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Progress in Extra-Solar Planet Detection

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INTRODUCTION

The solar system's existence poses this fundamental question: Are planetary systems a common by-product of star formation? One supporting argument is that flattened disks appear to be abundant around pre-main sequence stars (Strom *et al.* 1988). Perhaps the planetary orbits in the solar system preserve the form of such a disk that existed around the young Sun. Such heuristic evidence notwithstanding, real progress on the general question requires determining the frequency of occurrence of extra-solar planetary systems and measuring their characteristics (Black 1980).

At the current time (the beginning of 1989) no investigator has announced an extra-solar planet detection that is unqualified or that has been generally accepted as such. Indeed, the very definition of "planet" is ambiguous. The quest for planets is an arduous challenge—the classic astronomical grail.

This paper reviews progress to date. Several observing programs have measured direct light from sub-stellar masses orbiting other stars. Those observations are helpful in understanding why planets have not been found by the same techniques: their visibility is very low as compared with more luminous bodies like brown dwarfs.

Three investigator groups claim to have found evidence for smaller bodies, perhaps planets, by studying perturbations in star motions. Those observations are instructive about the specific strengths and weaknesses of indirect techniques for detecting planets with various masses and orbits.

More capable extra-solar planet searches are being planned for the

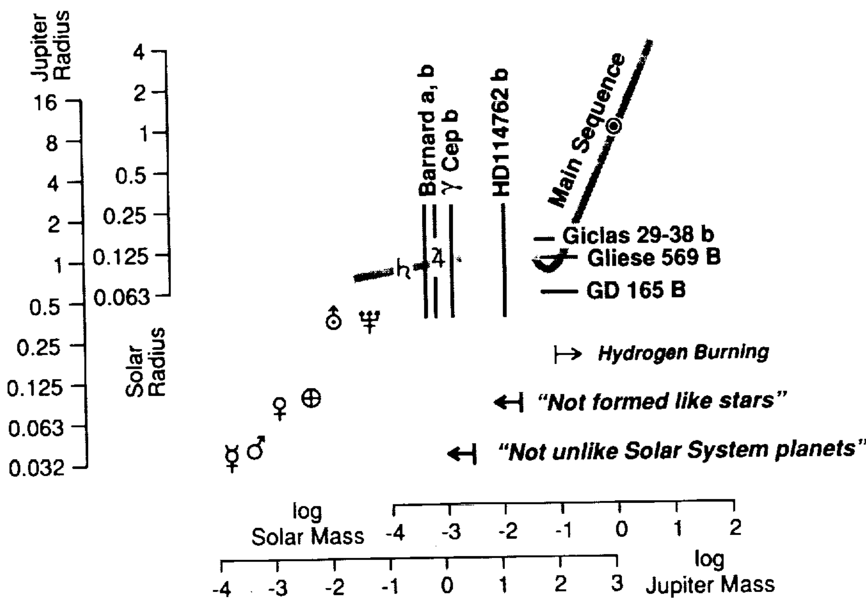

FIGURE 1 Mass-radius spectrum for planets, brown dwarfs, and stars. Solar system objects are indicated by their customary symbols. The vertical lines show the masses of claimed planet detections, but the radii are indeterminate. The horizontal lines show the radii of selected low-mass stars or brown dwarfs, but the masses are uncertain.

future. In the course of time, such observing programs will illuminate planet formation as an embedded process in star formation.

WHAT IS A PLANET?

First, what is a star? The mass range for stars is customarily stated as $M_* \geq 0.08M_\odot$, where nuclear energy generation dominates gravitational contraction over the stellar lifetime (Bahcall 1986). Smaller astronomical objects, if they are not planets, are "brown dwarfs".

Figure 1 shows the mass and size of solar system bodies greater than $10^{-7}M_\odot$. In a restricted sense, Jupiter is a maximal planet and, indeed, has some stellar characteristics. Its density is approximately solar, and its internally generated luminosity adds about 70% to the sunlight it re-radiates thermally. If increased in mass, Jupiter would grow hotter and more self-luminous. Starlight would exert less influence over the object's outer characteristics.

In the solar system, the planets' surfaces and atmospheres have properties that are determined primarily by their distances from the Sun. Based narrowly on such *intrinsic* characteristics, an object larger than a few Jupiter masses *could* be labeled a brown dwarf because it no longer resembles a solar system planet.

From the broader perspective motivated in the very first sentence, a planet is better defined by its *origin* (Black 1986). Multiple-star systems are thought to form by the fragmentation of spinning protostars. Generally, this mechanism produces elliptical orbits, and the process is not capable of producing bodies below a minimum mass—about $0.02M_{\odot}$ for solar metallicity (Boss 1986). A less massive secondary could form initially only by solid-body accretion in the special environment of a dense circumstellar disk (Wetherill and Stewart 1989). By the broad view then, any object less than $0.02M_{\odot}$ is a presumptive planet.

Hubbard (1984) has discussed the class of objects sufficiently massive ($M \geq 0.1M_{\odot}$) to stabilize by deuterium burning for a brief period ($\sim 10^7$ years), but which are not stars due to the fact that they continue gravitational collapse. Van de Kamp (1986) uses a similar criterion to set Jupiter's mass as the upper limit to planets and the lower limit to brown dwarfs.

