Searching For Planets Beyond Our Solar System: How Astrometry Helps*

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The detection of the first extra-solar planets, using ground-based radial velocity searches, has recently been announced. The ESA space astrometry project, Hipparcos, has subsequently provided distances to, and upper limits on the masses of, these planetary systems. The way in which astrometric searches for planets compare with other search methods presently being pursued or considered (optical and infrared imaging, occultations, gravitational lensing, and spectroscopic measurements) is described, and the potential capabilities of the proposed Horizon 2000 Plus Darwin and GAIA missions are described. Darwin could detect Earth-mass planets around nearby stars, while GAIA would be able to see the effects of Jupiter-mass planets around hundreds of thousands of stars in our Galaxy, if they exist.

The idea that planets, and possibly intelligent life, exist beyond our Solar System has stimulated popular and scientific imagination for centuries. Until last year, no planet detections had been reported—apart from Earth-mass objects discovered orbiting two distinct radio pulsars, where the formation process is considered to be very different from that of the formation of 'standard' planetary systems capable of supporting life.

There is, however, a simple equation which may be used to estimate the number of planets within our Galaxy (and by extrapolation, within the entire observable Universe) which harbour intelligent life. Named the 'Drake Equation', after its originator, Frank Drake, it is written as:

$$N = R_* \, f_p \, n_e \, f_l \, f_i \, f_c \, L$$

where R_* is the rate of star formation, averaged over the lifetime of our Galaxy, f_p is the fraction of stars with planetary systems, n_e is the mean number of planets per system suitable for life, f_l is the fraction of such planets in which life has originated, f_i is the fraction of such planets in which intelligent life has developed, f_c is the fraction of those developing a communication phase, and L is the mean lifetime of such technical civilisations. The terms are listed in the order corresponding to decreasing estimates of their reliability. The first two terms are fully determined by astrophysical considerations; the remainder can only be estimated by appeal to numerous diverse disciplines including biology, organic chemistry, biochemistry, evolution, neurophysiology, anthropology, psychology, history, politics and sociology. In many ways, the factors in this equation simply underline our ignorance of this field.

Only the first term in the Drake Equation can be considered as being even approximately well determined: there are some 10^{11} stars in our Galaxy, which is about 10 billion years old, leading

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* based on a lecture given at the Alpbach Summer School by M.A.C. Perryman, July 1995

Figure 1. The final trajectory of Comet Shoemaker-Levy 9 observed by the Hubble Space Telescope on 17 May 1994, when its train of 21 icy fragments stretched more than a million km through space. The comet was approximately 660 million km from the Earth when the picture was taken, on a mid-July collision course with the gas giant planet Jupiter (Courtesy of H.A. Weaver & T.E. Smith of the Space Telescope Science Institute, and NASA). Theories of the development of life are highly uncertain, but the presence of massive bodies within a planetary system may be required to 'protect' the lower mass planets from cometary impacts. If such theories are correct, intelligent life may stand a much better chance of existing around stars with massive planetary systems which are, in turn, much easier to detect than lower mass planets.

very roughly to a value of R_* of order 10 stars per year. But even coarse statistical information on, say, the second and third terms is not yet available. Presently, therefore, the equation is of little practical help in assessing whether planets are common, whether the conditions necessary for life are common and, ultimately, whether life itself is common elsewhere in the Universe. We remain completely unsure whether life exists in only one place within the entire Universe—on Earth—or whether the Galaxy, and indeed the Universe, teems with civilisations far more advanced than our own. Despite, or perhaps because of, these uncertainties, SETI-type searches (Search for Extraterrestrial Intelligence) have been running for a number of years.

