satellites: general - techniques: interferometric - techniques: photometric - techniques: radial velocities

1. Introduction

From time immemorial humankind has wondered whether it is alone in the universe. Gazing at the sky this wonder evolved from the question of deities to that of other corporeal beings on planets around other stars. But the problem lay in the detection of such planets. It was Giordano Bruno who, in the late 16th century, first articulated clearly the problem: *Sono dunque soli innumerabili, sono terre infinite, che similmente circuiscono quei soli; come veggiamo questi sette circuire questo sole a noi vicino. ...Come dunque circa altri lumi, che sieno gli soli, non veggiamo discorrere altri lumi, che sieno le terre ...? La raggione è, perchè noi veggiamo gli soli, che son gli più grandi, anzi grandissimi corpi, ma non veggiamo le terre, le quali, per esserno corpi molto minori, sono invisibili.* (Aquilecchia 1985) [1] The planet Jupiter is nine orders of magnitude less luminous than our Sun at optical wavelengths, and five orders of magnitude less bright than the Sun at roughly 25 microns (Fig. 1).

In 1992 the first planetary mass bodies beyond our solar system were detected–orbiting

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[1] There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous.

around pulsars (Wolszczan & Frail 1992). In was not until 1995 that the first planet around a main sequence star was discovered (Mayor & Queloz 1995), by the technique called *doppler spectroscopy*. From then the field exploded and over 500 planets are known to exist around other stars as of the end of 2010. In this brief report I review the techniques by which these planets were discovered and highlight the prospects for future discoveries, including the detection and characterization of Earth–sized planets around other stars.

2. Techniques that measure the mass

2.1. Radial velocity

Doppler spectroscopy is the technique by which most planets have been detected to date. [2]. While other definitions are possible, this one is easy to explain and unambiguous. The technique involves detecting the component of the stellar reflex motion along the line-of-sight to the observer, that is, the radial portion of the stellar barycentric wobble. This yields the mass times the sine of the inclination angle of the orbit to the star-observer line of sight, defined so that if the orbit plane is coaligned with the observer line-of-sight, the full stellar wobble is detected and sin(i) = 1. Because the inclination is not known *a priori* for most cases, statistical arguments must be used to compute a probability that the mass is within a factor n of the measured m sin(i) for a given ensemble of detected planet-star systems.

The initial discoveries in the mid-90s of extrasolar planets by RV were done with precisions of 15 m/s in sensing the barycentric wobble of the host star. At the time 3 m/s was regarded as a reasonable limit to which RV could eventually operate based both on then-possible instrumental capabilities and the projected ability to deal with the noise contributed by the stellar photospheres (arguments reviewed in Marcy & Butler 1998. Today programs are operating with precisions as good as 0.5 m/s on 4-meter-class telescopes, but more routinely at 1 m/s (Mayor & Udry 2008).

There are several sources of noise that contribute at comparable levels to limit the precision of state-of-the-art RV, including those intrinsic to the instrumentation and measurement process, and those associated with the star itself. The ESPRESSO project that is currently being implemented at the ESO Very Large Telescope, using one of the 8.2-meter telescopes, is designed to achieve a precision and long-term stability better than 0.1 m/s (Mayor & Udry 2008). At this level of precision, detection of Earth-sized planets around Sun-like stars is possible were the stars themselves sufficiently quiet. It is the stellar noise that is of greatest concern for achieving precisions two orders of magnitude better than was possible in 1995.

Stellar noise itself may be divided into several sources, all of which in principle may be partially overcome by characterizing the time spectrum of the noise source and, where possible, integrating for sufficiently long time periods. Noise associated with acoustic modes can be reduced to below 0.2 m/s through integrations of 15 minutes. Granulation–essentially photospheric convection–requires measurements spanning hours (Mayor & Udry 2008). Anisotropies such as starspots cause "jitter" in the astrometric signal which is harder to remove because of the lack of predictability; for the Sun this may limit planet detection with RV to 0.25 m/s at a signal-to-noise of 3-4 (Makarov et al. 2009). By moving toward the red end of the visible spectrum, where starspots have less contrast, the error may be reduced (D. Fischer, pers. comm, 2009), but eventually the photon noise will increase. Quieter stars will have fewer, or no, spots, but finding a sufficiently quiet cohort of Sun-like stars in the Suns neighborhood may be difficult. Looking for planets in Earth-like orbits around Sun-like stars, however, means looking at astrometric signals which span months, and so for stellar rotation rates like that of the Sun it may be possible to reduce further the jitter from stellar magnetic