Further, dynamical and physical aspects of planets are central to current theories of planetary system formation, such as circular orbits and aligned spins. These *systemic* aspects could provide other definitions of "planet" that are more directly based on the origins concept. For example, two $0.02M_{\odot} \leq M \leq 0.08M_{\odot}$ masses in co-planar, circular orbits around a star could be called a planetary system by the common-origins criterion. The bodies then, would be planets. Further, they might also be called brown dwarfs depending on scientific motivation and on whether an "origins" or "intrinsic" criterion were preferable for *that* definition.

Finally, life originated in the solar system, and its occurrence poses a second fundamental question that is related hierarchically to the first posed above: Is the appearance of life a common by-product of planet formation? Perennial interest in that question suggests further restrictive criteria on "planets," such as a benign primary star, orbital stability, and sufficiently cool temperature so as not to break chemical bonds.

Mass is the critical issue for current planet search programs, and this review uses mass as the discriminating factor for planets. In Figure 1, the mass range $0.003M_{\odot} \leq M \leq 0.02M_{\odot}$ is the transition zone from the narrow definition, meaning "not unlike solar system planets" to the broad definition, meaning "could not have formed like stars."

PLANET SIGNALS ARE WEAK

Astronomical light carries six dimensions of information: one each, spectral and temporal, and two each, spatial and polarization. In principle, a strategy based on any combination of these could provide evidence for planets around other stars, but the variations in time are most powerful: the *fact* of the orbit is confirming evidence, even if it is not the source of the observable effect itself.

Any experimental design for a search program presents particular opportunities and impediments to the astronomer. However, all approaches face one problem in common: the planet's signal is always very weak, in both absolute and relative terms.

Planet search techniques are either direct or indirect. Direct techniques use light from the planet itself. Indirect searches seek variations in starlight that imply the planet's presence.

Except for the most massive planets, the main source of difficulty for direct detection is the planet's low intrinsic luminosity. Starlight can easily overwhelm planet light. (Figure 2 compares the spectral luminosity of Jupiter and the Sun.) For indirect searches, the problem is the planet's small mass or small radius. Reflex motions are proportional to the planet/star mass ratio, and occultation effects vary with the planet/star radius ratio squared. Finally, the distance from the observer gives the planet orbit a small angular size, which is a problem for spatial techniques, either direct or indirect.

The Jupiter-Sun system is often used as a standard test example for planet detection schemes. Viewed from a distance of 5pc,[1] Jupiter would be 26^{th} magnitude in the visual, and, at maximum orbital separation, it would be located only one arc second from a 4^{th}-magnitude star. This poor flux ratio ($\sim 10^9$) improves to 11.5 magnitudes (4×10^4) at the wavelength of Jupiter's thermal spectrum peak, $\lambda = 20\mu$m. However, a diffraction-limited telescope operating at $\lambda = 20\mu$m must be 40 times larger than an optical telescope in order to separate the planet and star images as effectively. With regard to indirect detection, the solar reflex displacement in the Sun-Jupiter test case is only $1R_\odot$ or 0.001 arc seconds at 5pc distance. The reflex speed is only 13 meters per second or 0.6% of the Sun's equatorial rotation speed. (Intrinsic stellar phenomena can also produce observational effects that mimic reflex motion.) Finally, if Jupiter passes in front of the Sun, as it does for 0.1 % of the celestial sphere for just 30 hours every 12 years, the apparent solar flux is diminished by only 1%.

Low signal, high background, and low information rate: these are the trials awaiting those who would quest for extra-solar planets. Programs to detect planets must be exquisitely sensitive, robust, and patient.

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[1] Only about 50 stars are nearer than 5 pc, and none is closer than 1 pc.

