EXTRASOLAR PLANET-HUNTING TECHNIQUES

The two key "planet-hunting" techniques successfully used over the past decade to reign in a host of extrasolar planetary systems were initially suggested in 1952 by Otto Struve (1897-1963) while at the University of California, Berkeley[2]. Struve suggested that it should not be unreasonable that Jupiter-sized objects might be orbiting very close to its host star, in contrast to our own system. Finding a large planetary mass together with a small orbit radius and high orbital frequency would make it possible to detect the gravitationally-induced spatial oscillations of the host star due to the planet. Struve offered the important caveat that this approach would be most reasonable with orbiting systems that are aligned with a line of sight toward an observer on Earth near a 90° inclination; *i.e.*, so that the orbit crosses an observer's view point perpendicularly rather than straight on and the reactive motion of the star would face "toward Earth". He also suggested a second method also currently used today of detecting decreases in starlight intensity as an orbiting object passes directly between its host star and an Earth observer's line of sight.

With technological advances in instrumentation sensitivity since Struve's proposal, these very methods along with additional new ideas have been used with great success in discovering and measuring basic physical properties of extrasolar planets.

A. *Radial Velocity via Doppler Shifts – The "Wobble" Method*

The primary technique used by astronomers to search for and make *initial claims* of extrasolar planets is an indirect detection method based on Doppler shifts in starlight [3]. This "wobble" method is based on the idea that an orbiting planet will provide a gravitational tug on its host star directly causing slight shifts in the star's position with a potentially measurable radial velocity. The greater the mass of the orbiting planet, the larger its gravitational pulling and therefore the larger the positional shift of the star.

If the motion is properly aligned with the Earth, it is this physical oscillation of the star during a period orbit of the planet that is directly measurable by carefully observing the variations in the spectrum of light collected over an extended period of time. This data collection time must span at least a full period or two of the orbiting planet, which have been observed to be as brief as 3 Earth days to many Earth years.

The absorption-line spectrum measured from the light emitted by the host star is characteristic for that star, and contains wavelengths of light *not* absorbed by chemicals present in its upper atmosphere. If the star is physically moving due to a gravitational response of a nearby planetary mass, then the distance between the star and an observer on Earth might vary. If the star moves further from Earth along the observer's line of sight, then the emitted light must travel a greater distance and the apparent observed wavelengths in its spectrum increase (they become "more red"—a redshift). Alternatively, if the star moves closer to Earth along the observer's line of sight, then the light travels a shorter distance and it appears that the light frequencies increases, *i.e.,* the wavelengths decrease (they become "more blue"—a blueshift). This effect is a relativistic

Doppler shift, $\Delta\lambda$, and has been routinely used to measure speeds of stars and galaxies in relation to Earth.

A star emitting an intrinsic spectrum[a], λ_0, with N wave crests between itself and an Earth observer along its line of sight corresponds to the total distance traveled of the light, $N\lambda_0 = ct_0$. With the star moving relative and in line with the observer's line of sight at speed, v, the same N crests must travel a distance $ct + vt$ to reach the observer, thereby "stretching" or "squishing" the wavelength to λ such that $N\lambda = (c+v)t$. Taking the ratio of the intrinsic spectrum with the Doppler-shifted spectrum and substituting in geometric time dilation, $t = (1-v^2/c^2)^{-1/2} t_0$, gives

$$\frac{N\lambda}{N\lambda_0} = \frac{(c+v)}{c}\frac{t}{t_0}$$

$$\frac{\lambda}{\lambda_0} = \left(1+\frac{v}{c}\right)\left(1-\frac{v^2}{c^2}\right)^{-1/2}$$

$$\frac{\lambda}{\lambda_0} = \frac{1+\frac{v}{c}}{\sqrt{\left(1+\frac{v}{c}\right)\left(1-\frac{v}{c}\right)}} \cdot \frac{\sqrt{\left(1+\frac{v}{c}\right)\left(1-\frac{v}{c}\right)}}{\sqrt{\left(1+\frac{v}{c}\right)\left(1-\frac{v}{c}\right)}}$$

$$\frac{\lambda}{\lambda_0} = \frac{\left(1+\frac{v}{c}\right)\sqrt{\left(1+\frac{v}{c}\right)\left(1-\frac{v}{c}\right)}}{\left(1+\frac{v}{c}\right)\left(1-\frac{v}{c}\right)} \quad \rightarrow\rightarrow\uparrow$$

$$\frac{\lambda}{\lambda_0} = \frac{\sqrt{\left(1+\frac{v}{c}\right)\left(1-\frac{v}{c}\right)}}{\left(1-\frac{v}{c}\right)}$$

$$\frac{\lambda}{\lambda_0} = \sqrt{\frac{\left(1+\frac{v}{c}\right)\left(1-\frac{v}{c}\right)}{\left(1-\frac{v}{c}\right)^2}}$$

$$\therefore \frac{\lambda}{\lambda_0} = \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}$$

By convention [1], we'll label $\lambda/\lambda_0 = 1+z$, which represents a "redshift" if $z = (\lambda-\lambda_0)/\lambda_0$ is a positive result, and a "blueshift" if negative.

