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Edited by Mario Livio, Kailash Sahu and Jeff Valenti

Excerpt

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Extrasolar planets: Past, present, and future

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Human beings have long thought that planetary systems similar to our own should exist around stars other than the Sun. However, the astronomical search for planets outside our Solar System has had a dismal history of decades of discoveries that were announced, but could not be confirmed. All that changed in 1995, when we entered the era of the discovery of extrasolar planetary systems orbiting main-sequence stars. To date, well over 130 planets have been found outside our Solar System, ranging from the fairly familiar to the weirdly unexpected. Nearly all of the new planets discovered to date appear to be gas giant planets similar to our Jupiter and Saturn, though with very different orbits about their host stars. In the last year, three planets with much lower masses have been found, similar to those of Uranus and Neptune, but it is not yet clear if they are also ice giant planets, or perhaps rock giant planets, i.e., super-Earths. The long-term goal is to discover and characterize nearby Earth-like, habitable planets. A visionary array of space-based telescopes has been planned that will carry out this incredible search over the next several decades.

1. Introduction

Natural philosophers had hypothesized centuries ago that other planetary systems orbited the many stars in the night sky, that the Solar System was not unique. Up until 1995, however, there was no reproducible astronomical evidence to support this visionary viewpoint (Boss 1998). One decade later, a new field of astronomy has been born, with rapid observational progress that threatens to far outpace theoretical efforts to keep up. Major discoveries continue to appear on roughly a monthly basis, an unprecedented level of advancement in any field of science. While we have yet to find a true Solar System analogue, the planetary systems discovered so far leave little doubt that we will soon be discovering planetary systems that will be hospitable to the existence of Earth-like planets, the ultimate goal of this entire field of research.

Surprisingly, the very first planetary-mass bodies discovered outside our Solar System were roughly Earth-mass planets orbiting the pulsar PSR 1257+12 (Wolszczan & Frail 1992). These objects must have formed after their host star underwent a supernova explosion, as the explosion and accompanying stellar-mass loss would likely have removed any pre-existing planets. The fact that Earth-mass bodies later managed to form in a disk around the neutron star was taken as a strong proof of the resiliency of the planet-forming process of collisional accumulation of solids into larger bodies, even in a hostile environment. Nevertheless, the paucity of evidence for planetary systems around normal, main-sequence stars caused significant concern even after the pulsar planets were announced in 1992—where were the gas giant planets?

2. Past

The fantastic success of the *Hubble Space Telescope* (*HST*) at a wide range of astronomical observations has spoiled us all—we have come to expect to see images on a frequent basis of gorgeous cosmic locales, from nearby comets to distant galaxies. Taking an image of a nearby extrasolar planet is no more difficult than taking an image of a distant galaxy ($V \sim 30$ mag), except for the fact that the faint planet is located right

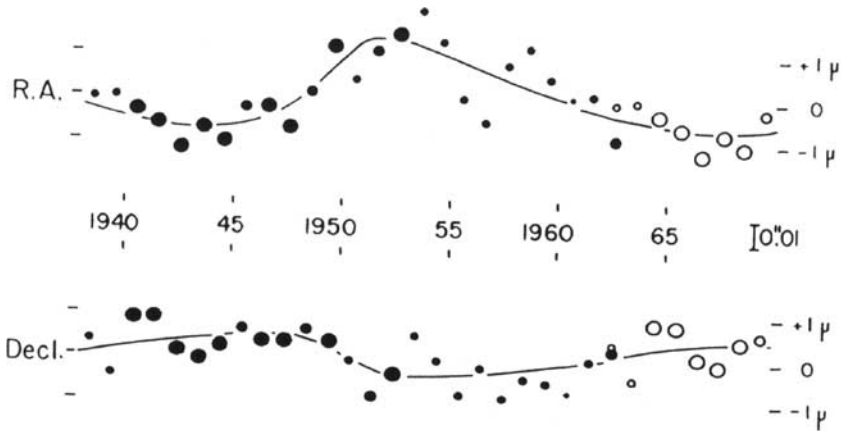


FIGURE 1. Apparent astrometric detection of a 1.6 Jupiter-mass planet orbiting Barnard's Star on a 24-year period, eccentric ($e = 0.6$) orbit (solid line), based on yearly means of Sproul Observatory data (van de Kamp 1963).

next to its much brighter host star. At optical wavelengths, the host star may outshine its planets by a factor of 10^9 or more. *HST* was not designed to be able to separate out the light of a planet from its host star.