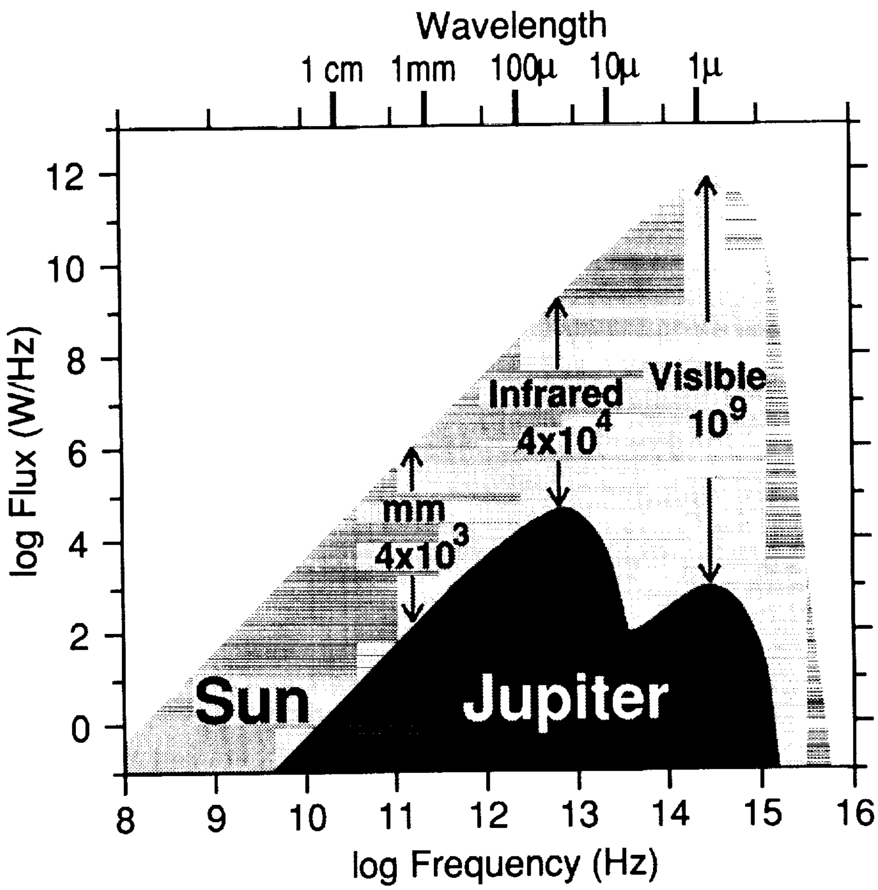

FIGURE 2 The specific fluxes of the Sun and Jupiter versus wavelength and frequency of light.

DIRECT TECHNIQUES: IMAGING AND SPECTRAL DETECTION

With a single exception that will be discussed immediately, no investigator has claimed a direct detection of an extra-solar planet. Therefore, this section's approach is to discuss the basic observational difficulties and the future prospects. The least massive objects that *have* been directly detected are brown dwarfs, and those observations are already described elsewhere.

The exception is "VB 8B". In 1985, McCarthy *et al.* reported the detection, via infrared speckle interferometry, of a cool (1360K) companion to the M dwarf star, VB 8. They stated that the observation might be the first direct detection of an extra-solar planet. However, subsequent star evolution models have shown that the described object could not have mass less than $0.04M_{\odot}$ (Nelson *et al.* 1986; Stringfellow 1986). More recent observations have failed to confirm the existence of the companion to VB 8 (Perrier and Mariotti 1987).

In principle, diffraction effects limit even an ideal telescope's ability to separate the planet image from the star image. The imperfect optics in real telescopes also scatter starlight into the planet image, masking its signal to some additional degree. For ground-based telescopes, the atmosphere aggravates the problem by refracting a further amount of light from the image core into the wings; an effect called "seeing."

For planet searches by direct imaging, the critical instrumental factor is the contrast in surface brightness, which is the ratio of the brightness of the planet's image core to the starlight in the same region of the telescope focal surface. In concert with the absolute planet flux, this contrast ratio governs the fundamental rate at which information can accumulate about the planet's presence or absence. If the information rate is too low, systematic errors will prevent the planet's detection (Brown 1988).

No existing long-wavelength or ground-based system offers sufficient contrast even to approach the direct imaging problem for extra-solar planets. Either the Airy diffraction pattern is too wide, or seeing is, or both are. In the foreseeable future, only space-based telescopes operating at visible and near- infrared wavelengths offer a reasonable chance of success. (Strongly self- luminous companions, very low-mass stars and brown dwarfs, are an exception discussed below.)

Free from seeing, space-based telescopes will improve the planet/star contrast ratio at shorter wavelengths by offering narrow, diffraction-limited cores. Even so, special procedures will still be needed to reduce the *wings* of the point-spread function so that direct-imaging planet detection will be feasible. (Very large, very young planets are an exception and are discussed below.)

Figure 3 illustrates the case of the Hubble Space Telescope (HST). Brown and Burrows (1989) computed the expected HST point-spread function and applied it to the test case, the Jupiter-Sun system viewed from 5pc. Because HST operates only from the ultraviolet to the near-infrared, it can detect only reflected starlight and not thermal radiation from a Jupiter-size planet. At $\lambda = 0.5\mu m$, figure-error scattering from the HST mirrors and Airy aperture diffraction contribute approximately equally to the unwanted background at the planet-image position.[2] In this example, the predicted Jupiter/Sun contrast ratio is 6×10^{-5}, which is unfavorable. Because of the

[2] Figure error scattering dominates at larger angles or shorter wavelengths.

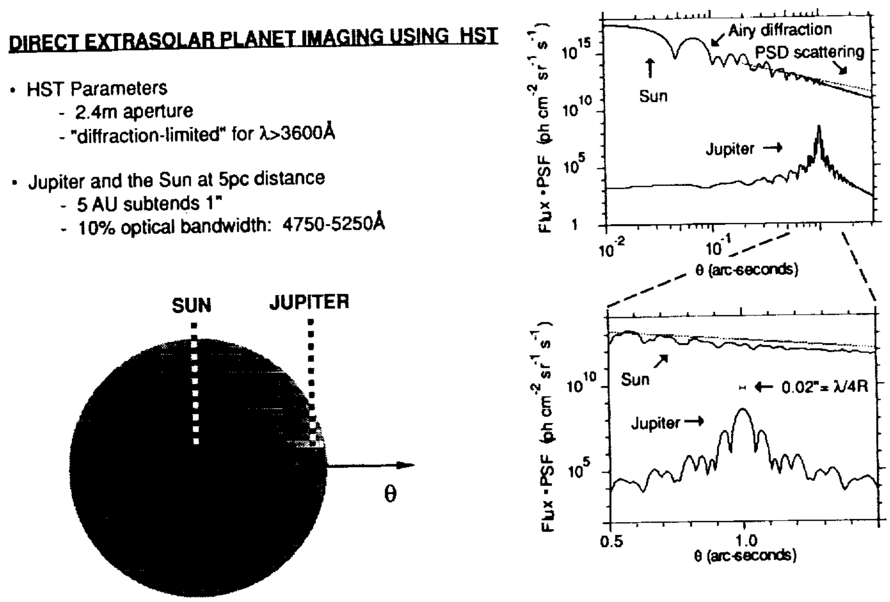

FIGURE 3 The contrast problem in detecting an extra-solar planet in reflected light. The example is Jupiter and the Sun as seen from 5 pc. Using HST, the predicted Jupiter/Sun contrast ratio is 6×10^{-5}, which is unfavorable.

lengthy integration times required by information theory, and the systematic problems they introduce, Brown and Burrows concluded that planet detection in reflected starlight is technically infeasible for HST.