As long as the moving object (here, the star's wobble) is much slower than the speed of light such that $v/c << 1$, then we may *approximate* to a nonrelativistic Doppler shift using a binomial expansion:

$$1+z = \frac{\lambda}{\lambda_0} \approx \sqrt{1+\frac{v}{c}} = 1+\frac{1}{2}\left(1+\frac{v}{c}\right)+\cdots$$

$$z \approx \frac{v}{c} << 1$$

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[a] Obtaining the baseline intrinsic spectrum to compare with the measured Doppler-shifted spectrum is not a straightforward task. Butler, R. P., *et al.* [3] describe how they take a very noisy spectrum and filter it down to an approximate intrinsic spectrum. This is accomplished by comparing to "essentially featureless" reference spectrums of bright, rapidly rotating stars taken just before the time of the primary measurements.

A typical example of results from this measurement approach is presented in Figure 1 as reported by Marcy, *et al*. [4]. The measured Doppler shift is converted to a nonrelativistic radial velocity by $v = zc$ and plotted versus the orbital phase of the star's position.

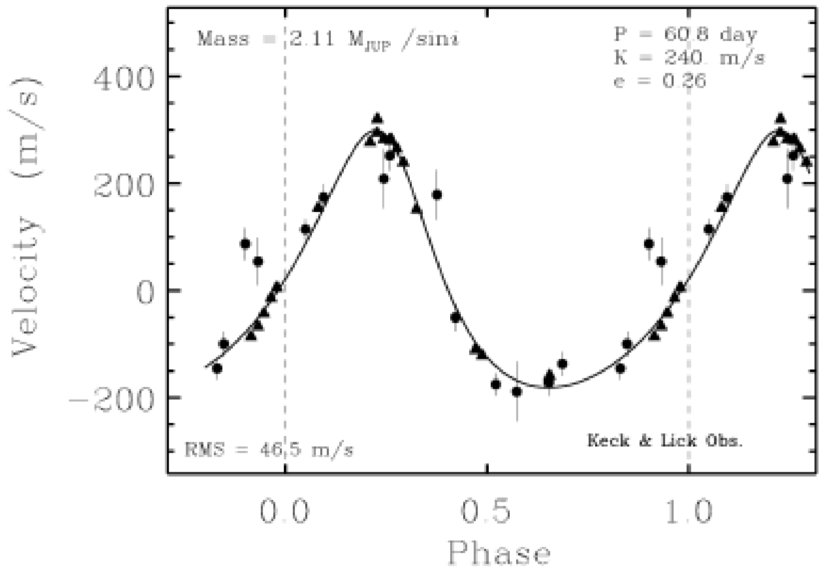

Figure 1. Combined measurements from two separate observatories for Doppler shifting star Gliese 876 due to an orbiting mass. *Image Credit*: Marcy, G. W., *et al.* THE ASTROPHYSICAL JOURNAL, 505:L147–L149, October 1, 1998.

Assuming there is only one orbiting planet—or only one planet with a large enough mass to cause the only observable gravitational oscillations of the star—the orbital period of the planet may be directly determined by plotting out the radial velocities via the spectrum Doppler shifts as a function of time (or orbital phase, as in Figure 1). With a planet covering an elliptical orbit, a sinusoidal curve should map out and the period may then be directly measured graphically. This direct measurement by Marcy, *et al*. is approximately 60.8 Earth days for Figure 1.

With the measured orbital period, P, and an independently determined stellar mass, the mass of the planet may be calculated by starting with Kepler's Third Law and solving for the elliptical orbit's semimajor axis length, a:

$$P^2 = \frac{4\pi^2}{G(M_* + m_p)} a^3$$

where m_p may be ignored here as long as it is much smaller than the star's mass. Approximating the orbit to be nearly circular, we take $a \approx r$, where r is the radial distance between the host star and its planet.