Searches for planetary systems are basically concerned with the second and third terms of the Drake Equation. In recent years, as technology has advanced, planet 'hunting' has become a serious subject for astronomical research—not only in order to be able to estimate the number of locations in our Galaxy which may be capable of supporting life, but to a large extent because the subject is expected to throw further light on a key problem in astrophysics: the details of the origin of our own Solar System. Numerous questions related to this problem remain unanswered: how was our Solar System formed? is planet formation a common or rare phenomenon? is our Sun's single status (many, if not most stars are found in binary systems) related to the fact that it has a planetary system?

Even more complex 'cosmic coincidences' may be necessary for the development of advanced life forms. As a specific example, it is possible that the presence of at least one of the more massive jovian planets (Jupiter, Saturn, Uranus and Neptune) in the outer part of the solar system was *necessary* for the development of life on Earth. The recent impact of Comet Shoemaker-Levy 9

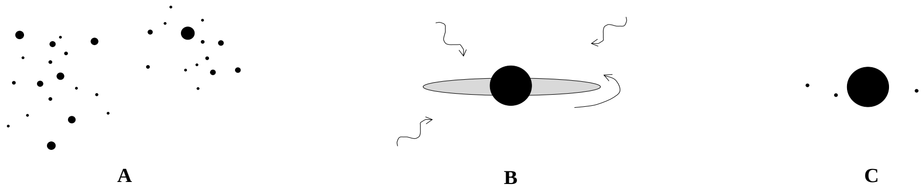

Figure 2. A highly schematic illustration of the possible formation of planetary systems: in (A) self-gravitating cores develop within interstellar molecular clouds; in (B) the young star, or proto-star, develops, fed by a nebular flattened disc and infalling material channelled towards it; in (C) as the infall terminates with the exhaustion of available material, the newly-formed star emerges along with planets formed from the material in the circumstellar disc.

with Jupiter in 1994 provided an outstanding illustration of why this might be so: Jupiter clearly acted as a gravitational 'vacuum cleaner', disrupting this particular comet on its previous visit to the Sun, and finally capturing it. This 'sweeping up' of cometary material must significantly decrease the possibility of a catastrophic encounter with the much less massive Earth, and in turn is likely to have permitted the ongoing, delicate, evolution of life on Earth to develop (Figure 1).

Planetary size may also be important for habitability; aside from the most obvious question of gravitational force on the planet surface, long-term climatic stability requires (at least on Earth) a mechanism for recycling of carbon dioxide from carbonate rocks back into the atmosphere: on Earth, this is done by plate tectonics, whereas much smaller planets would lack the internal heat necessary to sustain these motions.

Formation of our Solar System

Dating from the times of Laplace, but over the last few years in particular, an increasingly plausible picture has emerged as to how planetary systems like our own Solar System form. Present understanding is that they originate as a by-product of star formation, with the gravitational collapse of material within high-density 'molecular clouds'. As gravitational infall proceeds, clouds which start off close to equilibrium under the combined effects of gravity, gas pressure, rotation, and magnetic fields, become more dominated by the effects of rotation, leading to the formation of a flattened disc. Details of the physical mechanism responsible for the formation of these 'accretion discs' remain uncertain, but it is thought that an outward transfer of angular momentum is accompanied by an inward flow of mass to form a young star—this disc is believed to be the seeding ground for the birth of planets that form in association with the star (Figure 2).

Some current models are surprisingly specific: numerical modelling by G.W. Wetherill has suggested that the accumulation of 'planetisimals' during molecular cloud collapse can be expected to produce four 'inner' planets on average—two being approximately Earth-sized and two smaller!

