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Extra-solar system planets: searches, discoveries and characteristics

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Abstract. The study of planets outside our solar system constitutes a new branch of astronomy that literally did not exist a decade ago. This discussion begins with how people have thought about other worlds in the past and some of the reported detections that turned out not to be true. It continues with a brief description of several successful ways of finding exoplanets and the properties of the planets found and their host stars, and concludes with an attempt to look ahead. Most of the planets now known revealed themselves because their mutual orbits with their parent stars impose small, periodic radial velocity shifts in the stellar spectra, and most of the host stars are rich in heavy elements by the standards of the solar neighbourhood. The inventory of actual and potential detection methods has reached about two dozen.

1. Introduction

From 1930 to 1992, there were nine. Then there were eleven. And now there are considerably more than one hundred. Planets, that is. Clyde Tombaugh completed the inventory of our own solar system in 1930 (though you are welcome either to think of Pluto as a trans-Neptunian object or to continue to look for a planet X that perturbs comet orbits and such if you wish). Then, after many kinds of searches, and many false alarms, Wolszczan and Frail (1992) announced a pair of short-period, terrestrial mass planets orbiting the millisecond pulsar B1257+12. A third was reported later (Thorsett 1994). Then, on an October day that few astronomers will forget, came the report of 51 Peg B (Mayor and Queloz 1995), the first of the "hot Jupiters", planets with masses (and in one case at least the composition) of Jupiter but short orbit periods, 4.23 days for 51 Peg B. Confirmation was rapid, for astronomers at Lick, as well as in Geneva, had been actively monitoring radial velocity variations. And the new year saw discoveries of 70 Vir B (Marcy and Butler 1996) and 47 U Ma B (Butler and Marcy 1996) The number

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discovered through perturbations of the radial velocities of their host stars passed 100 in 2003 (Butler et al. 2003). An up-to-date list of orbit parameters can be found at `http://exoplanets.org`. The inventory includes two triple systems in addition to the pulsar family (Ups And and 55 Cnc) and a handful or more of doubles, plus a good many remaining smaller residuals likely to represent second and third planets.

Just what are they and others looking for and beginning to find? Undoubtedly, in the long run, planets as much as possible like Earth. Earlier scholars, however, had several other ideas in mind when they spoke of other worlds. Some of these we would now call separate universes (or the multiverse), arising from eternal inflation. Others were separate worlds in temporal succession, like the modern brane worlds. Another set of astronomers, including William Herschel, attributed Earth-like characteristics to the Moon, Sun, and other planets. Probes for water on Mars and, someday perhaps, for subsurface life on the large moons of Jupiter are part of that tradition. And the concept of stars as suns with their own families of planets can be found as far back as the early 14th century (Buridan, Occam, Bradwardine) and became fairly well known — sufficiently well known to be dangerous — with the teachings of Thomas Digges and Giordano Bruno. See Trimble (2004) for additional details of these early thoughts.

What does it take to make an earth, if you mean a planet on which we, or our remote ancestors (Subramanian Stromatalite comes to mind), or our remote descendents might live? The order is meant to put the most important items first, but you might disagree.

- A solid surface, so you will have some place to put your keys. If present understanding of formation mechanisms is correct, this implies a mass not enormously larger than Earth's.
- Water and air provided and retained, that is, a supply of volatiles and a temperature between 273 and 373 K at least some of the time. Retention requires a mass not enormously smaller than Earth's.
- Plate tectonics, to maintain a balance of land and sea, and, later in the history of life to separate ores from the general mix of rocks and to turn biomass deposits into fossil fuels.
- Tides, to make tide pools to concentrate pre-biological molecules into a reactive soup (Darwin's warm little pond). The solar tides alone are about a third of the lunar ones and might be enough.
- A massive moon in any case, to stabilize the rotation axis. Earth nods up and down through only a few degrees, while Martian rotation axis excursions can be tens of degrees. The importance of this depends on how you feel about highly variable environments.
- A magnetic field to channel stellar (solar) energetic particles into Van Allen belts rather than down into the atmosphere. The existence of the terrestrial field seems

to require both a fluid core and rapid rotation (compare Mars and Venus), one or both of which may also be required to power mantle convection and plate tectonics.

- An outer massive planet to clear out debris and prevent excessive bombardment.
- The actual atmospheric signatures of the complex chemistry leading up to and resulting from life. That is, for instance, O_2, O_3, H_2O, CO_2 and beyond. My own favourite is the co-existence of O_3 (relatively detectable) and CH_4 (relatively undetectable) as signatures of plants and animals respectively. The red absorption edge produced by chlorophyll would be a higher-order indicator (Woolf et al. 2002).