Newton's Laws applied to the gravitational interaction between two massive bodies in terms of their separation $\vec{r} = \vec{r}_* - \vec{r}_p$ can be expressed as $\frac{d^2\vec{r}}{dt^2} = \frac{G(M_* + m_p)}{r^3}\vec{r}$. To simplify, we'll take its dot product with $\vec{v}_p = \frac{d\vec{r}}{dt}$ to give

$$\vec{v}_p \cdot \frac{d\vec{v}}{dt} = \frac{G(M_* + m_p)}{r^3}\vec{r} \cdot \frac{d\vec{r}}{dt}.$$

Noting that, in general, $\frac{d}{dt}|\vec{x}|^2 = \frac{d}{dt}(\vec{x} \cdot \vec{x}) = 2\left(\vec{x} \cdot \frac{d\vec{x}}{dt}\right)$, so that we may re-write the dot products in the above expression as

$$\frac{1}{2}\frac{d}{dt}|\vec{v}_p|^2 = \frac{G(M_* + m_p)}{r^3}\frac{1}{2}\frac{d}{dt}|\vec{r}|^2.$$

Re-arranging, we simplify and approximate the orbital speed of the planet, again by taking its mass to be much less than its host star:

$$\frac{d}{dt}\left[\frac{1}{2}{v_p}^2\right] - \frac{d}{dt}\left[\frac{1}{2}\frac{G(M_* + m_p)}{r^3}r^2\right] = 0$$

$$\frac{1}{2}\frac{d}{dt}\left({v_p}^2 - \frac{G(M_* + m_p)}{r}\right) = 0$$

$${v_p}^2 = \frac{G(M_* + m_p)}{r}$$

$$v_p \approx \sqrt{\frac{GM_*}{r}}$$

Finally, to estimate the mass of the planet, we write conservation of momentum for the system as $m_p v_p = M_* V_*$. The stellar velocity may be determined directly from the Doppler shift curve (velocity *vs*. time of Figure 1) by relating the maximum amplitude, *K*, of the sinusoidal curve (*not* denoted in the figure) and the orientation of the motion with Earth's line of sight by $K = V_* \sin i$, where i is the unknown orbital inclination angle[b] representing the orientation of the stellar rotational axis with the observer on Earth.

Finally,

$$m_p = \frac{M_* K}{v_p \sin i}$$

$$m_p \sin i = \frac{M_* K}{v_p}$$

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[b] Ideally, the inclination angle is very close to 90° corresponding to an "edge-on" view of the orbiting system from Earth. This allows for sin *i* to be approximately unity resulting in the closest possible estimate to the planetary mass calculation.

This method was successfully demonstrated early in 1998 by the Marcy and Vogt group with measurements of a planetary mass of around 2.1 $M_{Jupiter}$ orbiting a dwarf star named Gliese 876 [4]. An unexpected feature that was identified with this particular system and others at the time was that these large planets also had short periods (about 60 Earth days for this example) and very tight orbits (0.21 AU), which is in stark contrast with our Solar System. It is this observation that was in fact predicted as a reasonable scenario by Struve [2] over four decades earlier.

B. *Transit Photometry – The "Wink" Method*

The passing of one celestial object in front of another and observing the changes in observed light along the observer's line of site has been used for detecting properties of objects in our solar system [1]. In particular, the rings of Uranus were discovered in 1977 by James Elliot, *et al*. by measuring the light intensity of a distant star during its occultation by Uranus.[c] Additionally, accurate dimensions of planets, moons, and asteroids have been measured during stellar occultation, as well as information about atmospheric temperatures and composition of planetary upper atmospheres in the Solar System [5].

This method, as used by Elliot's team, mapped out the intensity from a specific star as it appeared to move behind a planet due to relative motion between Earth and the planet. (See Figure 2 for the data showing how Elliot identified Uranus' rings.) As the distant star passes behind the nearby occulting planet, the starlight's observed intensity drops as different components of the planet either absorb or scatter the star's light.

The same idea may be applied by observing the light intensity variation of a star as a *smaller object* near that star transits its stellar disk (See Figure 3). If a star has such an orbiting mass, the star's intensity can be directly measured to decrease as the planet passes between the star and the Earth observer's light of sight. This same dip in intensity should then be observable again during the planet's next transit, thus providing a method to estimate an orbital period for the planet.

[c] To be clear on terminology, "occultation" is when a large object passes in front of a smaller object along an Earth observer's line of sight; the opposite term "transit" is when a small object passes in front of a larger one; and an "eclipse" is the line of sight overlap of two objects each about the same size (at least from the observer's relative viewpoint).