As a result, essentially all of our information about extrasolar planets has come from indirect detection methods, where the existence of the planet is inferred based on the gravitational reflex motion of its host star as it orbits the center of mass of the entire system. This motion can be detected in several different ways, with the first studies having sought the back-and-forth motion of the star on the plane of the sky with respect to nearly stationary, background stars: the astrometric technique.

2.1. *Barnard's Star*

In 1937 Peter van de Kamp became the Director of Swarthmore College's Sproul Observatory. In the next year, he began a long term astrometric program to search for low-mass companions to nearby stars with the Observatory's 24-inch refractor telescope. One of the first stars he added to the target list was Barnard's Star, discovered in 1916 by E. E. Barnard. Barnard's Star is a red dwarf with a mass of $\sim 0.15 M_{\odot}$, close enough at 1.8 pc that only the Alpha Centauri triple system is closer to the Sun, but so faint that it cannot be seen with the naked eye. As a low-mass star very close to the Sun, it is an excellent candidate for an astrometric planet search: a Jupiter-like planet would force Barnard's Star to wobble over a total angle of ~ 0.04 arcsec, a wobble of several microns on the photographic emulsions used to record the trajectory of Barnard's Star, as it sped across the sky at 10 arcsec per year.

Astrometric claims for very low-mass companions to the stars 70 Ophiuchi and 61 Cygni had been made in 1943 by two different groups, but these claimed detections of objects with masses in the range of 10 to 16 Jupiter masses could not be verified and were soon discarded, if not forgotten. Only after taking 2,400 observations of Barnard's Star for over two decades was van de Kamp ready to announce his discovery of a planet, given this unfortunate prior history. In 1963 van de Kamp announced that he had found the first extrasolar planet: a planet with a mass only 60% greater than that of Jupiter, orbiting Barnard's Star with a period of 24 years (van de Kamp 1963). In order to be certain of its reality, he had waited for an entire orbital period to elapse before making the an-

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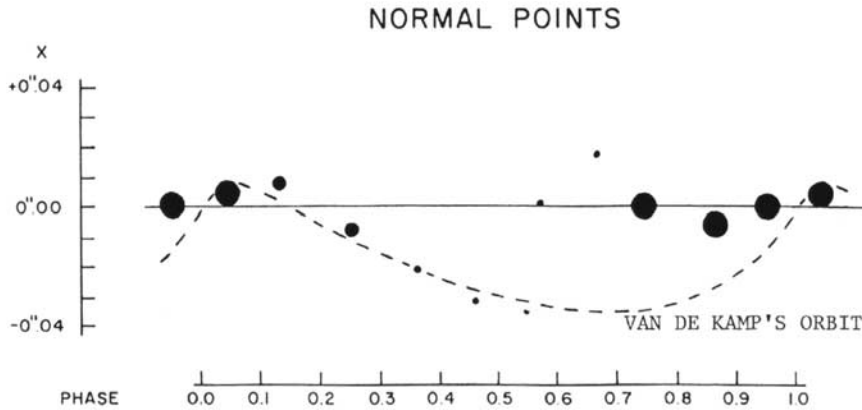


FIGURE 2. Refutation of a planetary companion to Barnard's Star, based on an independent data set and astrometric analysis (Gatewood & Eichhorn 1973). The size of the data points indicates their weight in the astrometric solution—smaller data points have larger errors. Only one astrometric axis (x) is shown.

nouncement (Figure 1). The semimajor axis of the planet was 4.4 AU, similar to Jupiter's 5.2 AU, and the fact that the orbit was considerably more eccentric than Jupiter's orbit did not raise too many questions about what had been found. Astronomers expected gas giant planets to exist elsewhere, and within a few years, Barnard's Star literally became the textbook example of another star with a planetary system.

