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Perspective

In search of planets and life around other stars

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The discovery of over a dozen low-mass companions to nearby stars has intensified scientific and public interest in a longer term search for habitable planets like our own. However, the nature of the detected companions, and in particular whether they resemble Jupiter in properties and origin, remains undetermined.

The first detection of a planet orbiting around another star like our Sun came in 1995, after decades of null results and false alarms. As of this writing, 18 objects have been found with masses potentially less than 12 times that of Jupiter, but none less than 40% of Jupiter's mass, around main-sequence stars (1) (see Table 1). In addition, several planetary-mass bodies have been detected orbiting pulsars. Although these are interesting as well, the exotic environments around neutron stars make it unlikely that their companions are abodes for life. It is the success in finding planets around Sun-like stars that provides a technological stepping stone to one of the great aspirations of humanity: to find a world like the Earth orbiting around a distant star.

The only technique to have succeeded in finding Jovian-mass companions to main-sequence stars involves measuring periodic variations in the radial velocity of the target star as seen from Earth. These variations are caused by the gravitational tugging of the planetary companion as it orbits around the star. Typical velocity perturbations are tens of meters per second and can be detected only by measuring the Doppler shift of spectral lines in the photosphere of the star on the order of 1 part in 10 million wavelength shift. To make reliable measurement of such small shifts over multiple observing runs requires superposing narrow calibration absorption features generated in the optical path of the starlight going through the telescope; iodine or hydrogen fluoride are the spectroscopically active gases employed (2). In practice root-mean-square scatter of 6 meters per second has been achieved (1); an ultimate limit of 3 meters per second appears to be set by convective motions in the photosphere that broaden the stellar lines. Measurement of the transverse perturbed velocity, by astrometric determination of the shift of the star against the stellar background, has yet to produce a definitive detection despite being a technique that long precedes the radial velocity approach.

The first radial velocity detection was that of a companion to the solar type star 51 Pegasi (3). Most striking about the companion is its proximity to the parent star: it is a body at least one-half Jupiter's mass with an orbital radius one-tenth that of Mercury about our own Sun. However, 51 Peg B would ultimately be only 1 of at least 14 Jovian mass bodies orbiting within 1 AU (the Earth–Sun distance) of their parent star (see Table 1). In part, this preponderance of close companions is a selection effect, because the radial velocity technique is most sensitive to massive objects in tight orbits. But the simple existence of giant planets in such orbits was unexpected given the architecture of our own solar system. The masses determined for these objects are lower limits, because the radial velocity technique is only sensitive to the component of the planet's orbital velocity along the line of sight of the observer. Hence, the true masses are larger by the factor (sin i)$^{-1}$, where i is the orbital inclination relative to the target star–Earth plane. In only one case, where the companion's parent star has a disk whose aspect ratio can be measured, is i known (4).

Table 1. Jovian-mass planets around main-sequence stars

Star	Star's mass	Semi-major axis, AU	Period, days	Eccentricity[*]	Mass[†]
HD187123	1.00	0.042	3.097	0.03	0.57
HD75289	1.05	0.046	3.5097	0.00	0.42
Tau Boo	1.20	0.047	3.3126	0.00	3.66
51 Peg	0.98	0.051	4.2308	0.01	0.44
Ups And	1.10	0.054	4.62	0.15	0.61
HD217107	0.96	0.072	7.11	0.14	1.28
55 Cnc	0.90	0.110	14.656	0.04	1.5–3[‡]
GJ86	0.79	0.114	15.84	0.04	4.90
HD195019	0.98	0.136	18.3	0.05	3.43
GJ876	0.32	0.210	60.9	0.27	2.10
rho CrB	1.00	0.230	39.6	0.11	1.10
HD168443	0.84	0.277	57.9	0.54	5.04
HD114762	0.82	0.351	84.0	0.334	11.02
70 Vir	1.10	0.480	116.7	0.40	7.42
HD210277	0.92	1.097	437.	0.45	1.28
16 Cyg B	1.00	1.61	803	0.69	1.67
47 Uma	1.03	2.09	1086	0.11	2.45
14 Her	0.85	>2.50	>2000	0.36	3.35
Sun	1.00	5.203	4332.6	0.048	1.000[¶]
Sun	1.00	9.539	10759.2	0.056	0.299[¶]

All companions listed have minimum masses between 0.1 and 11 times the mass of Jupiter. Table adapted from ref. 1. Stellar mass given relative to Sun's mass.