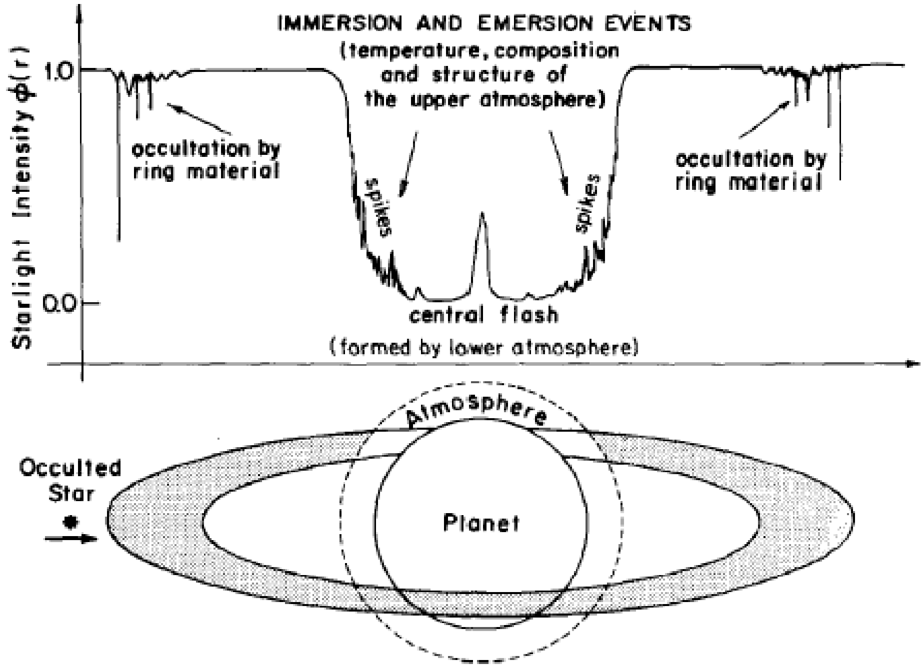

Figure 2. The upper graph maps the star's light as it passes "behind" the nearby planet relative to the Earth. The side-line intensity dips were evidence that additional absorbing material was surrounding the planet. The so-called "central flash" peak is due to the planetary atmosphere acting as a lens and refracting the light toward the observer. *Image credit:* Elliot, J. L., ANN. REV. ASTRO. AP., **17**, 1979, 445.

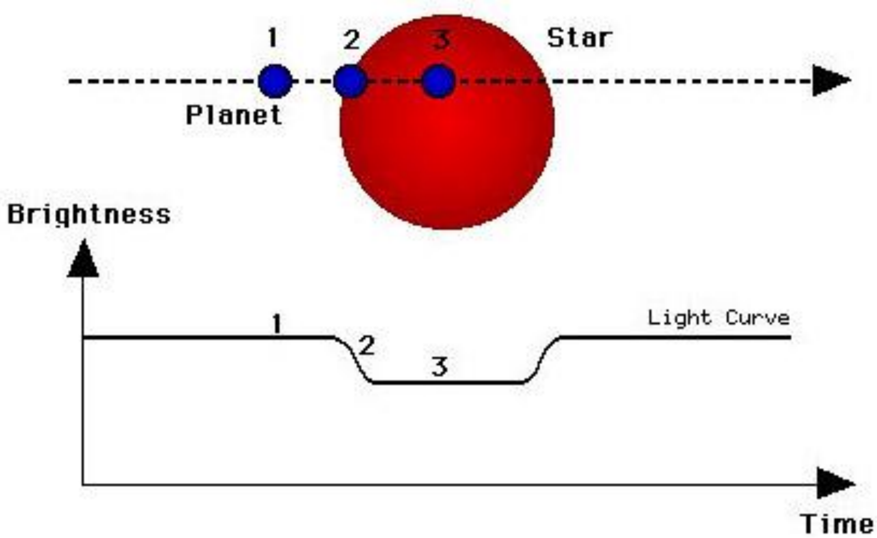

Figure 3. Schematic diagram showing the relationship between the measured light curve of the star as an orbiting mass transits the stellar disk. The depth of the intensity dip corresponds to the ratio of the area of the planet to the area of the host star providing a route to estimate planet size. *Image Credit:* Deeg, H. "Transits of Extrasolar Planets" Group via http://www.iac.es/proyect/tep/transitmet.html.

Among the first attempts to utilize the transit observation technique were two competing groups—comprised of many of today's top planet-hunters—each taking detailed photometric measurements of the star HD 209458 [6, 7] positioned some 153 light-years from Earth in the constellation Pegasus. Because these particular observations confirmed previous measurements on the same star using the wobble method, these studies provided among the first *conclusive* evidence that planets in fact do exist orbiting other stars.

The star was measured both during times of expected planetary transit to directly observe the dips in light intensity and during off-transit periods to verify that the intensity levels were otherwise consistent so as to not likely be affected by non-planetary influences.

The data collected from the Charbonneau team is presented in Figure 4 and clearly illustrates the intensity changes from a separately-measured baseline level as a function of the time during the transit period. Two separate transit observations are actually combined together in this data set. The decrease in light intensity measured was a mere 1.6% of the baseline levels, so high sensitivity is certainly required in these types of measurements.