[2] In this paper we simply define planets as being those objects which do not undergo deuterium fusion, that is, for solar elemental abundance are below 13 times the mass of Jupiter (M_J) (Burrows et al. 2001)

activity simply by looking for planets with orbital periods much longer than the starspot periodicity.

2.2. Astrometry

Astrometry measures the periodic shift of a star against the plane of the sky. The full amplitude of the stellar reflex motion is detected no matter what the orientation of the orbit of the planet on the sky. Hence, in principle, astrometry is a more quantitative approach than radial velocity for what concerns the mass. The problem is in the implementation; astrometry requires very accurate stellar position measurements to 100 microarcseconds for giant planets to better than 1 microarcseconds for terrestrial planets. To date no planets have been detected by astrometry, which has been done entirely from the ground, although future large ground-based telescopes may reach the required precision. The spaceborne interferometric telescope Gaia (planned for launch in 2012) will detect giant planets, but a planned follow-on called the Space Interferometry Mission –capable in principle of detecting Earth-sized planets–was not recommended by the US Decadal Survey report recently released (National Research Council 2010).

Astrometry and radial velocity studies are complementary in the sense that the former becomes more sensitive with increasing distance of the planet from the star, while the latter decreases in sensitivity–both up to the point at which the observational time baseline is exceeded by the orbital period. Beyond an orbit of that size, the sensitivities of both decrease sharply with planet-star semi-major axis (Fig. 2).

2.3. Microlensing

A third technique for measuring the mass of a planet depends the general relativistic effect of the bending of starlight by the force of gravity. Gravitational microlensing occurs when a foreground star passes nearly in front of a background star as seen by a distant observer. The foreground star acts as a lens which divides the source star into two images as seen by the observer. Typically, because of the low probability of such events, the so-called ”lens star” and the background “source” star are thousands of parsecs from us, and hence the images are unresolved. Hence the term ”micro”lensing, referring to the angular unresolved size of the images. However, these images are magnified as seen by the observer, and the amount of magnification depends on the angular lens-source separation. The magnification is variable because the source star and lens star are moving relative to each other. If the foreground star happens to have a planet orbiting about it, with projected separation near the projected paths of the unresolved images, the planet will produce its own much shorter lived signature by further perturbing the images of the source star. In this way, the planet-to-star mass ratio can be determined. The mass of the planet itself can only be determined if the mass of the star can be determined; this is done by observations which lead to the identification of the lens star itself, months or years after the event, as well as through particularly strong lensing events by which the character of the light curves enables constraint on the planet mass (Gaudi et al. 2008).

The geometry of microlensing as applied to planet searches involves looking to the Galactic bulge, some 8 kiloparsecs from the Sun, and searching for microlensing events caused by intervening stars typically 1-7 kiloparsecs distant from us. The scale of the microlensing sensitivity is set by the radius of the so-called “Einstein ring”, which is the circular image formed when source, lens and observer are perfectly aligned. Because the geometry is roughly fixed within a factor of a few by the galactic scale, so is the physical scale of the Einstein ring, the sensitivity of the technique for detecting exoplanets can be displayed on a plot of absolute star-planet separations, as shown in Fig. 3. In many ways microlensing is the most sensitive of the planet detection techniques in play today, having the capability to detect planets down to the mass of Mars in orbits equivalent to those of the terrestrial planets around our own Sun.