The following discussion of low-mass stars and brown dwarfs is not complete. Its purpose is to demarcate the frontier for direct observations of sub-stellar objects.

Because of their self-luminosity, the very low-mass stars are now detectable in multiple star systems using near-infrared array detectors. Becklin and Zuckerman (1989) have imaged an example next to the white dwarf GD 165. Though GD 165 is about six times hotter than the discovered secondary, 12,000 K vs. 2,130 K, the white dwarf is about six times smaller than its companion, GD 165 B. Based on the temperature and the measured flux, the radius of GD 165 B is $0.061R_\odot \pm 0.015R_\odot$ versus $0.011R_\odot$ for GD 165 A. The increased surface area compensates for the temperature difference, and the two sources appear about equally strong in the near infrared.

The mass and nature of GD 165 B are uncertain. Classically, stellar spectrophotometry is translated into mass using a theoretical model of luminosity and *effective* temperature versus mass and age; evolutionary tracks on the Hertzsprung-Russell (H-R) Diagram. Currently, though, it is not possible to do this confidently in the mass range $0.05M_{\odot} \leq M \leq 0.2M_{\odot}$. Models predict that heavy brown dwarfs dwell for a long time ($\sim10^9$ years) in the region of the H-R Diagram near the least massive stars (Nelson *et al.* 1986; D'Antona and Mazzitelli 1985). Furthermore, existing models disagree as to where the evolutionary tracks actually lie.

Observational factors compound the confusion in using a theoretical mass-luminosity relationship for cool objects. Because the spectral characteristics of the cool emitting atmosphere are poorly understood, the reduction of the observed color temperature into an effective temperature is somewhat uncertain (Berriman and Reid 1984).

Cool companions to white dwarfs can also be directly detected by spectroscopy even when the image cannot be isolated. For example, Zuckerman and Becklin (1987) have found excess flux in the near-infrared spectrum of Giclas 29-38. At $\lambda = 1\mu m$, the two components have approximately equal signals, but the cooler source is 10 times more luminous than the white dwarf at $\lambda = 5\mu m$. The color temperature of the excess flux is 1200K. In this case, since the secondary source has not been separately imaged, the observations do not rule out dispersed dust as a possible source. Nevertheless, Zuckerman and Becklin (1987) favor the condensed source interpretation, "Giclas 29-38 b," for which the estimated photometric radius is $0.15R_{\odot}$.

No star could conceivably be as cool as 1200K. Giclas 29-38 b would be a definite brown dwarf, but its mass is indeterminate in the range $0.04M_{\odot} \leq M \leq 0.08M_{\odot}$. For the age of the white dwarf however, the radius of Giclas 29-38 b is in conflict with existing models, which predict the radius should be 50% smaller than observed.

For GD 165 A/B and Giclas 29-38 a/b, the primary and secondary are comparably bright in a limited spectral region because the objects are very different. The same situation occurs, of course, in cases where the objects are *similar*; for example, very unmassive. In just such a case, Forrest *et al.* (1988) have used an infrared array detector to image a cool companion to the red dwarf star Gliese 569. The colors and fluxes measured by Becklin and Zuckerman (1989) place Gliese 569 at a hotter (2775K), more luminous point ($0.11R_{\odot}$) on the H-R diagram than GD 165 B. Because brown dwarfs theoretically spend much less time in their hot, luminous stage, Gliese 569 B is more likely to be a star than GD 165 B. Nevertheless, a young age, a lower mass, and a brown dwarf label for Gliese 569 B are not ruled out.

The radii of GD 165 B, Giclas 29-38 b, and Gliese 569 B are plotted in Figure 1. The significance of these observations for planet searches is two-fold. First, they exemplify the breadth and intensity of current interest in probing the environments of stars. Second, they show the advancing state of the art in cool-object spectrophotometry and the benefits of the new infrared array detectors. However, they have not demanded the major improvements in telescope imaging characteristics required by the extra-solar planet problem.

If Jupiter could not be imaged at a distance of 5pc using current telescope systems, but a brown dwarf could, what about a *large, young* planet (Black 1980)? Consider the pair $M = 0.02M_\odot$ and $M_* = 0.35M_\odot$ at a mutual age of 10^7 years. The planet flux would be 2% or more of the stellar flux longwards of $\lambda = 1\mu m$, and with an appropriate detector, HST could easily detect this planet. Outside the first bright Airy ring ($\theta >$ 0.2 arc seconds at $\lambda = 1\mu m$), HST will suppress the image wings by $>10^3$ with respect to the core. Under those conditions, the contrast ratio for this planet-star pair would be a favorable 20-to-1.