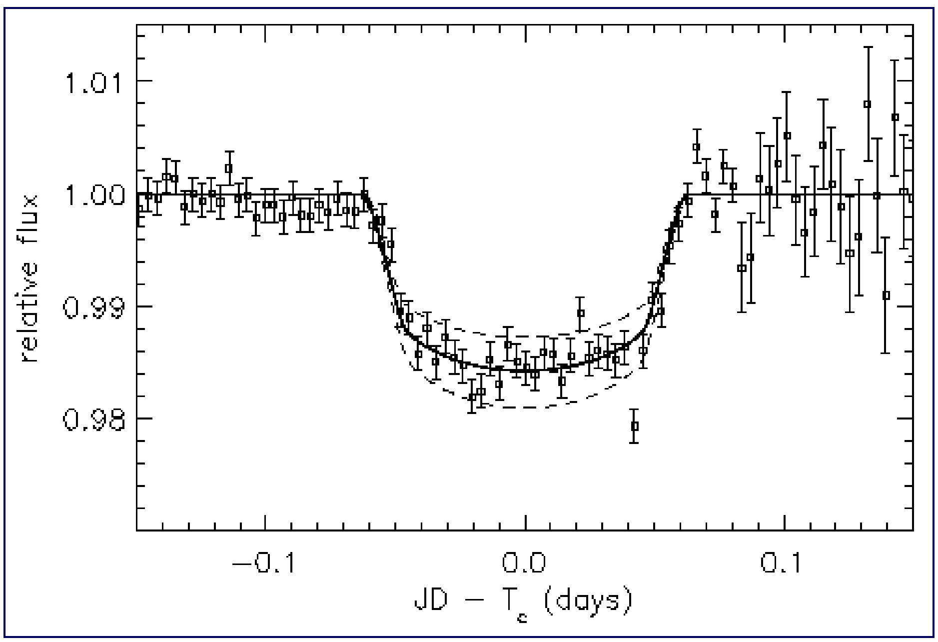

Figure 4. Intensity variations of star HD 209458 during possible planetary transits on September 9 and 16, 1999. The sloping transit curve corresponds to the initial and final crossing of the planet at the edge of the star, the depth of which is related to the size of the planet. The lower curved portion extends the transit perido as the planet is entirely in front of the star as viewed from Earth. *Image Credit:* Charboneau, D. *et al*. THE ASTROPHYSICAL JOURNAL, 529:L45-L48, 2000.

The significant advancement made through the combination of the transit observations with the radial velocities on the same star was the ability to better predict the orbiting planet's properties. Previously determined quantities for the HD 209458 stellar radius, R_*, and mass, M_*, were used in a series of "best-fit" calculations by Charboneau's team to iteratively determine likely values for the radius, R_p, and mass, M_p, of the orbiting planet as well as the orbital inclination angle, *i*. With this star actually being similar to the

Sun with $R_* = 1.1R_{Sol}$ and $M_* = 1.1M_{Sol}$, their calculated planetary values were estimated to be $R_p \approx 1.27R_{Jupiter}$ and $M_p \approx 0.63M_{Jupiter}$. The upper and lower dashed lines in Figure 4 are for comparison and represent the fitted transit curves if a 10% smaller and larger planetary radius is assumed, respectively.

C. *Alternate Methods – Gravitational Lensing & Pulsars*

Several other methods are being utilized for detecting extrasolar planets, but we will only briefly mention their approaches here.[d]

An otherwise "invisible" planet positioned between a far-away star and Earth along our the line of sight will act as a gravitational body altering space in a way that might bend the star's light. If the alignment is just right, this bending of the light could actually cause an apparent "focusing" and therefore brightening of the star as observed from Earth. A one-time "flash" of the star could be observed to suggest the possibility of an orbiting planet.

Unfortunately, this perfect "heavenly alignment" required for this sort of observation likely would not occur again in a predictable time frame for a repeat measurement. So, any observed "flash" event must be quickly reported for more observations. An additional complication, here, is that the lensing phenomena requires the planetary system to be significantly further away than the systems under study using the "wobble" and "wink" methods, so extensive comparisons of data can be more difficult, if not impossible.

To assist with the quick reporting requirements, the University of Washington established the Global Microlensing Alert Network (GMAN)[e] to work directly with The MACHO Project,[f] which incorporates gravitational lensing observations in its primary study of the so-called dark matter in the halo of the Milky Way.

Another, more recently established, informal group supported by Ohio State University, called the Microlensing Follow-Up Network (MicroFUN)[g], is also working to assist the close monitoring of microlensing events in order to expedite new discoveries. Along with an international set of collaborators, this group participated in a very recent exoplanet discovery [8] in May 2005. This is claimed to be the second confirmed observation using the gravitational microlensing method, with the first official discovery occurring only a year earlier by Bond's team in 2004 [9]. This planet is modeled by the team to have a planet-star mass ratio of 0.0071.