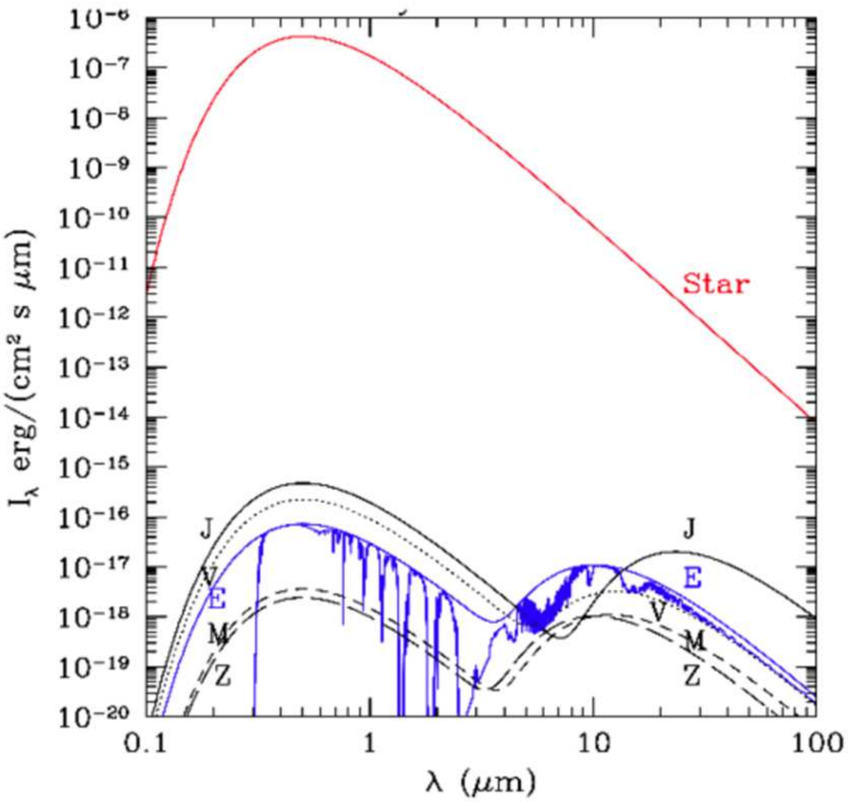

Fig. 1. The problem of detecting planets. Plotted as reflected sunlight and emitted thermal radiation are the signatures of the planets Jupiter (J), Venus (V), Earth (E), Mars (M) and the zodaical dust emission (Z). Earth's actual spectrum is also shown. The blackbody curve of the Sun ("star") is also shown. The absolute values of the received intensity is appropriate to observing our solar system from a distance of 10 parsecs. Plot drawn by K. Jucks and W. Traub; published in DesMarais et al. (2002).

Microlensing is not a technique that detects and measures the masses of planets around nearby stars, in contrast to astrometry and radial velocity. Instead, its strength is in its ability to obtain statistics on the architecture of planetary systems–that is, the distribution of orbits and masses of planets around other stars. Thus, although microlensing cannot provide a "target list" of stars to be followed up later by direct imaging to measure the size and make spectra of planets, it can help to guide strategies for direct detection of Earth-sized planets by indicating whether Earth-sized planets are common or uncommon in the Galaxy. However, to do so requires a continuously observing, space-based system. Ground-based networks that exist today cannot reliably track with sufficient continuity all stellar microlensing events to catch the much briefer signature of a planet, and thus many planetary microlensing events are likely being lost citeppeale. Even future ground-based systems, subject to the weather, would be vulnerable.

3. Techniques that determine size

The three techniques described above all determine the mass, or the scaled or projected mass.