Relatively *unobscured* T Tauri stars would be prime targets for HST to examine for large, young planetary companions. They have the right age, and they permit viewing into the immediate stellar vicinity. The young stars in the Taurus-Auriga dark cloud complex are at a distance 150pc, where 0.2 arc seconds corresponds to 30AU. For these stars, HST would be expected to image very large planets within 10-20AU.

INDIRECT TECHNIQUES: REFLEX MOTION AND OCCULTATIONS

Three investigator groups have claimed indirect detections of what may be extra-solar planets based on observed stellar reflex motions. This section discusses the general methods involved and the planet findings. Indirect detections of low-mass stars or brown dwarfs are not discussed.

A star with a single planetary companion executes a reflex orbit that is isomorphic, co-planar, and synchronous with the planet orbit. The star orbit is smaller than the planet's by the ratio of the planet to star mass. If it can be detected, the star's miniature orbit implies that a second body exists. Further, if the star's orbit can be measured, and the star's mass estimated, the companion's mass and orbital radius are discovered.

For multiple planet systems, the reflex motions are independent and additive in the short term. The following discussion treats the restricted case of a single planet in a circular orbit.

The reflex orbit's two measurable aspects are first-order changes in the star's line-of-sight speed and second-order variations in its apparent position. (The lower-order terms are the components of normal inter-star motion: constant radial velocity and proper motion.) Figures 4 and 5 explain the basic geometry, physics, and parameterizations for the two types of planet search based on stellar reflex motion: the astrometric search and the radial velocity search.

The radial velocity and astrometric techniques produce respectively one- and two-dimensional data records versus time. The objective is to discover periodic variations in those records.

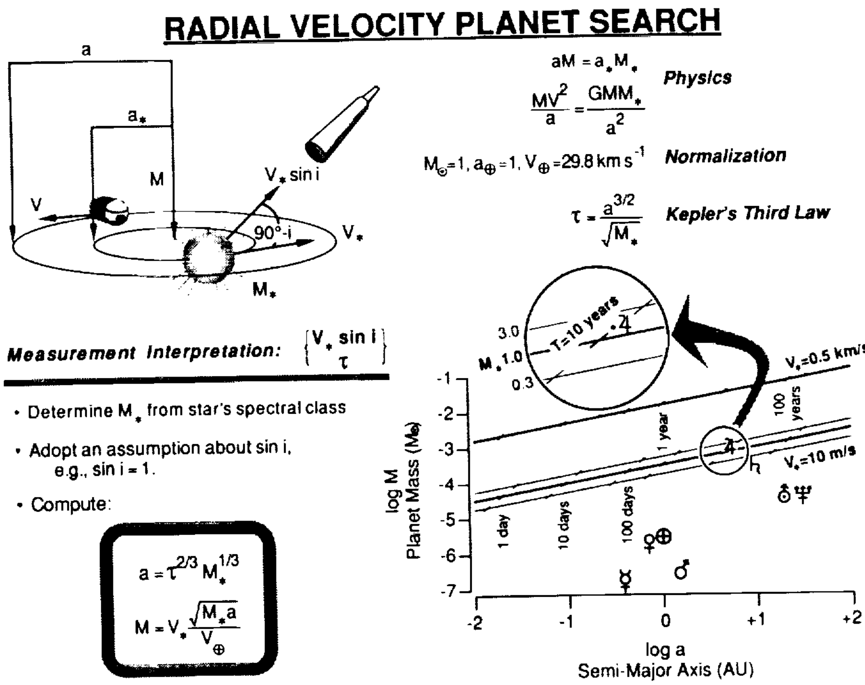

FIGURE 4 A tutorial on the radial velocity technique for indirectly detecting extra-solar planets.

The Scargle periodogram (1982; Horne and Baliunas 1986) is a standard procedure to discover and assign statistical significance to periodic signals. Black and Scargle (1982) have discussed it in the context of astrometry, and their mathematical results also apply to the radial velocity approach. The detection efficiency, for example, is the key to knowing the minimum detectable signal and for interpreting null results.

For long periods, where the observations may cover only about one cycle, the periodogram's performance needs to be better understood in purely mathematical terms.[3] Black and Scargle (1982) have also identified a potential source of systematic error in the long-period regime due to incorrect accommodation of linear drifts. Because long periods are associated with wide orbits, these factors further impede drawing valid early results from planet searches.

In practice, systematic rather than random errors may determine the

[3]Horne and Baliunas remark on page 761, "clear arrow signals with period slightly longer than T can sometimes be detected, but with poor resolution."