On the advice of a senior professor at the University of Pittsburgh who must have doubted the existence of van de Kamp's planet, George Gatewood undertook a second study of Barnard's Star. Investigating an independent collection of photographic images of Barnard's Star, Gatewood used a new plate-measuring engine at the U.S. Naval Observatory to remove the human element from the plate-measuring process. Applying mathematical techniques derived by his thesis advisor, Heinrich Eichhorn, Gatewood analyzed 241 plates taken at the University of Pittsburgh's Allegheny Observatory and at the van Vleck Observatory in Connecticut. Surprisingly, their analysis was not able to confirm the existence of a planet orbiting Barnard's Star (Gatewood & Eichhorn 1973). Figure 2 shows that their data precluded the large amplitude wobble in van de Kamp's data.

The situation got much worse for van de Kamp's planet in the same year, when a colleague of his at the Sproul Observatory published an analysis of the astrometry of GL 793, another nearby red dwarf star. John Hershey had found that both GL 793 and Barnard's Star were wobbling about their proper motion across the sky in much the same way. When one star zigged, so did the other. When one star zagged, so did the other. This could only mean one thing: systematic errors in the Sproul refractor. In retrospect, the spurious zig-zags could be traced to several changes that had been made to the optical system, but evidently had not been completely corrected for in the error terms for the astrometric solutions: a new cast iron cell for the 24-inch lens and new photographic emulsions in 1949, and a lens adjustment in 1957.

After 1973, the strong evidence for Barnard's Star having a gas giant planet began to fade from view and from the textbooks. Astronomers have continued to monitor Barnard's Star for planetary-induced wobbles, as it remains an attractive target. Van de Kamp also continued to pursue Barnard's Star, convinced that some day a planet

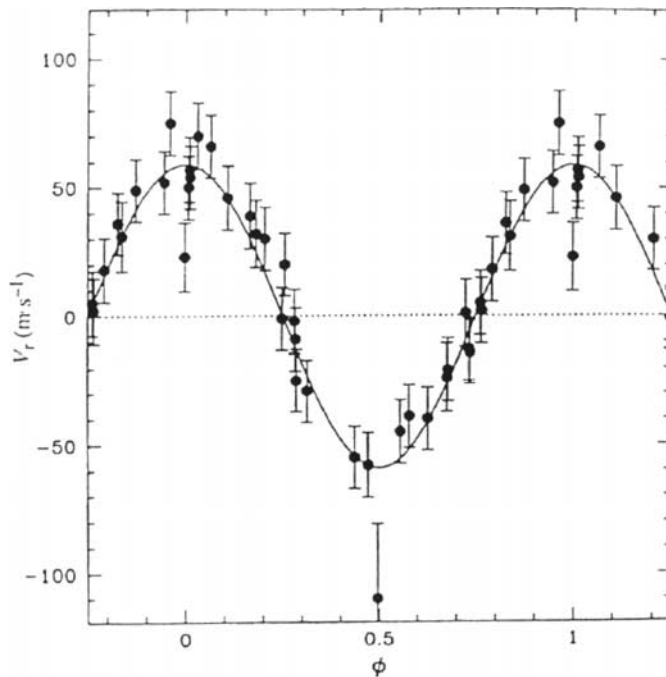


FIGURE 3. Discovery data for the first extrasolar planet around a main sequence star, 51 Pegasi (Mayor & Queloz 1995), detected by measuring the periodic Doppler velocity shift of 51 Pegasi induced by the planetary companion. The solid line shows the Doppler shift expected for a solar-mass star orbited by a 0.6 Jupiter-mass planet on a circular orbit with a semimajor axis of 0.05 AU.

would be found in its grasp. Van de Kamp died in 1995, just before the first reproducible evidence for an extrasolar giant planet was announced to the world.

2.2. 51 Pegasi

The existence of an extrasolar planet can be inferred indirectly, not only by measuring the two-dimensional, astrometric wobble in the plane of the sky, but also by searching for the one-dimensional oscillation of the star to-and-fro along the line-of-sight to the star by measuring the Doppler shift of the star's spectral lines. For a Jupiter-like planet orbiting a solar-type star, the Doppler shift has a semiamplitude of 13 m s^{-1} . Beginning in the late 1970s, a group at the University of British Columbia had pioneered a technique of using a cell of hydrogen fluoride gas in the optical path of the telescope as a source of stable reference lines, which could be used to measure tiny Doppler shifts in stellar spectra. By 1995, however, they had searched for over a decade and had found no unambiguous evidence for planets in the two dozen stars they had been following—their results appeared to place upper limits only on the masses of planets that might exist in orbit around their target stars (Walker et al. 1995). It looked like extrasolar Jupiters might not be very common, contrary to long-standing theoretical and philosophical expectations.