One has to be a little careful not to make the definition too narrow, or one ends up with no other habitable planets in the galaxy (Ward and Brownlee 2004) or with them all crowded into the galactic bulge (this is actually my best guess) or lurking far in the future (Lineweaver et al. 2004). Actually neither of these references is quite so pessimistic as I have made it sound, but the title of the first, *Rare Earth*, is meant to be taken seriously.

2. False alarms and the strategies that yielded them

1. Direct imaging. The most obvious way to look for exoplanets is to look for them, that is, direct imaging; and this is always the strategy that textbooks explain will be very difficult because of the enormous brightness contrast (even in the infrared) between star and planet and the very small separation in the sky. It was also the first method to produce a false alarm, from the remarkable American, frequently fraudulent, Thomas Jefferson Jackson See (an 1897 article in *Atlantic Monthly*, a magazine for the general public, with no particular scientific focus). Quite recently, there was a report of a NICMOS (HST) image of a run-away planet (Terebey et al. 1998) which turned out to be something else.

2. Proper motion residuals. The method in general should work. After all, this is how Bessell found the white dwarf companions of Sirius and Procyon, decades before they were imaged. It also has a long history of false alarms, beginning again with See (1896) and continuing down to van de Kamp (1982), who thought he had evidence for a Jupiter and a Saturn (in masses and, approximately orbit periods) orbiting Barnard's star. Upper limits set using HST rule these out by large factors (Benedict et al. 1999). Analysis by others blames a change in telescope configuration for the apparent residuals.

3. Periodic residuals in radial velocities. This is, of course, our winner-and-still-champion method, but it, too, got off to a bad start (Campbell et al. 1988) with reports of periods of a few years and amplitudes of 10's of m/sec for more than half the solar-type stars examined. Some combination of variable star activity and under-estimation of error bars seems to have been responsible. Implied masses were a few Jupiters.

4. Periodic residuals in pulsar timing. Another eventual success, but it began in defeat. Bailes et al. (1991) announced a companion to PSR B1829–10, and dozens of models were in press before the authors announced that the planet responsible was Earth and incorrect allowance for the eccentricity of its orbit. The models then acquired the status of predictions when true pulsar planets turned up (Lyne & Bailes 1992).

5. Microlensing by single planets. Well, it seemed as if something of the sort was going on in the globular cluster M22, a considerable surprise given the association of planets then known with metal-rich stars. But the short-duration flashes turned out to be cosmic ray hits on HST images (Sahu et al. 2002).

3. Successes and the strategies that yielded them (plus a few retractions)

1. Direct imaging. The two main problems are the enormous brightness contrast between stars and planets and the small angular separations between planet and host for anything more than a very few parsecs away. All right, then look for very young planets, not yet so faint, which are not (or no longer) orbiting stars. This, it seems has been a success, extending the initial mass function downward from the brown dwarf regime to a few Jupiter masses, especially in the vicinity of Sigma Orionis (Barrado y Navascues et al. 2001, Zapatero Osorio et al. 2002, Martin et al. 2003) and also probably in one other star formation region (Oasa and Inutsaka 2001). Now you have to decide what to call these. I rather like 'orphan planets", the more so as they may actually once have had parent stars (Reipurth and Clarke 2001).

2. Proper motion residuals. At least one planet has been seen through the reflex motion of its host star. It is not, however, a discovery, but an independent measurement of the orbit of G 876b, a radial velocity discovery, using the Fine Guidance Sensor on HST (Benedict et al. 2002). The orbit orientation thus no longer remains uncertain, so the mass of 1.89 M_J is well determined. Gatewood (1996) reported a planet for Lalande 21185, but, at best, it hovers between this and the previous section.

3. Periodic residuals in radial velocities. These have yielded all the successes whose properties are outlined in Sect. 5. But they got off to a ragged start, with Gray (1997) suggesting that the velocity variations were all due to non-radial pulsations and running waves on the stars, but coming out in favour of planets the next year (Gray 1998).

4. Periodic residuals in pulsar timing. The one with three planets is B1257+12, in case you need to phone it. Interactions between the two larger ones permit measurement of their masses as about 4.3 and 3.9 time Earth (Konacki and Wolszczan 2003). The only other good case seems to be PSR B1620−26 in the globular cluster M4, a planet or two orbiting which was announced as early as 1993 (Backer et al. 1993). A decade later, it turns out to have a white dwarf and a planet, and the data collectors (Sigurdsson et al. 2003) believe that the system has resulted from a fairly complex process of star exchange.