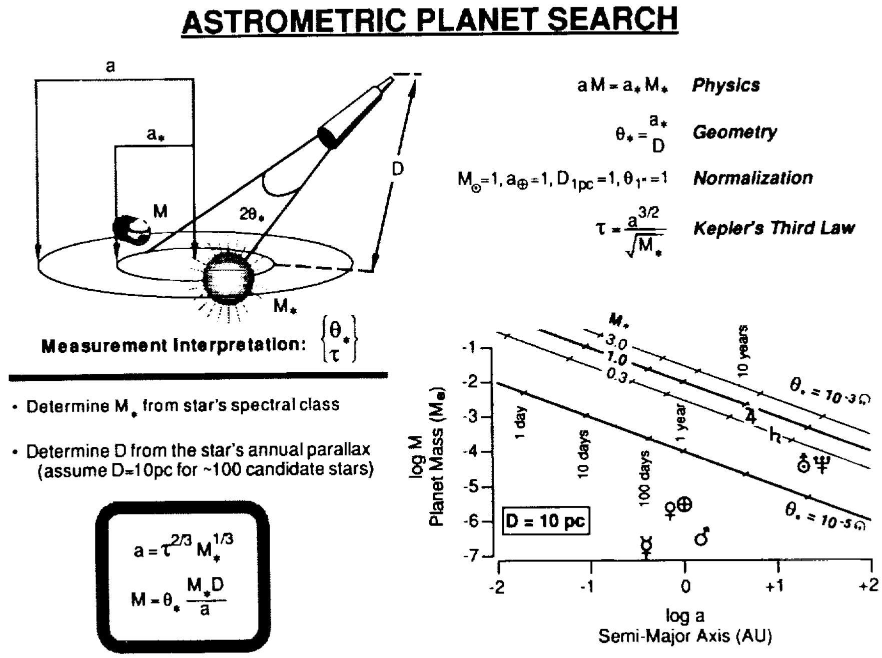

FIGURE 5 A tutorial on the astrometric technique for indirectly detecting extra-solar planets.

minimum detectable signal in reflex motion searches. The systematic errors may be real variabilities of the star (Gilliland and Baliunas 1987) or limitations of the instruments. As a class, systematic errors demand the planet searcher's assiduous attention.

Once detected, the amplitude of the reflex signal, V_* or θ_*, and its period, τ, provide specific information about the planetary mass and semimajor axis. The graduated lines in the graphs in Figures 4 and 5 signify the interpretation. The star's mass is required, and for main sequence stars, M_* can be determined adequately from the stellar-spectral type. For evolved stars, the mass assignment is more uncertain.

The radial velocity amplitude, V_*, is independent of Earth-star distance. The true orbital speed is $V_*/\sin(i)$, where the orbit's inclination angle, i, with respect to the line of sight is unknown unless it is determined separately. The average value of sin(i) in a random sample is 0.79.

The astrometric amplitude, θ_*, is a two-dimensional vector with components of right ascension and declination. When viewed from an inclined angle, a circular orbit is an apparent ellipse on the celestial sphere. In principle, the secular motion of the star along this elliptical path uniquely determines the true orbit, including the inclination angle.

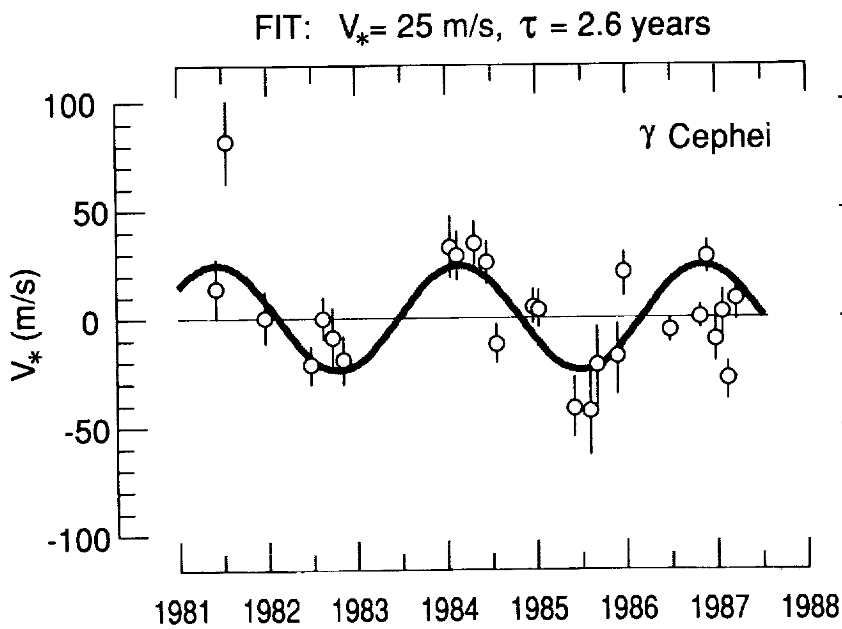

FIGURE 6 The data for the "probable" detection claimed by Campbell *et al.* of a planetary companion to γ Cephei.

Campbell *et al.* (1988) have conducted a search program that measured the radial velocities of 15 stars for six years with a precision of about 10 meters per second. The authors report statistically significant, long-term accelerations for seven stars, and in one case, they claim the "probable" detection of a period. The λ Cephei observations, with a large quadratic drift subtracted, are shown in Figure 6. The investigators have fitted a sine wave with amplitude $V_* = 25$ meters per second and period $\tau = 2.6$ years to the data.

γ Cephei is classed as spectral type K1 III-IV, indicating it has evolved far from the main sequence on the HR diagram. The rather uncertain mass estimate is $M_* = 1.15 \pm 0.1 M_\odot$ Therefore, the period implies an orbital semi-major axis a = 2AU, which subtends 0.13 arc seconds at the 15pc distance of γ Cephei. Assuming the orbit is viewed edge-on, the implied mass for γ Cephei b is $M = 1.3 \times 10^{-3} M_\odot$.