Shortly after the Walker et al. (1995) results appeared, a new claim for the detection of a gas giant planet was announced by a team composed of Michel Mayor and Didier Queloz of the Geneva Observatory. Duquennoy & Mayor (1991) had published the definitive catalog of binary stars in the solar neighborhood, including binaries found by several different methods, but primarily by searching for the Doppler spectroscopic wobble. As a result of this survey, Mayor had a list of roughly 200 nearby solar-type stars that

appeared to be single, though a number of them showed evidence for having a very low-mass companion. In 1994, a new spectrometer on the 2 m telescope at the Haute Provence Observatory with a spectral accuracy of $\sim 13 \text{ m s}^{-1}$ permitted Mayor to begin a serious spectroscopic search for extrasolar giant planets. By the summer of 1995, Mayor & Queloz had struck oil—the solar-type star 51 Pegasi appeared to be wobbling with an amplitude well above their measurement errors. Following a final, confirmatory observing run in September 1995, Mayor & Queloz (1995) announced their discovery of a ~ 0.6 Jupiter-mass planet on a *circular* orbit (Figure 3), as expected based on Jupiter’s low eccentricity ($e \sim 0.05$) orbit. While the mass and circular orbit of the planet seemed normal, its orbital period was far from the expectations for an extrasolar Jupiter: 4.23 days rather than 12 or so years. This meant that the planet was orbiting its star 100 times closer than Jupiter orbits the sun, at a distance of ~ 0.05 AU rather than out at 5.2 AU. At that distance from its star, 51 Pegasi’s planet would have an atmosphere that was thermally evaporating: it would be a “hot Jupiter.”

Was 51 Pegasi’s planet real or not? Following the announcement in October 1995, several other groups of astronomers ran to their telescopes to see if they could confirm this audacious claim—and they did. The first team to confirm the reality of 51 Pegasi’s planet was that of Geoff Marcy and Paul Butler, using the Shane reflector on Mount Hamilton (Marcy et al. 1997). Several other teams followed in their footsteps and also confirmed the detection of 51 Pegasi’s planet. Suddenly the idea of extrasolar planets around solar-type stars did not seem so preposterous anymore.

Marcy and Butler had begun their spectroscopic planet search in the late 1980s, using an iodine cell as a reference source for their spectrometer (since hydrogen fluoride is a deadly gas), and they were soon achieving accuracies of 10 m s^{-1} or better. Given their significant head start on the Swiss group, Marcy and Butler began a frantic effort to reduce their many years of data, allowing them to announce the discovery of two more planets in January, 1996—planets orbiting the solar-type stars 47 Ursae Majoris (Butler & Marcy 1996) and 70 Virginis (Marcy & Butler 1996). The field of extrasolar planets had truly been born. *Time Magazine* celebrated the event with a cover story breathlessly entitled, “Is Anybody Out There? How the discovery of two planets brings us closer to solving the most profound mystery in the cosmos.”

3. Present

In a field as fast moving as extrasolar planets, any attempt to summarize the current status is doomed to appear rather antique in a short period of time. Several major discoveries have been announced in the two months between the May 2005 Symposium at ST ScI and the writing of this summary (early July 2005), with more sure to follow once the Symposium proceedings go to press. With that caveat, the status of the field as of the time of the May 2005 Symposium can be summarized by the plot of discovery space shown in Figure 4. Here, the masses of extrasolar planets are shown as a function of the semimajor axes of their orbits. By May 2005, well over 130 planets had been discovered and submitted for publication in refereed journals. The International Astronomical Union’s Working Group on Extrasolar Planets maintains a list of extrasolar planets that meet the Group’s requirements for inclusion on their web site at <http://www.dtm.ciw.edu/boss/iauindex.html>. This web site also addresses the question of defining what is and what is not a “planet.”