[*] Eccentricity of companion's orbit, where 0 = circular and >1 = unbound (hyperbolic).

[†] Companion mass × sine of the system inclination to Earth in units of Jupiter's mass (1.899×10^{27} kg).

[‡] The system inclination, and hence companion mass, is constrained by the presence of a disk (4).

[¶] The Sun's two major companions (Jupiter and Saturn) have masses directly determined by various techniques.

The new class of Jovian mass bodies in tight orbits around solar type stars cannot be studied directly; are they indeed "planets" like Jupiter and Saturn? The paradigm of giant planet formation requires that a lot of solid material be available to make cores that then nucleate gaseous envelopes from the surrounding protoplanetary disk (5). This model seems to require that ice must be present to make a giant planet, because it is by far the most abundant condensable available in a gas of solar composition (6). Hence, giant planets are expected to form no closer to the parent star than the water–ice stability line [3–5 AU for the protoplanetary disk around a solar-type star (7)]. Migration of such planets inward by interaction with the gas of the parent disk (8) or residual solid material (9) could explain some of the modest star–companion distances in Table 1, but the very close-in objects

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such as 51 Peg B are puzzling. The termination of migration at very small orbital distances requires invoking special mechanisms. These mechanisms might include truncation of the protoplanetary disk itself (8) or stripping of the planet by the star leading to an outward torque on the former (10). The production of eccentric orbits (Table 1) is another problem: it requires dramatic gravitational interactions among several giant planets (11), as-yet-unquantified disk–planet interactions, or retreat from the notion that these objects formed in the same way as Jupiter (12).

There is no evident physical reason why the direct collapse of interstellar cloud material cannot produce a body with a mass less than 0.07–0.08 times the mass of the Sun—the threshold below which self-sustained hydrogen fusion is not possible. Stars too small to undergo hydrogen fusion are referred to in the astrophysical literature as "brown dwarfs," and like planets, they too have proved observationally elusive. Unlike main-sequence stars, whose brilliance is steady or slowly increasing with age, brown dwarfs dim dramatically over time. Hence, they are difficult to detect directly unless they are very young or close to the solar system, and only in the past half-decade has success been achieved in their detection and study. Brown dwarfs are not only formed in isolation: computer simulations show that stars possessed of massive disks during their formation (exceeding 10% of the final mass of the star), may end up with stellar or substellar mass companions as a result of the direct collapse of disk gas.

So, are the newly detected companions listed in Table 1 planets or brown dwarfs? If the distinction has to do with how they formed, then it might reveal itself as a peak or trough in number of objects as a function of mass. Plotting the number of radial velocity detections versus mass (really mass × the sine of the unknown orbit inclination) reveals a steep decline in detections above a few Jupiter masses, with only one detection at 11 Jupiter masses and nothing beyond (1). This trend runs inversely to what is expected from an observational selection effect, and unless we have been unlucky in finding systems with a highly nonrandom distribution of line-of-sight inclinations, reflects a true decline in companions beyond 5–10 Jupiter masses. This in turn suggests that the process that formed these bodies is mass-limited, in just the way that giant planet formation is predicted to be. At much higher masses, near the threshold of the main sequence around 80 Jupiter masses, the number of detected objects (companion or free-floating) begins to increase. Objects near but below the main sequence boundary are probably the result of stellar-like birth and would be appropriately termed brown dwarfs.

Regardless of whether one accepts the planet/brown dwarf distinction, it is clear that the star–planet architectures being detected by radial velocity do not resemble that of our own solar system. In a general sense, this should not be surprising, as extrapolations from single examples almost always fail to anticipate the variety contained in nature. But it is also the case that if a system identical to ours were under surveillance by existing radial velocity surveys, only Jupiter would be detected (and with difficulty). In this respect, the search for extrasolar planets is not yet a search for solar system-like architectures or Earth-mass planets.

Ultimately, the search for other planets is motivated by the question of the existence of extraterrestrial life. The suitability of a planet for supporting life is usually referred to as habitability. Because we know of life on only one planet, Earth, the general requirements for habitability are very poorly understood. There is general consensus among biologists that carbon-based life requires water in which to stage self-sustaining chemical reactions. Therefore, the search for habitable planets within and beyond the solar system has focused on the search for environments in which liquid water is stable for the billions of years that advanced life required for development on Earth.