5. Microlensing. The first discovery in this realm was that single objects of planetary mass do not make up most of the dark matter in the galactic halo (Alcock et al. 1998, Renault et al. 1998), or there would have been many more short-duration MACHO events than observed in the direction of the Large Magellanic Cloud. The second discovery is that one can occasionally identify planets orbiting the stars that do act as microlenses in the direction of the galactic bulge. The planets introduce a small, asymmetric blip in the main cusp of brightening caused by the parent star microlensing a background star.

A major plus to this method is that you can monitor a very large number of stars at once, if you have a suitable telescope (smallish) and computer (biggish). The major disadvantage is that the event will not recur. There is also some degeneracy in determining the speed of the lens through space, the star-planet separation, and the masses. An early candidate appears in Rhie et al. (2000). The cleanest case so far was observed by both the OGLE (Poland-Princeton) and MOA (New Zealand et al.) collaborations, and the best fit to the data has a 1.5 Jupiter mass planet orbiting an MV star (Bond et al. 2004). If the alignment of lens and background star is precise enough, even a terrestial planet mass can yield a detectable blip. Such alignments are bound to be exceedingly rare, but one might contemplate eventually being able to determine the mass function of planets this way.

6. Transits. This search strategy, like microlensing, needs a moderate-sized telescope plus lots of software and hard work. Thus, like some of the items listed later, it could be a good fit to the capabilities of some observatories in India. Transit searches, like microlens searches, allow you to follow vast numbers of stars at once, but the events will recur, so that radial velocity and spectral measurements can then be brought to bear on them. An early report, for CM Dra (already an eclipsing binary) came from Guinan et al. (1996). A transit of 51 Peg b (Krisciunas 1999) seems to have been a one-shot operation. The author said at the time that he was perhaps premature in the announcement but that he preferred not to be a candidate for the James Challis Prize.

The first undoubted success (like 51 Peg b a planet already known from variable radial velocity of its host) was HD 209458 (Charbonneau et al. 2000, Henry et al. 2000). The period is only 3.5 days, and observing the transits rapidly became a cottage industry for both professional and amateur astronomers. And once you know exactly when to look, it becomes possible to get a good value for the radius of the planet (which is less dense than Jupiter) and to look for small distortions of line profiles during ingress and egress. This has led to the recognition of sodium, hydrogen and oxygen in the atmosphere of the planet (Queloz et al. 2000, Charbonneau et al. 2002, Vidal-Madjar et al. 2004). The planet is somewhat "puffed up" relative to a colder Jupiter. The good news is that neither it nor other short-period planets will boil away soon (Lecavalier des Estanges et al. 2004). The bad news is that, although there are now predictions of atmospheric structure extending all the way from M dwarfs through brown dwarfs to exoplanets, the data are not yet quite ready for comparisons (Lodder 2004).

The OGLE data base has yielded a number of candidates for transit planets (Udalski et al. 2003), and additional ground-based searches are coming on line (e.g. Rauer et al. 2003). These need confirmation from radial velocity data, because it is possible to be misled by an eclipsing binary superimposed on a bright fore- or background star that makes the light amplitude look very small (Konacki et al. 2004).

The sensitivity of ground-based transit searches is set largely by atmospheric changes. Thus an earth crossing a sun, which blocks only about 10^{-4} of the light, can be caught this way, but only from *Kepler* or other future space missions.

Before going on to less certain methods, it is worth noting that planets still get undiscovered. Gatewood et al. (2001) promoted Rho CrB to a brown dwarf. HD 166435 has been demoted to a rotating, spotted star (Queloz et al. 2001), while HD 192263 went from planet-bearer to rotating, spotted (Henry et al. 2002) and then to rotating-spotted planet bearer (Santos et al. 2003).

4. Methods with Future Potential

These will be ordered from properties of pre-main-sequence stars, to the main sequence, to evolved stars, followed by most speculative suggestions. In a number of cases, one can say that the observed phenomenon exists, but that an exoplanet is not the most likely explanation.

7. Distortions and disturbances of disks. Beta Pic was the first widely-publicized proto-planetary disk and also the first one whose warp was advanced as evidence for a planet in formation (Brunini and Benvenuto 1996). The idea persists (Weinberger et al. 2003). A gap in a planet-forming disk due to an annulus swept clean in the process is another possibility (Rice et al. 2003, Dent et al. 2000). More complicated structures in disks and shells around very young stars have been suggested as planet signatures by Holland et al. (2003) and by Kholtygin et al. (1997). Men'shchikov et al. (1999) suspect that HL Tau has an infrared spectrum indicative of dust growing to planetesimal size.