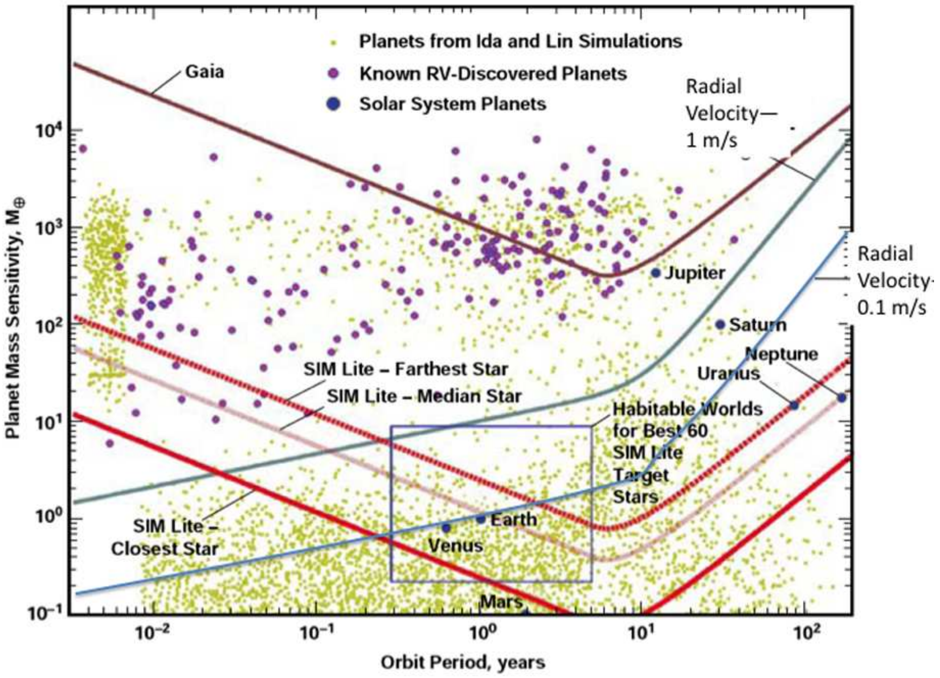

Fig. 2. Sensitivity of astrometric and radial velocity detection programs to planet mass versus orbit period for solar mass stars. The background green dots are a theoretical simulation of planet formation not germane to the discussion in this white paper. Radial velocity limits for 1 and 0.1 m/s are compared to SIMLite (a less expensive version of SIM) and Gaia limits. For RV sin i is assumed equal to unity. Modified from Davidson et al. (2009) by adding the 0.1 m/s line and altering labels).

In this section techniques that detect the size of the object are reviewed.

3.1. Transits

A transit is the passage of a planet in front of the disk of its parent star. During a transit, a small fraction of the starlight is blocked. One may discover a transiting planet by monitoring a large sample of stars, seeking periodic and short-lived dimming events. One may also seek transits of planets that have been discovered through the Doppler technique but whose orbital inclinations are unknown. In these cases, if the planet transits its star, one can immediately conclude that the orbit plane of the planet around the star is aligned with the line-of-sight to the observer, the radial velocity measurement is providing the physical mass, and then from transit-derived size the density of the planet is determined. The unambiguous planetary mass and radius, along with the possibility of obtaining spectra as described below, are why transits are so valuable.

Approximately 110 transiting planets are known. The ground-based wide-field photometric surveys have detected planets with transit depths ranging from 0.5% to 3%, by employing a variety of approaches to remove systematic effects due to the atmosphere and instrument. The planet sizes correspond to giant planets thermally-inflated beyond the radius of Jupiter, to objects that are the size of Uranus and Neptune. The variation in density among

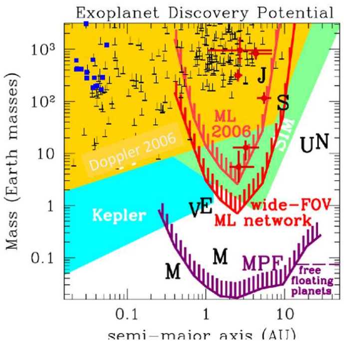

Fig. 3. Plot of sensitivities of techniques in the minimum detectable mass of a planet versus the planet-star physical separation in astronomical units. The purple curve is a proposed space-based microlensing mission ("Microlensing Planet Finder", or MPF), while the red curves show ground-based microlensing capabilities as of 2006 and in a proposed extensive network of wide-field telescopes. Known planets as of 2008 are plotted as small symbols with the planets of our solar system shown by their initial letters. The sensitivity of doppler is as of 2006 and for space-based astrometry (SIM) refers to the most distant stars in its proposed target list; hence the sensitivities of both may be higher. Figure provided by D. Bennett.

giant planets, aside from the thermal effects of being so close to the parent star, suggest a significant variation in the abundances of elements heavier than hydrogen and helium in the deep interiors of these bodies. While Jupiter may have a heavy element core of some Earth masses (perhaps up to 10 Earth masses) at least one of the transit-observed giant planets may be a hybrid object with significant amounts of heavy elements despite being more massive than Saturn (Winn et al. 2008).