Yet even the stability of liquid water on the Earth over its geologic history is not well understood. It is only by invoking numerous feedbacks in the atmosphere and crust that the long history of oceanic stability contained in the geologic record can be understood. The principle driver of this complexity is the well known increase in solar luminosity over time, a phenomenon common to main-sequence stars like the Sun (13). When the Sun entered the main sequence some 4.6 billion years ago, its luminosity was ≈70% of its present value. The current Earth's atmosphere, with its modest greenhouse blanket of atmospheric carbon dioxide and water, would be too cold to sustain liquid water oceans under such conditions, and yet rocks from almost 4.0 billion years ago show strong evidence for liquid water (14). Apparently the Earth had a much greater amount of carbon dioxide in its early atmosphere, and through the action of geological and biological processes this has declined steadily through much of Earth's history (15).

The story of Earth's habitability is surprisingly complex (16). In consequence, it is difficult to define with confidence the so-called continuously habitable zone, the width of the region around any given star within which planets can sustain life over much of that star's main-sequence lifetime. Our own planetary neighbors, Venus at 0.7 AU and Mars at 1.5 AU, are not habitable today. But Mars shows evidence for an ancient epoch in which liquid water was apparently stable on its surface for some time (17). And yet the notion that Mars was habitable in its early days runs into severe problems with the faint early Sun: so much atmospheric carbon dioxide would have been required to warm the surface sufficiently that thick clouds of dry ice would have formed (18). The effect of such clouds could have been to short-circuit the greenhouse warming. Venus seems to be more readily interpretable: its proximity to the Sun triggered evaporative loss of any liquid water early in its history (19). The same models, disturbingly, predict that the Earth will suffer the same fate under a modestly brightening Sun just 1–2 billion years from now, long before the Sun leaves the main sequence. The end result of such calculations is that the width of the continuously habitable zone around solar-type stars is 0.2 AU, which provides a reasonable chance for habitability in a system containing several rocky planets within the first few AU (20). For systems in which the zone is occupied by a Jovian-type planet, habitability is presumably limited to putative moons of such objects, and even then there could be significant problems in sustaining biota (21).

To validate or contradict these speculations is a daunting task: Earth-sized planets must be found around stars in the solar neighborhood, and their habitability determined. The detection of Earth-mass planets is extremely difficult with existing indirect techniques. Radial-velocity measurements are ultimately limited by photospheric noise to detecting planets larger than Neptune. Astrometric precision of 0.3 micro-arcseconds is required to see, from 10 parsecs (or just under 33 light years) distance, the transverse stellar wobble induced by an Earth-mass planet. A precision of 20 micro-arcseconds is anticipated from use of the twin Keck telescopes as an interferometer, or with the European Very Large Telescope Interferometer: both near-term developments (22). Only spaceborne techniques hold promise of obtaining the required two orders of magnitude improvement in precision. The Space Interferometry Mission (SIM), under preliminary development leading to a launch in 2006, has micro-arcsecond astrometry as its goal (23). A survey of stars within 10–20 parsecs using SIM would map the frequency of planets nearly, but not quite, down to the mass of our own.

Two other indirect techniques seem capable of detecting planets the size or mass of Earth. Transit photometry detects the decrease in stellar brightness as a planet moves across the face of the star. Because a planet the size of the Earth dims a solar-type star by only 0.01%, novel spaceborne techniques would be required to provide the necessary extraordinary precision (24). Gravitational microlensing refers to the effect of a planet, orbiting a star acting as a gravitational lens brightening a background star, to produce a short-lived secondary brightening. Careful monitoring could detect events from Earth-mass planets (25), and indeed one such event has recently been reported (26). However,