ESA's science mission ISO (the Infrared Space Observatory) is expected to contribute significantly to studies and developing theories of these star and planet formation processes, since it can look, in the infrared, into star-forming regions which are, by their nature, highly obscured by the very 'dust' associated with their origins. ISO should also prove to be very useful in searches for extra-

Figure 3. This image of a protostellar object, called HH-30, was taken with the Hubble Space Telescope, and reveals an edge-on disc of dust encircling a newly forming star. Light from the star illuminates the top and bottom surfaces of the disc, making them visible, while the star itself is hidden behind the densest parts of the disc. The reddish jet emanates from the inner region of the disc, expanding for several billion kilometres from the star whilst remaining confined to a narrow beam. HH-30 is 450 light-years away in the constellation Taurus (courtesy C. Burrows (STScI and ESA), the WFPC2 Investigation Definition Team, and NASA)

solar zodiacal light, as already known around the nearby star Beta Pic. Ground-based, as well as Hubble Space Telescope, observations have already been highly successful in imaging stars with proto-planetary discs (Figure 3).

The Search for Planets

In astronomy, masses are usually and conveniently described in terms of the mass of our Sun: a 'solar mass' or $M_\odot$. It is considered that below about $0.08M_\odot$ nuclear hydrogen fusion will not occur; masses below this and down to the 'deuterium-burning limit' of about 13 Jupiter masses are referred to as 'brown dwarfs' or, if lighter still, as superplanets or planets. (Jupiter weighs in at roughly one thousandth of a solar mass, the Earth being a further factor of 300 less massive still.)

It has become generally accepted, largely from 'radial velocity searches' described below, that planetary systems, or at least systems with very massive planetary companions, are relatively rare. Nevertheless, a variety of direct and indirect detection methods have been undertaken in recent years, and with techniques rapidly improving, searches have intensified.

The astronomical world was greatly excited by the announcement last year of the first detection of a 'planetary mass' companion around a nearby solar-type star. Earlier this year, two further planetary candidates were reported, and additional suspects have been discovered even more recently. Somewhat surprisingly, the characteristics of these 'planets' was not quite what had been expected—in one case a very massive object was deduced to lie very close to the parent star, and uncomfortably so compared with existing theories of planetary formation. These theories are presently undergoing rapid re-appraisal, with spiralling in of a massive planet towards the parent star, after formation, being one possibility. Dramatic and fundamental though these discoveries are, it now becomes important to acquire information on further systems: as Dr David Black has commented in the Astronomy & Astrophysics Encyclopedia (van Nostrand Reinhold, 1992) *'Although the discovery of another planetary system would be exciting, significant scientific returns begin with the more difficult task of gathering statistical information. Only then will we be able to view the formation of our own planetary system in context.'*

The problem is, of course, that planets are small and faint, and much smaller and fainter than the relatively massive and bright central star around which they orbit. The difficulties of 'direct' detection of a planet—where the radiation reflected or emitted by a planet is observed—is apparent when considering the case of Jupiter and the Sun: at visible wavelengths, the Sun is about a factor of one billion times brighter than Jupiter. At infrared wavelengths the contrast is less extreme, but still very significant. Searches for radio decametric emission from Jupiter-type objects are also planned.

There are about 250 stars within a distance of 10 parsec from our Sun, and at such a distance a Jupiter-type planet 5 AU from the Sun* would lie at a maximum distance of only 0.5 seconds of arc from the parent star. Observationally, this is a very difficult problem; it has been attempted, but it is realistically beyond the capability of even, say, the Hubble Space Telescope, for all but the very nearest stars; this is because the HST's relatively small aperture, combined with static, small-scale wavefront errors. Future developments in ground-based 'adaptive optics', in which the telescope is deformed rapidly to adapt to the atmospheric effects which normally distort all ground-based images, may offer some possibilities, and the prospects in the infrared are more promising, especially for younger (and warmer) Jupiter-type planets. But the problem is still a daunting one. The proposed Darwin mission, submitted for consideration as part of the Horizon 2000 Plus programme (and a similar concept is being considered by NASA as part of its 'Origins' programme) aims to detect this very faint infrared emission from a possible planet close to the target star. An interferometer with four or five cooled apertures, a baseline of 40–50 m, and placed well beyond the Earth's orbital distance from the Sun in order to avoid contamination from the Solar System's own zodiacal emission, would search for planetary candidates out to distances of 10–20 parsec from our Sun. Detection of Earth-mass, and not simply Jupiter-mass objects, may be feasible using this approach.