Takami et al. (2003) propose that planets may be relevant to the collimation of bipolar outflows from proto-stars. They may well be right, but bipolar outflows are so ubiquitous in the universe that it is hard to regard them as evidence for anything. Goodman and Rafikov (2001) note that once planets form, they may accelerate the decay of residual disks.

In the "win some lose some" column we find the eclipsing binary KH 15D, advocated only a year or so ago (Barge and Viton 2003) as occultation by 1–10 cm particles trapped in a planet-forming vortex. This year (Johnson and Winn 2004) it is merely a close pair with stuff around that sometimes completely obscures one of the orbiting pair and sometimes does not.

8. "Exozodi". This is the equivalent of our zodiacal light coming from another system. The infrared disk is not left-over material from formation but debris shattered off comets, asteroids, and moons. It should be fairly common, and is the largest noise signal for those wishing to image planets in the infrared, but has not been seen (Greaves and Wyatt 2003, Kenyon and Bromley 2002, Dominik and Decin 2003, Moro-Martin and Malhotra 2002). Tamburini et al. (2002) suggest that a mild correlation of polarization of scattered starlight with having a radial-velocity planet might be an exozodi phenomenon. Do inhabitants of the planets responsible for such secondary dust pay special attention to the star patterns through which their host star passes each year? Probably not.

9. Light reflected by the planet. This is another way of probing atmospheres that, unlike transit absorption, does not require any special orbit alignment. Cameron et al. (1999) drew attention to Tau Boo, where the possible effect was presence of Doppler-shifted star light due to a high-albedo atmosphere. For a planet with a transparent atmosphere and solid surface, the red edge due to chlorophyll (Woolf et al. 2002) would be a particularly exciting discovery, but most of us would be content with signs of CO_2, O_3, and such.

10. Induced chromospheric activity. This could be due to tidal or magnetic interaction. Shkolnik et al. (2003) have made a case for HD 1779949 and think that magnetic interaction is the more likely possibility.

12. Maser and laser activity in the planetary atmospheres or on their surfaces. Slysh et al. (1999) propose CH_3OH for one planet-bearing star, and Reines and Marcy (2002) have put upper limts on laser emission in the process of analyzing their radial velocity search data.

13. Periodic residuals in timing of eclipsing binaries. Deeg et al. (2000) have perhaps seen this in CM Dra, the star mentioned as an early transit candidate. The amplitude is all of 17 seconds.

14. Pollution of host atmospheres. This is not the general answer to why the hosts are metal-rich, both because planets of Jovian mass are not particularly metal-enhanced and because it predicts a composition-surface temperature correlation that is not seen (Heiter and Luck 2003). Li^6 may be a special case (Israelian et al. 2001, 2003, 2004), but in general this is a phenomenon that difinitely exists, but the composition is probably the cause of the planet formation, not conversely.

15. Oxygen-bearing molecules in the spectra of carbon stars. Again the phenomenon exists. Ford and Neufeld (2002) and Ford et al. (2003) propose that comets are being evaporated as the stars become red giants. The alternative is sequential winds from M giants that become carbon giants. Both H_2O and OH have been seen. A 25 μm excess due to sublimed ice from Kuiper Belt Objects orbiting evolved stars (Jura 2004) is a related signature that has not been seen.

16. Spin-up of evolved stars. Spin-up of evolved stars due to late accretion of planets has been suggested for rapidly rotating subgiants (Lucatello and Gratton 2003) and metal-poor horizontal branch stars (Carney et al. 2003).

17. Mira variables. Mira variables undoubtedly exist, and most of us suppose they are driven by a kappa (opacity) mechanism. Berlioz-Arthaud (2003) would, however, like them to be engulfed planets in giant atmosphere. Retter and Marom (2003) similarly attributed the outbursts of V838 Mon to the engulfing of planets. The majority view (e.g. Banerjee et al. 2003) is in favour of something like a nova (nuclear explosion) mechanism.

18. White dwarfs. White dwarfs might have their atmospheres polluted with metal and dust (Jura 2003, Debes and Sigurdsson 2002) or have their spectra adulterated by hydrogen recombination lines when gas giant atmospheres get heated (Chu et al. 2001). An Io-type mechanism (Willes and Wu 2004) might make them sources of electron-cyclotron maser radio emission. Curiously, some pulsating WDs have such stable period that these can be used to put interesting limits on planets around them (Mukadam et al. 2003).