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[d] With only a brief mention of two additional techniques, here, we only reference general overviews for these methods written by Laurence Doyle of the SETI Institute for Space.com. Additional information on current research activities may be found through the Microlensing Planet Search Project at Notre Dame via http://bustard.phys.nd.edu/MPS as well as through other groups' referenced elsewhere in this paper.

[e] http://darkstar.astro.washington.edu

[f] http://wwwmacho.mcmaster.ca

[g] http://www-astronomy.mps.ohio-state.edu/~microfun

It might be initially considered that stable planets—especially, habitable planets—would not be happy companions of hyper-dense neutron stars. In fact, they certainly aren't at some point because a neutron star is considered to be generated only after supernova explosions of giant dead stars. These explosions would annihilate any and all orbiting bodies, but maybe planets could still form again after the neighborhood settled down.

The key advantage to looking for planets around neutron stars, however, is that the star might be acting as a "pulsar", which are extraordinarily regular astronomical clocks emitting radio waves at precise time intervals. An orbiting planet, even a tiny Earth-size or smaller planet providing only the faintest gravitational tug to wobble the host neutron star, would cause a clear and measurable change in the otherwise absolute precision of the radio pulses.

E. *Direct Measurements – Reflected star light and Hubble imagery*

So far, no widely-accepted *direct measurement* nor photographic image has been confirmed of an extrasolar planet. Charbonneau and Vogt, *et al.* [10] developed a model idea to suggest how much starlight a planet might reflect for direct observations. They tested their model—which required significant assumptions—against actual observations from a particular star using a hypothetical large planet, $1.2R_{Jupiter}$, with a very tight orbit, 0.046 AU. They were not able to find any matching results in the data, but the attempt was a clear beginning to work out possible approaches for direct observations of extrasolar planets.

The Hubble Space Telescope has been taking its best shots on several planetary candidates[h] among its most recent efforts. In particular, Steinn Sigurdsson and graduate student John Debes at Penn State University, have been developing extensive image processing routines for ground based telescope observations [11] and on a Hubble image of a white dwarf.[i] They have made preliminary claims of possible direct observations of companion objects to the images stars, but they have yet to be confirmed, even by Sigurdsson's own group, as actual direct images of planets and not simply background objects.

Recent Hubble activity from early 2005 provided a near-infrared shot of a possible companion object of a brown dwarf 225 light-years away (See Figure 5)[j]. The observing group using the European Southern Observatory's Very Large Telescope (VLT) in Chile with Hubble imagery follow-up claims high confidence that the body is actually orbiting the brown dwarf as a candidate giant planet weighing in at minimum $5M_{Jupiter}$ in an orbit 53.79 AU from its star. Additional measurements are still required to confirm that the two objects are in fact gravitationally bound.

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[h] http://hubble.nasa.gov and http://www.hubblesite.org

[i] http://news.bbc.co.uk/2/hi/science/nature/3707185.stm and http://nai.arc.nasa.gov/news_stories/news_detail.cfm?article=secondchance.htm

[j] As reported on HubbleSite via http://www.hubblesite.org.

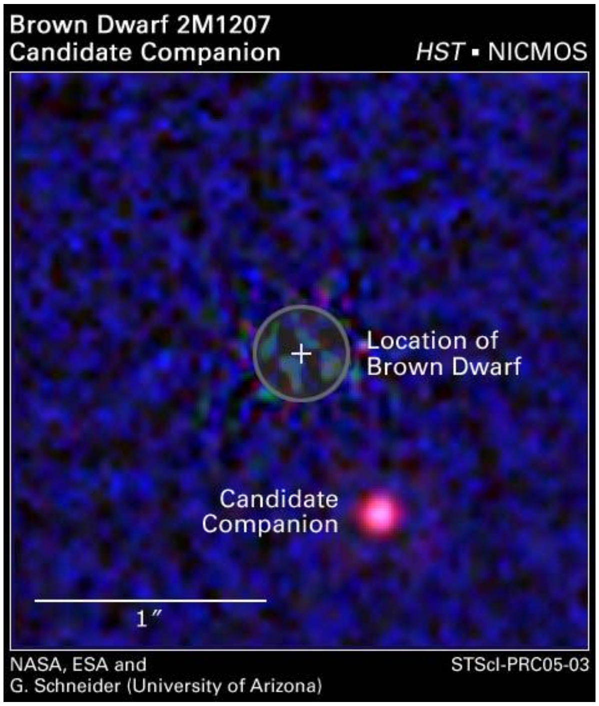
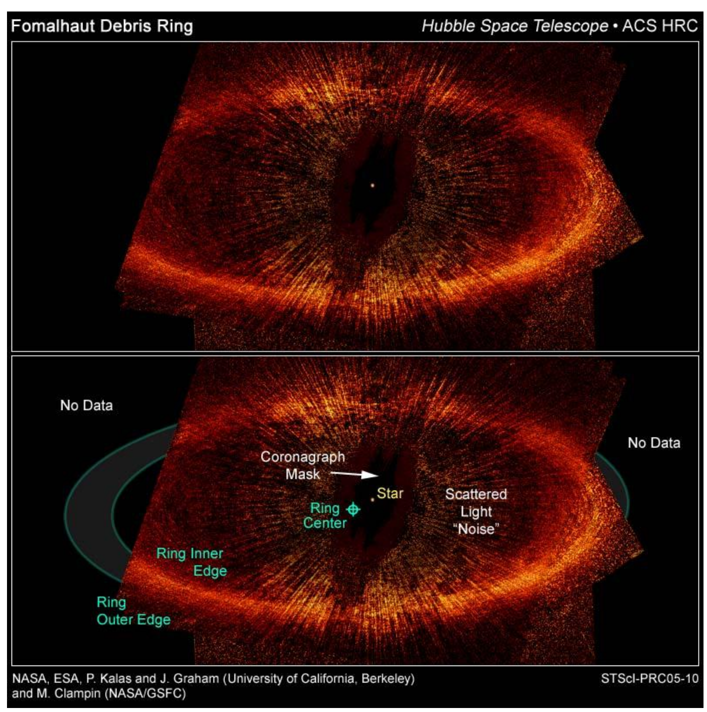