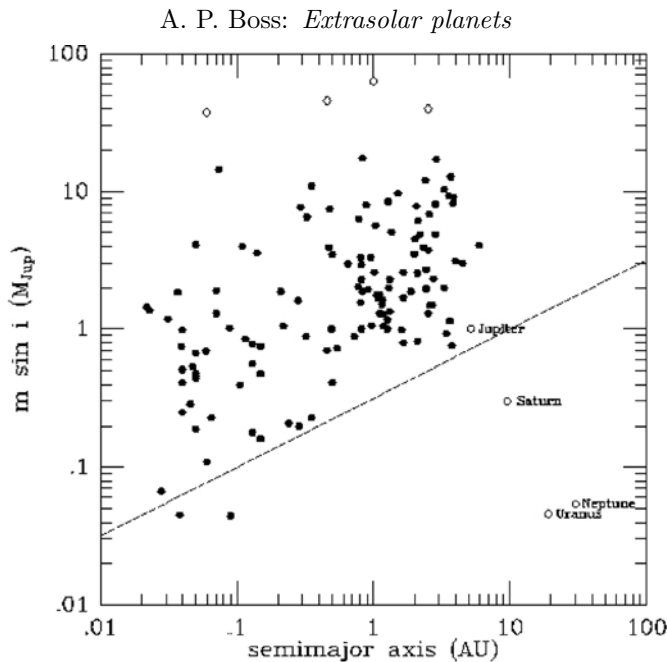


FIGURE 4. Extrasolar planet discovery space as of May 2005, showing primarily minimum masses of planets discovered by Doppler spectroscopy as a function of orbital semimajor axis. The oblique dashed line shows how the sensitivity limit of Doppler spectroscopy depends on semimajor axis for accuracies of $\sim 2\text{--}3 \text{ m s}^{-1}$ and a signal-to-noise ratio of ~ 4 —short-period, massive planets are the easiest to detect. Brown dwarfs (open symbols near the top of discovery space) are infrequent companions to solar-type stars.

3.1. Doppler Spectroscopy

Nearly all of the planets shown in Figure 4 were discovered by the Doppler spectroscopy method, which yields only a lower limit on the mass of the planet because of the unknown orientation of the planet's orbit with respect to the line-of-sight to the star. If the planetary orbit is being observed nearly pole-on, then the mass of the companion is larger by a factor of $1/\sin i$ (where i is the inclination of the planet's orbit; $i = 0$ for pole-on) than the minimum mass plotted in Figure 4. Assuming that planetary orbital planes are randomly distributed, the typical true planetary mass should be a factor of $4/\pi$ larger than the minimum mass, i.e., ~ 1.3 times higher.

Given the drive to find Solar System analogues and their spectroscopic suitability, most of the target stars in the ground-based spectroscopic planet searches have been late F, G, and K dwarfs, though these searches have also been extended to early M dwarfs. It is evident from Figure 4 that solar-type stars tend not to have brown dwarf companions, i.e., companions capable of burning deuterium (requiring a mass greater than ~ 13 Jupiter masses for solar composition), but not hydrogen (implying a mass less than ~ 75 Jupiter masses). This is consistent with the lack of binary companions with mass ratios much larger than 10:1 (Duquennoy & Mayor 1991)—solar-mass primaries generally do not have brown dwarf companions.

Figure 4 also makes it clear that such stars do typically have planetary-mass companions, though evidently the process that produces these objects does not always adhere to the IAU definition of a planet as being an object less massive than 13 Jupiter masses. Note that the absence of planets with semimajor axes greater than a few AU does not imply their nonexistence, but rather is a result of the need to follow a target star for an

entire planetary orbit before announcing a detection in order to minimize the risk of interpreting noisy data as a detection. The spectroscopic surveys are just now entering the phase of their programs where they have been monitoring stars with sufficient accuracy (a few m s^{-1}) long enough (a decade or so) to begin to detect long-period planets similar to Jupiter.