19. X-ray flashers. These might be the result of planetary collisions, but only if the orbits are counter-rotating, not very easy to achieve (Zhang and Sigurdsson 2003).

20. Gamma ray bursts. Gamma ray bursts, in the days when they were thought to have positron annihilation lines in their spectra and to come from galactic objects were once (Harris 1990) attributed to exhaust from interstellar spacecraft. The author looked for lines of them in the sky; he didn't find any.

21. Other possibilities. A variety of phenomena that might be attributed to extra-solar-system life, thus implying the existence of exoplanets of various sorts have been discussed. Among these are panspermia (Wickramasinghe et al. 2003), a positive result from SETI (Gray and Ellingsen 2002, upper limits only), and visits of Little Green Persons.

Have we truly exhausted all the possible planetary (or cometary) signatures? No, not quite. Shevchenko and Ezhkova (2001) and Trimble and Aschwanden (1999, Sect. 12.1) mention some still more indirect, though not, I think, more unlikely, indicators. And you yourself may well be able to come up with something that has not previously been thought of or, at least, not previously published very conspicuously.

5. The Current Inventory

The first reports were of "hot Jupiters" — massive planets in short-period orbits. Later reports include more planets with orbit periods longer than a year, up to a current maximum of 14 (Mayor et al 2004, Naef et al. 2003, Marcy et al. 2002). The distribution of periods (incomplete, of course at the upper end) has a peak at less than five days, with a cut-off near three (Masset and Papaloizou 2002), a relative minimum at 5–50 days, and a gradual rise beginning around 100 days (Jones et al. 2003). By a separation of 100 AU (periods of more than 1000 years) Jupiters are again rare (Neuhauser et al. 2003, a near infrared search around young stars, not radial velocity data like the other items!)

How many stars have planets? At least 5–10% of those (all nearby and with solar-range masses) that have extended radial velocity data, and the total could be 100% (Lineweaver and Grether 2003). Binary hosts are not as much discriminated against as one might have expected (Patience et al. 2002), and at least one G giant has a Jupiter (Sato et al. 2003).

An assortment of marginal correlations of masses, periods, and orbit eccentricities have also been found, most not of enormous statistical significance and most capable of explanation either in terms of formation mechanisms or in terms of migration thereafter, when the planets interact with residual disk material. See Trimble and Aschwanden (2004, Sect. 5.1) and earlier papers in that series for some of the possibilities. One of the more complicated correlations is the preponderance of binary and multiple planets for those with large mass, small period, and small eccentricity (Eggenberger et al. 2004), at least partly a requirement for stability, one supposes.

The most important correlation is surely that with heavy element abundance. For compositions as metal rich as the Sun, 10% or more of the stars investigated have yielded planets. This drops to a few percent or less for metallicities less than 10% of solar (Gonzalez 1997, 2003). It is no longer possible to regard this as a selection effect (due to metal-rich stars having more lines to monitor in radial velocity data) or as the effect of planets falling into stars. It is telling us something about how planets form.

6. Theory and the Future

Even a crude discussion of planet formation mechanisms and the changes in orbit parameters that occur later would require another article as long as this one. Here are merely a few links. The main competitors for formation processes are gravitational instability (Boss et al. 2002) and gradual assemblage from dust to planetesimals to embryos (Rafikov 2003a,b). Ida and Lin (2004) predict the distribution of masses and semi-major axes for the latter. Lecar and Sasselov (2003) address later migration. The chief difficulty is that disks are observed (from incidence vs star age) to last only a million years or so, which is only just enough for the gradual assembly process (Kalas et al. 2004, Armitage et al.

2003). Accumulation of planetesimals in vortices (Johansen et al. 2004) can push the assembly time scale closer to the short, safer instability time scale.

The immediate future belongs to ground-based optical and infrared observers (with some help perhaps from Spitzer Space Telescope and SOFIA in studying star formation regions), to whom nearly the full range of those 20 methods is open. Some things can be done only from space, and this inlcudes both transit detection and direct imaging (as a precursor to detailed spectroscopy) of earth-mass, earth-location planets. The US transit (and stellar seismology) mission, Kepler, is still somewhere in the queue, but the ESA one, Eddington, is out, at least for a decade or so. Looking ahead about 20 years, the American Terrestrial Planet Finder and the European Darwin are still on the books with current debate centering on whether a multi-element interferometer or a coronagraph design is the better bet (Beichman 2004). How long into the future these sound probably depends a good deal on your age. But if you remember 1994 and even 1984 reasonably well, they are no further ahead than those behind.

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