Figure 7 shows a radial velocity detection by Latham *et al.* (1989) which has been confirmed independently by the CORAVEL program. For the low-metal, but otherwise solar-type star HD114762, the Center for Astrophysics team obtained 208 measurements with a typical precision of

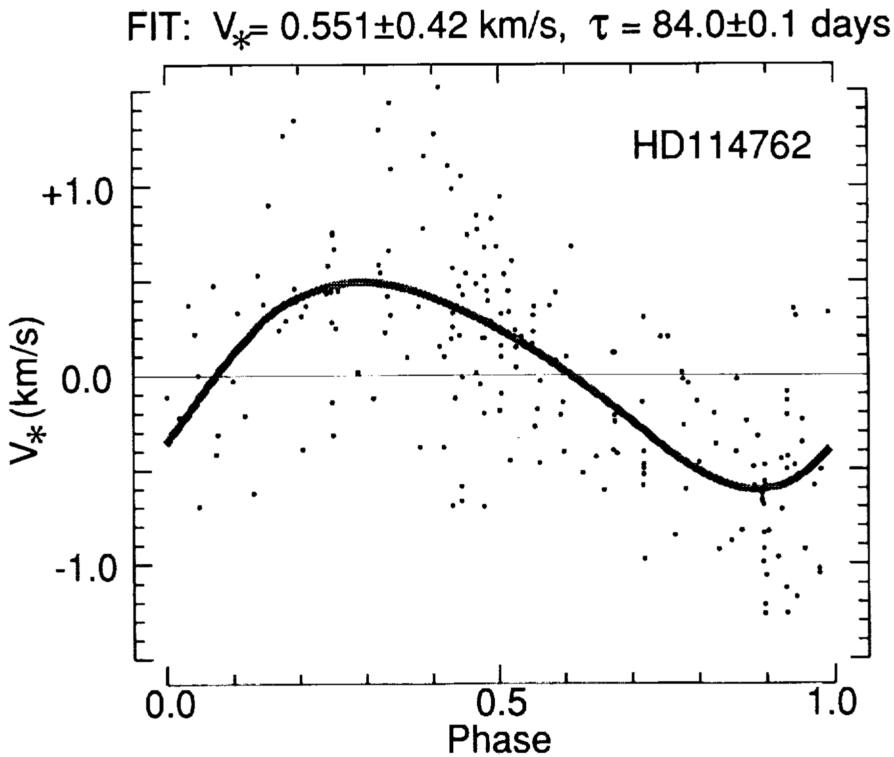

FIGURE 7 The data for the detection claimed by Latham *et al.* for a planetary companion HD114762.

0.4 kilometers per second over a 12-year interval. A periodogram analysis indicates a highly significant signal with period $\tau = 84 \pm 0.1$ days and amplitude $V_* = 0.551 \pm 0.042$ kilometers per second. The best fit is not a pure sine wave, which may indicate either an elliptical orbit or another orbiting body.

Estimating the mass of HD114762 at $M_* = 1M_\odot$, the short period indicates an orbit like Mercury's: a = 0.38AU. At the 28pc distance of this system, the estimated semi-major axis subtends 0.14 arc seconds. Assuming a *single* orbit is viewed edge-on, the implied mass for HD114762 b is $M = 1.1 \times 10^{-2} M_\odot$.

Van de Kamp (1986) claims the detection of two planets in his astrometric record of Barnard's star, which is shown in Figure 8. Barnard's star is late-type M dwarf, which is faint ($m_v = 9.5$), although close (1.8pc). Van de Kamp fits his data with two amplitude-period combinations: (0.0070 arc

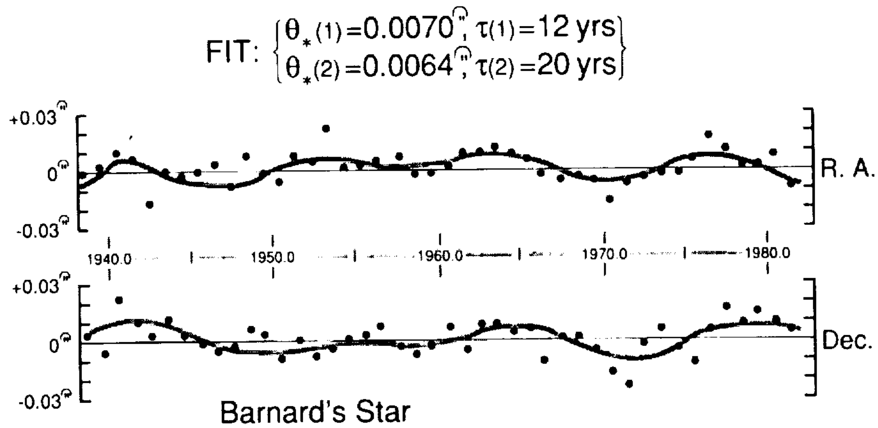

FIGURE 8 The data for the detection claimed by van de Kamp for two planetary companions to Barnard's Star.

seconds, 12 years) and (0.0064 arc seconds, 20 years). Estimating the mass of Barnard's star at $0.14M_\odot$, the semi-major axes are $a_b = 2.7$AU and $a_c = 3.8$AU. (For the astrometric technique, the semi-major axis is independent of the system's inclination angle.) The masses derived for the companions are $M_b = 6.6 \times 10^{-4}M_\odot$ and $M_c = 4.2 \times 10^{-4}M_\odot$.