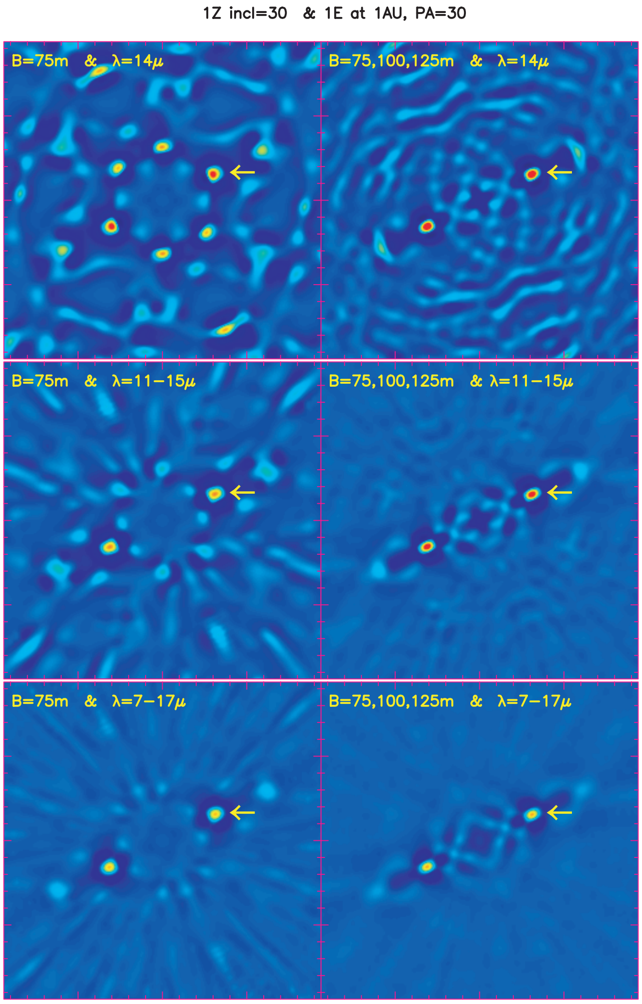

FIG. 1. Simulation of the detection of an Earth-sized planet around a star 10 parsecs from us. A spaceborne TPF system with two 3.5-m mirrors and two 1.8-m mirrors is assumed capable of precision stationkeeping so as to create multiple baselines, each of which is rotated about an axis pointed at the target star. Each panel represents a reconstructed image for a given baseline or set of baselines (B) and a wavelength or wavelength range (λ). For example, *Top Right* image is constructed with 3 baselines of 75, 100, and 125 meters length and a single channel at 14-μm wavelength. A Sun-like star at the center of each image is nulled out almost completely. The nature of the interferometric processing leads to a factor of two ambiguity in the position of the planet; this may be removable with more elaborate algorithms. T. Velusamy and C. Beichman conducted the simulation; figure reprinted from ref. 30 with permission.

planets closer than a few AU from their parent star (i.e., in the habitable zone for solar-type stars) would not produce a distinguishable signal. In addition, follow-up of such an event by direct observation is exceedingly unlikely given the strong chance that the detected system is far from the solar neighborhood (because of the intrinsically very low probability of microlensing events).

A complete survey of the solar neighborhood with the sensitivity to detect Earth-like planets, and to determine habitability, requires a step beyond the techniques discussed above. Direct detection of an Earth-sized planet is exceedingly difficult: the Earth is 10^7 times less bright than the Sun at 10-μm wavelength (and orders of magnitude dimmer still in the optical). To directly see such planets from many parsecs distance requires novel developments in large-aperture optical and infrared interferometry. One concept, the Terrestrial Planet Finder (TPF), relies on the technique of spaceborne nulling interferometry (27). By using multiple telescopes mounted on a fixed beam or maintained on separate, station-keeping spacecraft, an interference pattern can be centered on a target star of interest such that its glare is essentially eliminated. Then, if the pattern is rotated like a pinwheel around the pointing axis, putative planets in orbit around that star pass in and out of the bright fringes (28). With suitable aperture and beam lengths for the interferometer, it is possible to directly detect, and make spectra of, Earth-sized planets in Earth-like orbits around stars up to 15 parsecs away from us (Fig. 1). Spectroscopy could reveal atmospheric gases that are potentially diagnostic of habitability (29).

While TPF appears to hold enormous promise for taking the exobiological exploration of planets beyond our own solar system into the galactic neighborhood, it is fraught with technical challenges (30). NASA plans a phased program of ground and space-based trials of key systems; SIM itself will serve as a crucial test of spaceborne precision astrometry. Then there is the cost, which might exceed a billion dollars. Whether TPF, or something like it, ever flies depends on the priority we attach to answering the ancient question of just how unique is Earth in the cosmos.

Note Added in Proof. R. P. Butler *et al.* (*Astrophys. J.*, submitted) have announced the discovery of two additional planets around Upsilon Andromedae, making this a triple planet system and the first such multiple system to be discovered by the radial velocity technique. In addition to the inner planet reported in Table 1, there is a roughly 2 Jupiter mass body in an eccentric orbit between 0.7 AU and 1 AU, and a 4 Jupiter mass body in an eccentric orbit beyond 2 AU from the parent star. (Masses are minima since the system inclination is not known). The noncircular nature of the orbits raises interesting questions about the origin and stability of this planetary system.

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