Figure 4 shows that the range of masses of extrasolar planets is considerably greater than in our Solar System: planets with masses ten times that of Jupiter exist, as well as masses smaller than that of Saturn. Recently, the attainment of Doppler spectroscopy precisions of $\sim 1 \text{ m s}^{-1}$ means that the lower mass limit has been extended down to Neptune masses by the discoveries of planets orbiting GJ 436 (Butler et al. 2004), Mu Arae (Santos et al. 2004), and ρ^1 Cancri (McArthur et al. 2004). These three might well represent the first examples of a new class of planets, i.e., they could be ice-giant planets, given the similarity of their masses to those of Uranus and Neptune, or they might be super-Earths, rocky planets with masses well above that of Earth and Venus. The former explanation seems to be inconsistent with the occurrence of several gas-giant planets on longer-period orbits in both the Mu Arae and ρ^1 Cancri systems, implying that the Neptune-mass planets formed inside the orbital radii of their gas giants, and then migrated inward. While this explanation seems most plausible, it will remain for a transit detection of a “hot Neptune” to measure one of these planets’ mean densities, and so determine whether it is composed primarily of rock or of rock and ice/water.

The orbital radii evident in Figure 4 cover a wide range—from the semimajor axes of 0.02 AU of the “hot Jupiters” out to 5.2 AU for the “cold Jupiters,” with a number of “warm Jupiters” orbiting in between. The close-in orbits of the hot and warm Jupiters imply significant post-formational inward orbital migration, given the difficulties in forming gas giants so close to their stars. Perhaps most surprisingly, many of the orbits are highly eccentric, making the low eccentricities of the major planets in our Solar System seem out of the ordinary, rather than the norm. The origin of these eccentricities has become another major theoretical puzzle—are they a result of the formation process or of the orbital-migration process?

It is notable that there have been no discoveries of extrasolar planets to date with the astrometric technique, though there have been two astrometric measurements of previously-known planets (for GJ 876 and ρ^1 Cancri) using the Fine Guidance Sensors of *HST* (McArthur et al. 2004).

3.2. *Transits*

The first planet seen to transit its host star was the hot Jupiter orbiting HD 209458, detected by Doppler spectroscopy (Charbonneau et al. 2000; Henry et al. 2000). Because of the short-period orbits of the hot Jupiters, orbiting at roughly 10 stellar radii, the chances of having the orbit of a hot Jupiter aligned so as to lead to a transit are roughly 10%. We had to wait for the tenth hot Jupiter to be discovered by spectroscopy before one of them was discovered to be a transiting planet—hopefully we will be luckier with the hot Neptunes.

HD 209458’s planets provided the first strong evidence that many, if not most, of the objects in Figure 4 are indeed gas-giant planets. A transit fixes the orbital inclination, and thus the mass of the planet, and the depth of the transit allows the radius of the planet to be determined as a fraction of its host star’s radius. HD 209458’s planet’s mass is $\approx 0.7 M_J$, and it has a radius and a density roughly equal to that expected for a hot Jupiter. In addition, sodium was detected in its atmosphere (Charbonneau et al. 2002), as predicted for a hot Jupiter (Seager & Sasselov 2000).

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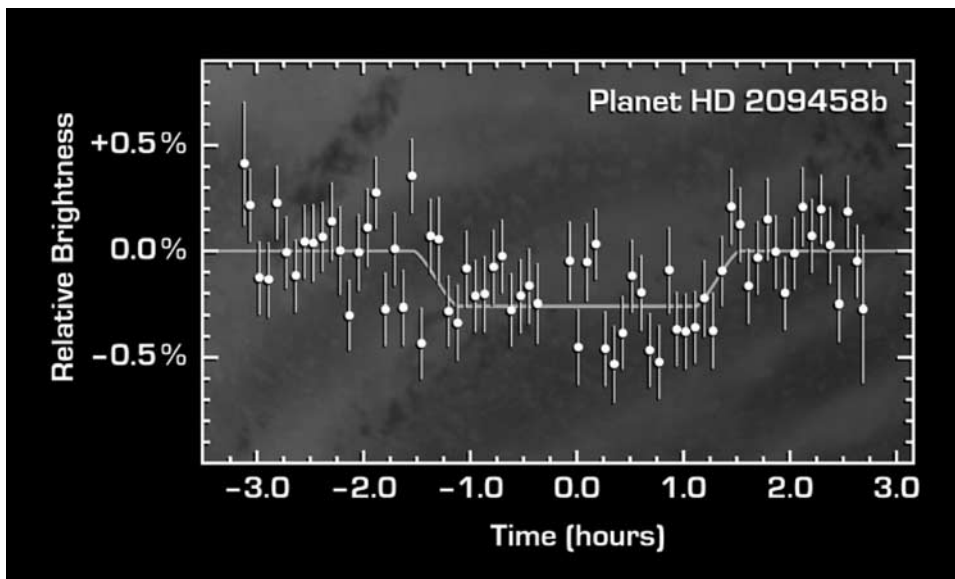
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FIGURE 5. *Spitzer Space Telescope (SST)* 24-micron photometry of the star-planet system HD 209458 during a secondary eclipse of the planet by the star, constituting the first direct detection of light from an extrasolar planet (Deming et al. 2005). A similar detection was accomplished for the TrES-1 system by Charbonneau et al. (2005) using *SST*.