A space-based transit survey conducted by a joint French-ESA (European Space Agency) satellite called CoRoT (Convective Rotation and planetary Transits), has been ongoing since December of 2006. Designed to do both stellar seismology and transit planet searches, CoRoT's telescope has a 27 centimeter diameter telescope with a field of view of 8 square degrees. It has demonstrated photometric precision for individual objects of better than 1 part in 10^4, which is difficult to achieve from the ground, and has detected planets as small as two Earth radii (Queloz et al. 2009).

To probe the occurrence of planets the size of the Earth requires improving the photometric accuracy by an order of magnitude, or more, the goal of NASA's Kepler mission launched in 2009. Kepler's field of view is about 100 square degrees provided by a 0.95 meter diameter Schmidt-type telescope. Launched into an Earth-trailing heliocentric orbit, Kepler observes roughly 100,000 F,G, and K class stars, most of which are between 600 and 3000 light years from Earth, in an area between the constellations Lyra and Cygnus. Assuming a random distribution of orbit inclinations relative to Kepler, about 1% of stars with Earths in the habitable zone should show transits. After several years of observations, that is, in 2012, Kepler should have accumulated enough observations to detect Earth-sized planets in the habitable zone of Sun-like stars (biased inward of 1 AU) to be detected through photometric transits (Fig. 3), and the statistical occurrence of Earths around Sun-like stars in relatively close-in orbits, complementary to those of microlensing, will be determined. As of today, Kepler has discovered 8 confirmed planets, but over 1000 potential candidates are reported or said to exist in presentations by members of the Kepler team–these candidates all require follow-up before they can be confirmed as planets. As is usually the case with transits, some of these candidates will be eliminated as false positives. However, if most are confirmed, then initial indications suggest that roughly one of ten Sun-like (F,G,K type) stars possesses a planet within a factor of two of the size of the Earth.

Transits also allow spectra of planets to be obtained. When the planet passes in front of the star (primary transit), the variation in the observed size of the planet as a function of wavelength due to the varying absorption in its atmosphere represents a transmission spectrum (Hubbard et al. 2001). When the planet passes to the other side of its orbit, it is briefly seen fully illuminated (dayside) by both reflected starlight and infrared emission, and then as it passes behind the star (secondary transit or eclipse), it is obscured. The difference in the spectrum of the system in these two configurations provides the planet's reflective or absorptive spectrum, and has been done successfully for extrasolar giant planets (Grillmair, C.J. 2008). Planets down to two or three times the size of the Earth could be spectroscopically examined in transit around cool M dwarfs by the James Webb Space Telescope (JWST) to be launched in 2015 or 2016. Because the telescope is not designed as a survey instrument, JWST will not search for exoplanets but instead study those already detected by ground-based and space-based surveys.

Finally, transits provide information on the inclination of the planet's orbit with respect to the equator of rotation of the star itself through the Rossiter-McLaughlin effect, as the transiting planet blocks the portion of the rotating stellar disk first moving toward, then away, from the observer. As long as stellar spectral lines can be observed with sufficient resolution, it is possible to resolve the path of the planet across the disk of the rotating star (Gaudi and Winn 2007), and hence the inclination of the planet's orbit.