Part of the problem is knowing which of the stars should be targetted for such a careful search! Nevertheless, a Darwin-type mission could aim to include a still more ambitious goal: specific spectroscopic features, for example the ozone line at 9.6 microns, would be possible indicators of an atmosphere out of chemical equilibrium—and thus an indication of the possibility of life. Other constituents, such as CO_2, H_2O, or O_2, could be searched for (although not necessarily by the Darwin mission), on the grounds that they are either essential for (aerobic) life, or produced by life.

Whilst direct imaging of planetary systems is likely to remain challenging for the foreseeable future (and the difficulty increases for stars further away, partly since the planetary system becomes ever closer in angular separation from the parent star) astronomers have investigated other possible search methods. In one, the effect of the planet is inferred by 'occultations' as the planet passes across the face of the star, leading to a temporary and very tiny decrease in brightness of the

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* 1 AU, or astronomical unit, is the mean distance between the Earth and the Sun; 1 parsec, or 3.26 light-years, is the distance at which one astronomical unit subtends an angle of 1 second of arc. The nearest star to the Sun lies at a distance of about 1 parsec, or 3×10^{13} km.

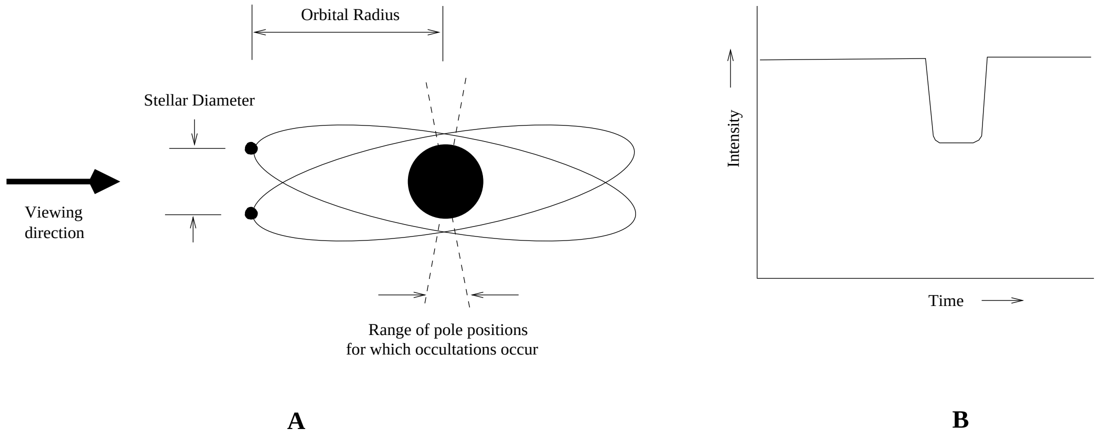

Figure 4. Principle of detection of an extra-solar planet around a star by occultation. The planet passes across the face of the star (A), resulting in a characteristic time-dependent signal (B), which will be repeated at the orbital period of the planet (12 years in the case of Jupiter). The possibility of detection demands, of course, an appropriate inclination of the planet's orbit with respect to the line of sight to the star. Such observations have been proposed for a variety of ground- and space-based programmes, for example the proposed NASA FRESIP mission, as a by-product of the STARS asteroseismology mission (an unsuccessful candidate for the ESA Horizon 2000 M3 mission), and as one of the main objectives of the COROT mission under consideration by CNES for launch in 2002 (figure adapted from the NASA FRESIP proposal).

target star (Figure 4). The geometric probabilities of such an event being observable (the ratio of the stellar diameter to the orbital radius), and the resulting drops in the observed intensity of the star (the ratio of the area of the planet to that of the star), can be simply calculated: for an Earth-like planet the probability of the event being observed is about 0.5 per cent, the brightness decrease is about 1 part in 10 000, and the event duration is about 13 hours; for a planet the size and orbital distance of Jupiter, the numbers are 0.09 per cent, 1 part in 100, and 25 hours duration respectively. Interestingly the method yields the size of the planet directly. In the near future, astronomers will get a better understanding of whether these searches will be successful.