While Doppler spectroscopy has been by far the leader at detecting new planets, the transit detection technique has now accounted for the discovery of six, all confirmed by follow-up Doppler spectroscopy. The first planet detected by transit photometry was a hot Jupiter orbiting a star toward the galactic bulge (Konacki et al. 2003), that had been observed to have photometric variations consistent with a transiting planet (Udalski et al. 2002). This planet is known by the name of the transiting event, OGLE-TR-56. The Optical Gravitational Lensing Experiment (OGLE) project (Udalski et al. 2002) at the Las Campanas Observatory in Chile has discovered a large number of possible planetary transits, and four more so far have turned out to be caused by planets, all as a side benefit of the OGLE project. A sixth transiting planet (TrES-1) has been found by a new ground-based transit search program, the Transatlantic Exoplanet Survey (Alonso et al. 2004). Because transit surveys preferentially find short-period planets, all of the planets found to date by transits are hot Jupiters, though they are mostly smaller and denser than HD 209458's planet (Sozzetti et al. 2004).

3.3. *Microlensing*

A third technique that has found a planet around a main-sequence star is microlensing, where the photometric variations caused by gravitational bending of background starlight by a foreground star can be enhanced for a period of a few days by a planet orbiting at the Einstein radius. The first microlensing detection was accomplished by Bond et al. (2004) associated with the microlensing event known as OGLE 2003-BLG-235/MOA 2003-BLG-53. [Clearly there is a need for more succinct names for some of these extrasolar planets.] The inferred planet has a mass of ~ 1.5 Jupiter masses and orbits at ~ 3 AU from the presumed main sequence host star.

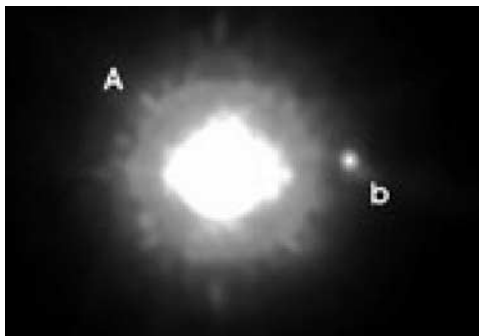


FIGURE 6. The apparent first spatially-resolved image of an extrasolar planet (b) orbiting ~ 100 AU from the young star GQ Lup (A). The image was obtained with the adaptive optics instrument NACO on the VLT by Neuhäuser et al. (2005).

3.4. Pulsar Timing

Astronomers have continued to search for more planetary-mass companions to pulsars by looking for minute variations in the pulsars' precise pulsation periods, as was used by Wolszczan & Frail (1992) to discover the pulsar PSR 1257+12 planetary system. However, searches of over 100 pulsars to date have yielded very little evidence for more planetary-mass companions, unlike main-sequence stars. The exception is the detection of a gas-giant planet-mass companion to a binary star system containing a white dwarf and the pulsar PSR B 1620-26 in the M4 globular cluster by Sigurdsson et al. (2003). Evidently gas-giant planets can form in regions quite different from the galactic disk, including extremely metal-poor environments such as an ancient globular cluster.

3.5. Direct Detections

The field of extrasolar planets took another enormous leap forward in 2005 with the announcement of several direct detections of extrasolar planets. The previous evidence for sodium in the atmosphere of HD 209458's planet (Charbonneau et al. 2002) was obtained by noting a depletion of the host star's light at the wavelengths of the sodium doublet lines during planetary transits, so formally speaking, this discovery did not detect photons from the planet itself, but rather the absence of stellar photons that had been absorbed in the upper atmosphere of the planet. All that changed in 2005, when the *Spitzer Space Telescope* (*SST*) enabled the first direct detection of the light from two transiting planets, HD 209458 (Figure 5; Deming et al. 2005) and TrES-1 (Charbonneau et al. 2005). Because the hot planet is relatively bright at mid-infrared wavelengths, when the planet disappears behind the star (the secondary eclipse) the total amount of mid-infrared light is observed to decrease by a measurable amount. When observed out of eclipse, then, the extra photons must be coming from the planet.