Figure 5. Potential direct image of a candidate extrasolar giant companion object. The light from the brown dwarf, 2M1207, has been masked and additional image processing performed. It is not yet confirmed that these objects are in deed orbiting bodies. *Image Credit:* NASA and Schneider, G. *et al.* via HubbleSite at http://www.hubblesite.org.

The most recent Hubble result is not a direct exoplanet image, but a detailed view of the extensive dust pattern around the Kuiper belt of the star Fomalhaut (HD 216956) (See Figure 6). The center of the dust belt is measured to be a significant 13.4 AU from the star, which strongly suggests additional gravitational objects are affecting the system. Paul Kalas and his colleagues developed a model [12] with the data to demonstrate the likelihood that unseen planetary masses are causing the observed distortions of the dust.

Figure 6. NASA's Hubble Space Telescope's image in visible light of the dust belt orbiting Fomalhaut (HD 216956). The suggestion is that the belt's particular shape could not be gravitationally sculpted by the star alone, but additional masses—possibly an entire planetary system—are present to cause the distortions. The image was created by blocking the star light, so the star's location has been artificially identified in the images. *Image Credit:* NASA and Kalas, P. *et al.* via HubbleSite at http://www.hubblesite.org.



FUNDAMENTAL LIMITS AND TECHNOLOGICAL RESTRICTIONS

The flood of extrasolar planetary discoveries over the past several years has been extraordinarily exciting. The techniques overviewed here are not entirely straightforward to perform in practice, however, and can take many years to collect enough data to obtain full orbital information that can be independently verified. The search for stars with orbiting masses requires large-scale systematic hunting, which also means a little luck can go a long way.

There are fundamental limitations astronomers much work around during exoplanet hunting; some technological limitations and other physical limitations that will likely always remain impossible hurtles, at least for as long as we stay on Earth.

The first physical limitation, which is actually correctable, deals with the Earth's relative motion to the star's motion. The "wobble" method requires measuring Doppler shifts due to oscillations *by the star*. However, the Earth itself might be the source of oscillations with respect to the star's light. So, this home-base wobble and other local motions must be corrected for in the Doppler shift calculations. Then, if tiny shifts are still recorded, it is more likely that the motion may be fully attributable to the star itself.

Both primary methods previously described, the "wobble" and "wink" methods, carry similar limitations that must be carefully understood when making claims about extrasolar planetary observations. Early on, Elliot listed several issues with occultation observations [5] that are also basic to today's planet-hunters. Obviously, Earth's weather plays the top limitation to ground-based telescopes, whereas space observatories, including the Hubble Space Telescope, immediately solves the issue—although certainly at a significantly increased cost!

Just as Elliot found it difficult to actually find an occulting event to observe, the frequency is very low of actually stumbling upon an extrasolar system that, literally, has all of its planets and stars aligned in harmony. Even though there seems to be a large collection of discoveries to date, these searches have covered statistically huge distributions of stars in order to narrow down the hunt in identifying candidate systems.

In particular[k], the successful observations to date have been of systems that align with the observer's line of site, which has been a characteristic repeatedly emphasized during the method overviews above. At a fundamental level, the Doppler shifts due to a star's wobble can only be detected if and only if the shifting velocity is oriented head-on to Earth. If the wobble motion is along any other orientation, our observations will only be capable of measuring the *vector component* of the Doppler shift along our direction.

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[k] Doyle, L. of the SETI Institute writing for Space.com. "Detecting Other Worlds: The Wobble Method." May 22, 2001.