Another interesting possibility is detection by gravitational lensing. Gravitational lenses are a prediction of general relativity, and first observed in astronomy in 1979, some 60 years after the first detection of gravitational light deflection by the Sun. Since then, the subject has flourished, and lenses potentially provide a powerful probe of 'dark matter' now believed to dominate the mass of the Universe. 'Microlensing' events are now being actively searched for from the ground, with the main aim of detecting very faint, very low mass objects, possibly constituting the dark matter, which would otherwise remain invisible, but which can be seen due to the gravitational influence on the light of the background stars. Several microlensing candidates have recently been detected from the ground, with durations ranging from several hours to several days, and with characteristically smooth, bell-shaped light curves. A planet would produce an 'aberration' in the

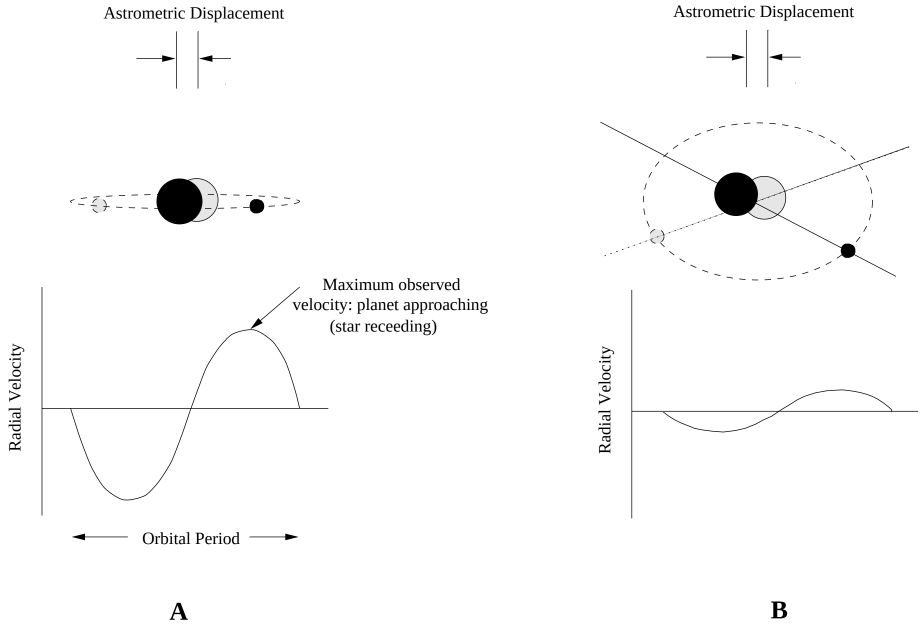

Figure 5. As a planet orbits the parent star, the centre of mass of the system moves with respect to the centre of mass (and centre of light) of the star. The effect results in a periodic Doppler motion of the spectrum of the star as the component of its motion moves back and forth along the line of sight. It also results in an elliptical displacement of the star's position with respect to the centre of mass of the system. In (A), where the orbital plane is almost along the line of sight, the (spectroscopic) Doppler motion is of maximum amplitude. In (B), where the orbital plane is almost face on to the line of sight (in the plane of the sky), the Doppler motion largely vanishes. In both cases the (astrometric) oscillatory motion of the parent star can be observed by measuring the position of the star as a function of time.

otherwise symmetrical lensing action of a star, causing an irregularity in the brightening of the background object, and thus producing a sharp additional peak in the light curve superimposed on the smooth background brightening. The effect is maximised for orbital radii near the so-called 'Einstein radius'; for searches now going on in the bulge of our Galaxy, this corresponds to a linear distance of a few astronomical units—fortuitously close to the orbital radii predicted for giant planets. The effect is large: several per cent of the main peak in the case of Earth to Jupiter-sized planets, with durations extending from several minutes up to about one day.