While pathbreaking, the *SST* direct detections of the HD 209458 and TrES-1 hot Jupiters were not direct detections in the sense of spatially resolving the light from the planet from that of the star. That honor appears to have been reserved for the detection of a multiple-Jupiter-mass planet in orbit around the T Tauri star GQ Lup. Neuhäuser et al. (2005) were able to obtain an image of GQ Lup's planet (Figure 6) by using the adaptive optics system on one of the Very Large Telescopes (VLT) in Chile. While the mass of the planet is uncertain, it could exceed the 13-Jupiter-mass upper bound for being a planet. The young age of this system (~ 1 Myr), when combined with recent models of the evolution of newly formed gas-giant planets, implies that this is indeed the first detection of a spatially-resolved extrasolar planet, though at a puzzlingly large

orbital separation of ~ 100 AU. This discovery has produced yet another challenge for the theorists: forming a gas-giant planet at such a large distance is likely to be difficult, implying that GQ Lup's planet may have been kicked outward to its present locale.

Prior to the discovery of GQ Lup's planetary candidate, another excellent discovery was made by the VLT. Chauvin et al. (2004) imaged a roughly 5-Jupiter-mass companion to the brown dwarf 2M1207. Because 2M1207 has a mass itself of only about 25 Jupiter masses, this system has a mass ratio of $\sim 5:1$, typical of binary star systems. The two components of the 2M1207 system thus seem most likely to have formed simultaneously during the collapse and fragmentation process that forms binary and multiple star systems. While the very low mass of the companion seems to place it in the planet category, the fact that it is in orbit around a brown dwarf argues against awarding this discovery the prize of the first spatially resolved, direct detection of a "planet." A number of planetary-mass objects had previously been imaged in regions of recent star formation, with masses as low as that of 2M1207's secondary, and these objects are believed to have been formed directly by the same star formation process that leads to main-sequence stars and brown dwarfs. Accordingly, such objects are perhaps better referred to as "sub-brown dwarfs."

4. Future

It is hard to think of an area of astronomy that has a more exciting or promising future than that of extrasolar planets. In ten years, a new field has been created—with ongoing, frequent, major discoveries—and the pace continues to quicken as more astronomers shift their research interests in this direction. While much has already been learned, so much more remains to be discovered that it boggles the mind. We have learned about some of the properties of a bit more than 100 planets out of the billions of planets that appear to exist in our galaxy alone. The variety of extrasolar planets discovered to date—and those remaining to be found—may approach the variations observed in stellar populations and galaxy types. Ground-based observatories plan to continue to lead the way forward. Both the U.S. National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have recognized the importance of this new field of endeavor, and have made far-reaching plans to build a series of ambitious space telescopes that will carry the search for extrasolar planets to its ultimate goal—Earth-like planets capable of originating and sustaining life.

4.1. *Ground*

Ground-based observatories bear the brunt of current extrasolar planet search activities, ranging from the Doppler spectroscopy programs of the Geneva Observatory, California/Carnegie, University of Texas, and other groups, to the several dozen transit and microlensing search programs underway around the world. The upgraded CCDs on the HIRES spectrograph on the Keck I telescope in Hawaii, the UVES spectrograph on the VLT, and the HARPS spectrometer on the 3.6 m ESO telescope at La Silla have allowed astronomers to push their Doppler precision to higher and higher levels, to the point where residual velocity jitters as small as $\sim 1 \text{ m s}^{-1}$ are now achievable, comparable to the convective velocity fluctuations in the photospheres of chromospherically quiet target stars. Maintaining these levels of Doppler precision for the next decade will allow the ground-based Doppler surveys to detect planets with masses similar to that of Saturn orbiting at 5 AU, and to detect planets with masses well below Neptune's mass on short period orbits—"hot Earths" could be found.