Therefore, because this physical limitation of uni-directional measurements, out-of-sightline motion due to the gravitational effects of the orbiting planet are entirely hidden. This restricts the extrapolated measurements by masking the complete picture on the gravitational interactions.

If the full extent of the planet's gravitational influences are unknown, then an accurate planetary mass measurement is fundamentally not possible. So, the "wobble" method may only place a *minimum mass* threshold for the orbiting planet. The problem herein is that if only the lowest possible mass is detectible, the actual companion object of the star might still be many times heavier in reality, potentially requiring it to be classified beyond what would be traditionally defined as a planet (*e.g.*, a failed companion star or brown dwarf).

On the other hand, if the orbiting body is too small, say on the order of the mass of Earth, then its gravitational effects on the host star might cause oscillations that are too small to be detectible by our current technologies. Recall that many of the detected planets had minimum masses on the order of Jupiter, and even they cause stellar velocity shifts of only 0.0124 *km/s* [3], which is rather minute in the world of objects on the order of 10^5 *km* located 10^{15} *km* away from the observation point. It has been a strong effort of Butler, *et al*. [3] to bring the error in measurements of radial velocities down to only 3 *m/s* and will be an ongoing technological improvement goal if we are to discover Earth-sized and smaller exoplanets.

Another interesting possibility that would complicate accurate radial velocity measurements is a phenomena that exists in the Solar System. Sun spot cycles will alter spectral emissions, which could then be mixed in with velocity Doppler shifts. If these cycles match the period of an orbiting planet—just as our Sun has spot cycles ~11 years, which is close to Jupiter's orbital period!—then the measured planetary properties could be unknowingly skewed.

The "wink" method, which has proved to be a critical addition to the "wobble" measurements, also is fundamentally restricted to line of sight phenomena. The orientation of transit observations was explicitly incorporated into the calculations above using the orbital inclination angle, *i*, where a 90° alignment corresponded to "edge-on" motion of the transiting planet to Earth's line of observation. The same requirement may also be considered as having the star's orbital pole be perpendicular to Earth's line of sight. The Universe will certainly not be pre-disposed to ensure all transiting orbits are perfectly aligned to Earth, so our efforts will be entirely limited to the likely small fraction of $i \approx 90°$ planetary systems, which could be less than 1%.[1]

[1] Doyle, L. of the SETI Institute writing for Space.com. "Detecting Other Worlds: The Photometric Transit or Wink Method." August 9, 2001.

THE NEXT STEPS

If ultimate sensitivities are required to measure the slightest of planetary tugs thousands of light-years away and further, or even to directly photograph these intrinsically dark objects, advanced space-based observatories must be developed and dedicated to this task. The Hubble Space Telescope is already playing a new key role in the hunt for exoplanets even as its ongoing maintenance and funding is dubious. NASA and other space organizations are already on task with a slew of missions on the drawing boards, some of which even have reasonable launch dates estimated. A few of the likely candidates for launch are summarized below:

http://kepler.nasa.gov
NASA's Kepler Mission is on it's way to a launch in June 2008. Designed to survey our galactic neighborhood using the same techniques overviewed above, it will push the discovery limits by focusing on Earth-sized planets. In particular, it hopes to find planets located within what is known as a system's "habitable zone" where the temperatures allow for liquid water exist, and possibly harbor life.

http://www2.keck.hawaii.edu
The ground-based Keck Interferometer has been enlisted in the planet hunt with the ability to make precise measurements of "wobbling" star locations with respect to other "fixed" stars (called astrometry). This method is potentially more versatile than Doppler spectroscopy because it would not necessarily be limited to systems with the wobble motion along Earth's observation because it uses other stellar objects as reference points..

http://planetquest.jpl.nasa.gov/SIM
The Space Interferometry Mission (or, SIM PlanetQuest) is currently scheduled for launch in 2011 and will be the space-based equivalent to the Keck Interfermometer. By establishing its own star-based grid as a measurement reference frame, SIM should be capable of making position measurements with accuracies down to 4 microarcseconds.[m]

http://planetquest.jpl.nasa.gov/TPF
Still in the early stages of development, NASA's Terrestrial Planet Finder projects (including multiple launches between 2014-2020) will feature an array of new space-based visible-light and infrared telescopes working together to attempt direct detection and characterization of planets orbiting other stars.

http://www.esa.int
The European Space Agency is also currently developing space-based projects to join the search for planets. The Darwin project will be similar to NASA's TPF with a set of four infrared telescopes to scan nearby exoplanets. Its primary goal will be to directly detect spectral signatures of potential biological activity on other planets.

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[m] A detailed white paper is available online at http://planetquest.jpl.nasa.gov/documents/WhitePaper05ver18_final.pdf

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