3.2. Direct detection

Direct detection is the direct sensing of the light of a planet, which almost always requires the blockage or suppression of the light of the star itself. Ultimately, the ability to *directly image* an extrasolar planet – i.e., separate the light emitted or reflected by the surface or atmosphere of a planet from that of the star it orbits – offers the greatest prospect for characterizing these worlds. In particular, direct imaging offers the possibility of determining the colors and spectra of a large number of planets at large separations from their parent star - analogs to Jupiter or ultimately Earth in our solar system. Because of the required suppression in the optical–9 orders of magnitude for Jupiter and ten for the Earth around a star like the Sun–this is also the most difficult technique to implement. Even in the infrared, where the contrast with the star is much smaller (5 or 6 orders of magnitude)–the presence of interference from thermally radiating dust that might be in the star-planet system makes the problem extremely challenging.

There are two distinct approaches to starlight suppression: coronagraphy (involving a blocking disk or mask) and interferometry (nulling of the starlight). An internal coronagraph blocks the starlight using optical elements within a telescope, while an external-occulter coronagraph blocks the starlight with a separate large starshade positioned in front of the telescope, usually many tens of thousands of kilometers away. The chief advantage of internal coronagraphs is their packaging simplicity – all of the hardware needed to detect an exoplanet is contained within a single telescope assembly. The ability to point and center the coronagraph on the central star is relatively simple. The challenge of this approach is how to achieve sufficient suppression of the star's light in a stable fashion for a sufficiently long time, close enough to the star, to integrate on the weak signal of the planet.

The appeal of external coronagraphs, which have been studied for many years, is their potential to circumvent many of the light suppression problems faced by internal coronagraphs by instead blocking the stellar light with a free-flying occulter located between 20,000 and 70,000 km. The main drawback of the the external occulter approach lies in its operational complexity relative to a single spacecraft – two vehicles must perform properly for this technique to work and source targeting requires aligning the two spacecraft. This technique has been proposed for the James Webb Space Telescope by flying an additional spacecraft to the L2 Lagrange point where JWST will reside (Soummer et al. 2010), but it is unlikely given budget pressures that this will ever be implemented.

At long infrared wavelengths where the planet-star contrast shrinks by several orders of magnitude, coronagraphs would become huge and unwieldy. Instead, interferometery is the favored approach. An infrared interferometer consists in its simplest form of two telescopes joined on a structure, or mounted on separate satellites that maintain a controlled distance by precision formation flying. The starlight is suppressed by introducing a shift in the phase of the incoming light in one telescope of the interferometer, so that there is destructive interference for light that arrives aligned with the axis between the two telescopes. Light that is off-axis, such as from a planet displaced from the star, arrives with a different phase shift due to the optical path delay. The destructive interference does not occur, and there is a high throughput for the planet, enhancing its contrast.

Significant technological development is required to obtain the accuracy required for an interferometer, either via a fixed beam or multiple formation-flying telescopes. Various proposals for ambitious planet-finding interferometer missions have been fielded, most recently the so-called "Darwin" mission proposed in 2007to the European Space Agency. The interferometric approach would likely be chosen first only if surveys of potential target stars revealed typical dust emission levels significantly higher than for our own solar system, too high for coronagraphic missions to overcome. It is also possible that typical dust levels are so high–an order of magnitude above our own–that neither technique would work. The source of the dust in a mature system would be the small bodies, such as comets, shedding material in close approaches to the parent star. It was Giovanni Schiaparelli who first worked out the relationship between meteor streams and comets in our own solar system (Schiaparelli 1873), and so he would have appreciated the importance of determining the distribution of dust emission in other planetary systems. This is work that can be done by the present generation of large telescopes in the 8-10 meter class.

4. The road to Earths

To develop a strategy for the detection and characterization of Earth-sized planets around other stars requires a balance between ambition and practicality in terms of cost. Figure (Fig. 4) illustrates one strategy based on that proposed by the Decadal Survey of Astronomy and Astrophysics (National Research Council 2010). It assumes that the fraction of Sun-like stars with Earth-sized planets is in excess