Spectroscopic and Astrometric Searches for Extra-Solar Planets

There are two further, well-established methods, with a common physical effect, which can be used for indirect detection. If a star has a companion, the centre of mass of the system is displaced from the centre of mass of the star. In the case of our Solar System, the centre of mass is dominated by the jovian planets, and describes a complex motion with respect to the centre of the Sun, according to the relative positions of all of the other objects in the solar system. Taking a simple example of a single massive planet orbiting a star in a circular or elliptical orbit, the star undergoes its own 'reflex' motion about the centre of mass of the system (Figure 5). This 'wobble' of the parent

Figure 6. Extra-solar planets are now known to surround the three stars, 51 Peg, 70 Vir, and 47 UMa. This figure shows how these systems compare in mass, and distance from the parent star, compared to the case of the Sun and Jupiter (taken from the work of G.W. Marcy & R.P. Butler, by kind permission of the authors). The proximity of the massive planet surrounding 51 Peg to its parent star was unexpected (models had not predicted that such massive planets could be formed so close to the star) and has already led to vigorous debate about the formation and evolution of the more massive planets. Note that the three candidates are each several Jupiter masses, and all therefore more than a factor of one thousand more massive than the Earth. The distance of the planet surrounding 70 Vir from its parent star is such that its expected surface temperature could be in the range necessary for water to exist in liquid form, at least for part of the orbit.

star can be detected in two ways—either using spectroscopy of the system (dominated by the light of the central star) to reveal Doppler line shifts corresponding to the line-of-sight component of the orbital motion relative to the observer, or more directly through astrometric measurements. The latter aim to measure the positional displacement of the star from the system's barycentre at successive times—while the centre of mass of the system moves linearly through space, the star will oscillate about it. Both methods can measure the period of the orbital motion. The spectroscopic method has a disadvantage that the effect is dependent on the angle between the line-of-sight and the orientation of the orbital plane of the planetary system, so that a system viewed face on will show no Doppler component. Also, stars display a variety of phenomena related to rotation and pulsation that may mimic true Doppler shifts. On the other hand, the minimum mass detectable for astrometric displacements is inversely proportional to the distance of the star; star 'spots' may also affect the observations by introducing measurement noise, although they will not mimic the stable periodicity of a planetary signal.

Both effects depend on the ratio of the masses of the star and the planet, on the planet's orbital period, and on its distance from the parent star. An idea of the measurements needed to observe such systems may be seen from the situation with the Sun and Jupiter: the Sun's velocity oscillates with an amplitude of 12 metres per second, and a period of 12 years, due to the presence of Jupiter. To detect this type of motion in other stars requires spectroscopic measurements of very high accuracy, using instruments stable over many years. Such measurement programmes have been ongoing for several years at different ground-based observatories, and the efforts were rewarded when the first positive detection (in the case of the star 51 Peg) was announced by M. Mayor & D. Queloz from the Geneva Observatory last year; confirmation and two further candidates (47 UMa and 70 Vir) were reported by G.W. Marcy & R.P. Butler (San Francisco State University) earlier this year. High precision radial velocity measurements pinned down the periods, masses, and semi-major axes of the planetary orbits. Strictly, the mass estimates derived by this method are only lower limits in view of the unknown orbital inclination of the systems with respect to the line of sight. The likely configurations of the resulting systems are illustrated in Figure 6.