The van de Kamp observations extend over more than 40 years, and they have been widely discussed and disputed. The independent observations of Barnard's star shown by Harrington and Harrington (1987) are not consistent with the orbit solution by van de Kamp.

SUMMARY

Three investigator groups have reported detecting objects that are candidates for extra-solar planets according to the broad definition of the term based on mass. The findings are summarized in Figure 9.

All three claimed planet detections are based on stellar reflex motions, an indirect method. Searches based on direct imaging are currently limited to brown dwarfs because smaller objects are not sufficiently luminous to overcome scattered starlight.

Latham *et al.*'s (1989) detection of HD114762 b is solid. If the orbit is viewed edge-on, this object has a mass about 10 times that of Jupiter and is a planet by the definition adopted in this review. However, the inclination angle of the orbit is uncertain, and if sin(i) is small, the edge-on assumption would cause the actual mass of HD114762 b to be significantly underestimated. On an *a priori* basis, though, this is improbable. More radial velocity observations will clarify whether the departure of HD114762

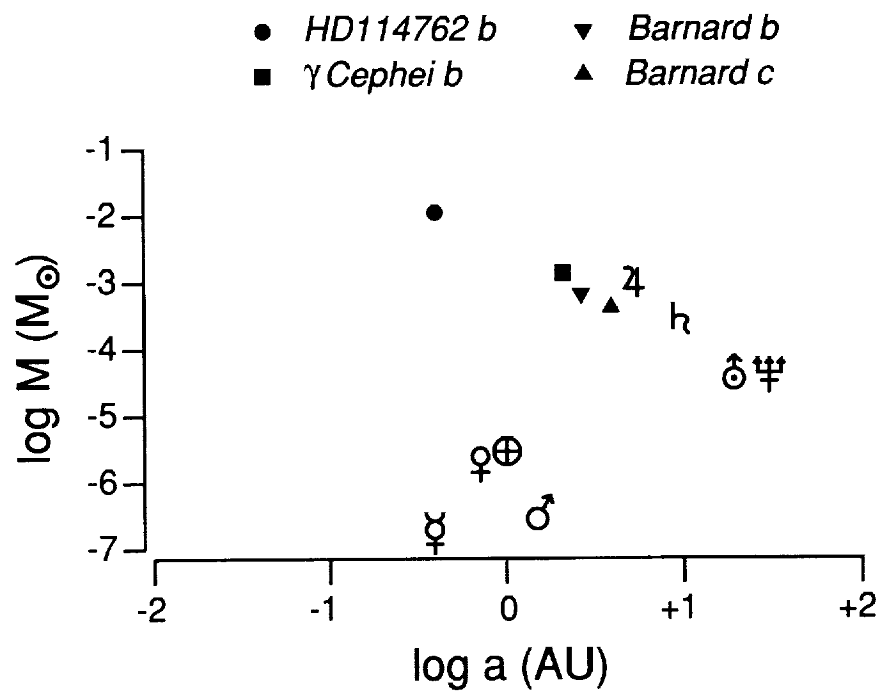

FIGURE 9 Summary of currently claimed extra-solar planet detections plotted versus orbital semi-major axis and mass.

b's radial velocity variations from a sine curve implies a non-circular orbit or a second orbiting body.

γ Cephei b and the companions to Barnard's Star are uncertain. More measurements over a longer time base are needed to confirm or deny their existence.

PROSPECTIVE CONCLUSIONS

The technological frontier for extra-solar planet detection lies in space-based systems. While the radial velocity approach is operating near the limits set by stellar atmospheric effects, the high-image quality potentially available in space will greatly benefit other search techniques (Borucki *et al.* 1988; Terrile 1988; Levy *et al.* 1988).

Regarding the future for extra-solar planet observations, Marcy and Moore (1989) offer a glimpse that is deceptively simple in a subtle way. They synthesize radial velocity, astrometric, and photometric studies of the low-mass ($0.067M_{\odot} \leq M \leq 0.087M_{\odot}$) companion of Gliese 623. These data sets are independent and complementary. Analyzed together, the measurements reveal a rich picture of the object, with regard to the special capabilities of the individual observing techniques. As a scientific bonus, the result challenges theory: the luminosity of Gliese 623 B is significantly greater than is predicted by current models for stars of its mass and age.

Liebert and Probst (1987) have reviewed the scientific issues for low-mass stars and brown dwarfs. For those objects, the key scientific questions are about their total numbers and their intrinsic properties. The issues are not systemic, and current observing approaches address the critical questions, as Marcy and Moore show.

The scientific issues for extra-solar planets are qualitatively different from those for low-mass stars and brown dwarfs. To understand the origin and evolution of the solar system in the context of the astronomical record, *systems* of extra-solar planets must be studied as such. That means finding and understanding multiple planets per star, because only then can systemic aspects can be measured.

This review has really discussed the observational progress toward "the existence theorem:" discovering *just the first* extra-solar planets. Measuring the joint properties of multiple-planetary systems is a qualitatively more difficult challenge that will demand major technological advances. Nevertheless, this goal has durable importance for planetary science.

Someday, with much investment, work, and care, incisive observations of extra-solar planetary systems will challenge our theories and ideas about the solar system's formation and evolution.

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