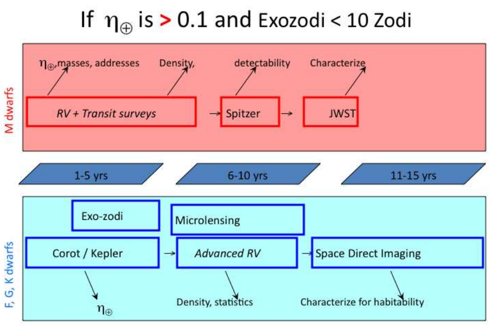

Fig. 4. Proposed strategy for discovering and characterizing Earth-sized planets around other stars. See text for details.

of 10%, and that infrared emission from dust around candidate planetary systems is less than 10 times that within our own solar system. The strategy divides in two, one line for M dwarfs and the second for F,G, and K dwarfs. The M dwarf track uses existing and planned resources to identify planets the size of the Earth or somewhat larger around M dwarfs, and then for those planets that transit, use JWST to obtain spectra of these systems. This would be completed within the next decade. The second track, for Sun-like stars, requires technology development to do space-based direct imaging. Before significant technology money is invested, the Kepler and Corot mission obtain by transit a more secure number for the frequency of Earths around Sun-like stars. If that number is ¿ 10%, one proceeds to develop the technology for spaced-based coronagraphy or interferometry by the mid-2020's. Meanwhile space-based microlensing, provided by the European Space Agency's planned Euclid mission–or a more ambitious but less mature plans for a US mission–determines the frequency of Earth-sized planets at larger separations.

Ground based efforts are intensified in the 6-10 year timeframe to drive the accuracy of radial velocity studies to the point where Earth-mass candidates (or those with M sin i at the value of the Earth) can be detected around nearby stars–possible candidates to be observed with the future space-based direct detection mission. If radial velocity cannot be made precise enough for this use, either one relies on the direct detection mission itself to make the discoveries–adding risk and eliminating the possibility of information on planetary masses–or a space-based astrometry mission in the 5-10 year timeframe is considered.

Should zodiacal dust emission be found to be too high, or most of the Kepler candidates turn out to be false positives, the ultimate goal of a space-based direct detection mission would be reevaluated. In its place might be a program to determine planetary architectures with an ambitious astrometry mission in the 10-15 year timeframe, or resources devoted to direct detection and spectroscopy from ground-based telescopes of extrasolar giant planets.

Regardless of what is finally done, the prospects for a major step forward in the Copernican Revolution–detection and characterization of an "Earth" around another Sun-like star–seem good sometime in the next few decades.

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References

Aquilecchia, G., ed. 1985, De l'infinito, universo e mondi, in *Dialoghi italiani. Dialoghi metafisici e dialoghi morali*, 2nd ed. Sansoni, Florence, p. 436

Borucki, W. et al. 2010, Science 327, 977

Burrows, A., et al. 2001, Rev. Modern Physics 73, 719

Committee for a Decadal Survey of Astronomy and Astrophysics; National Research Council 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*. National Academies Press, Washington DC.

Davidson, J. et al. 2009. *SIMLite Astrometric Observatory*. NASA, Washington, D.C.

DesMarais, D.J., et al. 2002, Astrobiology 2, 153

Gaudi, B. S. and Winn, J.N. 2007, ApJ655, 550.

Gaudi, B.S. et al. 2008, Science 319, 927

Grillmair, C.J. et al. 2008, Nature 456, 767

Hubbard, W.B. et al. 2001 ApJ560, 413

Makarov, V.V. et al. 2009, ApJ707, L73

Marcy, G.M. & Butler, R.P. 1998, ARA&A36, 57

Michel, M. & Queloz, D. 1995, Nature 378, 355

Mayor, M. & Udry, S. 2008, Physica Scripta T130, doi:10.1088/0031-8949/2008/T130/014010

Peale, S.J. 2003, ApJ126, 1595.

Queloz, D. et al. 2009, A&A506, 303.

Schiaparelli, G.V. 1873, *Le stelle cadenti* Fratelli Trevis Editori, Milano.

Soummer, R. et al. 2010, Proceedings of the SPIE, 7731, 77312I.

Winn, J.N. et al. 2008 ApJ675, 1531.

Wolszczan, A. & Frail, D. 1992, Nature355, 145