Results from ESA's Hipparcos astrometry satellite have already made an interesting contribution to this topic. Accurate distance measurements to stars within a few hundred parsecs of the Sun is a very difficult problem, and only the advent of space measurements has placed these measurements on a secure observational footing. The three planetary candidates are amongst the more than one hundred thousand stars in the Hipparcos Catalogue; the distance to each is now established with an accuracy of about 1 per cent, which compares very favourably with the much greater uncertainties which were present in previous estimates: as an example, 70 Vir, now established to lie at 18.2 parsecs from the Sun (and therefore one of the few hundred closest stars to us) had previous published distance estimates differing by more than a factor of three! These accurate distances, in turn, allow much better estimates of the luminosities, masses, and ages of the parent stars.

Additionally, the Hipparcos measurements allow an upper limit on the masses of the planetary candidates to be estimated: while the radial velocity measurements place a *lower* limit on their masses, because of the unknown orbital inclination, an upper limit can be derived given the fact that the resulting astrometric displacements of the parent stars are below a certain observed level (see Figure 7). It turns out that the Hipparcos measurements confirm that in at least two of the three cases, the companion masses are well below the hydrogen burning 'brown dwarf' mass limit, and indeed satisfy the semantic criterion for classifications as planets.

[Astrometric measurements with very high precision are also now being made, for radio stars, using the ground-based technique of Very Long Baseline Interferometry. Sophisticated 'timing' techniques can also be applied to radio pulsars and eclipsing binaries (binary star systems in which the secondary is revealed as a result of light eclipses of the primary star), where uniformally spaced signatures of the underlying spin or orbital motion will be perturbed by additional orbiting companions. However, in all these cases, the parent stars are unlikely to provide a suitable environment for the development of life.]

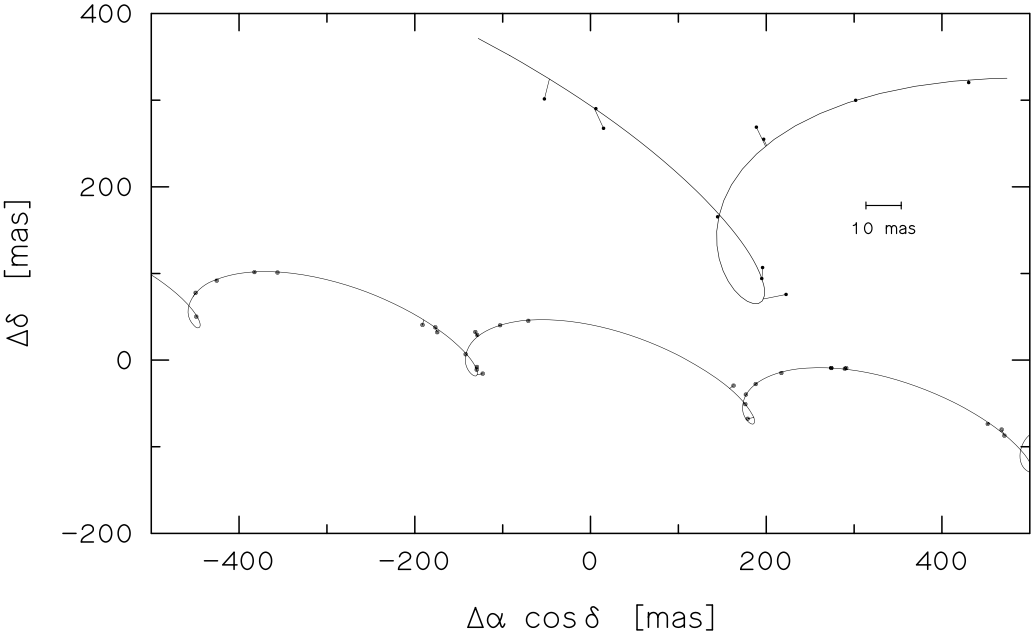

Figure 7. The path of 47 UMa (HIP 53721) across the sky, over a period of three years, determined by Hipparcos. The dots indicate the observed position at each moment of observation, with residuals indicated by the straight lines joining the dots to the modelled stellar path (solid line) at the corresponding epoch. The expanded region (top right) corresponds to the second 'loop', where the deviations between the elemental observations and the fitted curve are more evident. The amplitude of the oscillatory motion gives the star's parallax, or distance. The star has a proper motion of approximately −0.3 arcsec/yr in right ascension. The deviations of the observed positions from the smooth curve set limits on the mass of any companion object circling the star.

The Future: and the GAIA Mission

The next few years are likely to see the detection of further planetary systems, most probably from continued radial velocity searches, and rapid developments in the understanding of the formation and evolution of planetary systems. However, the detection of Earth-mass planets is likely to remain problematic from the ground for the foreseeable future. In addition to the proposed space missions Darwin and COROT, where the detection of such objects is a primary goal, space astrometry provides dramatic possibilities for the further detection of planetary systems. The proposed GAIA project is a 'super-Hipparcos' astrometric mission employing a scanning satellite, a fixed-baseline optical interferometer, and an advanced detection system (see ESA SP–379 'Future Possibilities for Astrometry in Space', June 1995). The milliarcsec accuracies on one hundred thousand stars delivered by Hipparcos will be upstaged by microarcsec level accuracies on tens of millions of objects. GAIA aims primarily at pinning down accurate stellar distances throughout our Galaxy, and determining stellar motions, again throughout the Galaxy.

As a by-product of the measurement programme, GAIA would be able to measure stellar orbits for binary systems—but not simply for binary systems with secondaries whose masses are comparable to one solar mass (as with Hipparcos). Rather, GAIA would be able to determine the presence of Jupiter-mass companions around solar mass stars out to distances of about 200 parsecs (and lower mass companions to somewhat smaller distances). At 100 pc a Sun-Jupiter type system would result in an astrometric displacement of the star of about 50 microarcsec. While an Earth-like planet around a solar mass star at 10 parsec would result in a displacement of only 0.3 microarcsec, with very good metrology, the detection of a few Earth-like planets is not beyond the realm of possibility for a mission like GAIA. Multiple planets around a given star will create additional problems in understanding the system.

Within the volume of space corresponding to a distance horizon of 200 pc (our Galaxy is some 30 000 parsec in diameter), there exist some 500 000 stellar candidates. If the occurrence of planets around other stars is a rare phenomenon, progress from the ground over the next few years will be a slow and laborious process, and GAIA would revolutionise the search. If the phenomenon is more common, GAIA could determine thousands, or tens of thousands, of such systems.

Stars like the Sun may have planets with conditions conducive to the development of life in the so-called 'habitable zone': bounded by the range of distances from the parent star for which liquid water would exist, by the range of stellar spectral types for which complex life had enough time to evolve (no earlier than spectral type F), and for which stellar flare phenomena, resulting in gross changes in the radiant flux impinging on the planet do not occur (no later than spectral type K). The provision of a massive data bank of the characteristics of such systems—their masses, orbital periods and eccentricities, and distances from the parent star, all as a function of the characteristics of the parent star—would promise a great advance in our understanding of the formation and evolution of planetary systems, and open up the more elusive and philosophically more profound terms of the Drake Equation. The statistical results would provide the necessary basis for more ambitious satellite missions, aimed at direct imaging and spectroscopy of stellar companions. The understanding of whether we are alone in the Universe would make one more significant step forward.

The authors acknowledge useful discussions with Dr J. Schneider, of the Observatoire de Paris-Meudon. Further details of some of the topics covered in this article can be found at various WWW sites: for the candidate Horizon 2000 Plus cornerstone missions Darwin and GAIA, see http://ast.star.rl.ac.uk/darwin/ & http://astro.estec.esa.nl/SA-general/Projects/GAIA/gaia.html respectively. For further details of planetary search programmes, see http://www.obspm.fr/planets and http://cannon.sfsu.edu/∼williams/planetsearch/planetsearch.html.