# Extrasolar Planet Update

*By Andrew J. LePage*

## The Floodgates Open!

With the first announcement of the discovery of an extrasolar planet circling a Sun-like star in October of 1995, the pace of discovery seems to be increasing at an exponential rate. Teams of astronomers all over the world have begun to analyze the data they have in hand as well as rush ahead with plans for new surveys for these illusive bodies. Since the article "The Discovery of Extrasolar Planets" in the Volume 2, Number 2 issue of *SETIQuest* went to press, several new discoveries have been announced and new information on previous planetary discoveries has become available. While it is still very early in the process and the number of suspected new substellar companions is limited, it is beginning to appear that these new objects fall into four broad categories: Bellerophons or epistellar planets, eccentric planets, Jovian planets, and brown dwarfs. The first two of these classes of substellar companions were not previously predicted by theory and hint at the diversity of the solar systems that exist in our galaxy.

## The "Bellerophons"

This first class of extrasolar giant planet (EGP) has been variously referred to as "hot Jupiters" or "epistellar planets" among others in the press and on the Net. Until a commonly used name comes into wide usage, in this article these EGPs are provisionally named after the appellation suggested by Marcy and Butler for 51 Pegasi B (1). Bellerophons are Jovian-mass planets in tidally evolved, close circular orbits with periods measured in days. This class of object has yielded the most discoveries to date due to the fact they are the most easily and quickly detected using precision Doppler velocity measurement techniques.

The archetype of this class is the companion of 51 Pegasi discovered in 1995 by Michel Mayor and Dider Queloz of the Geneva Observatory (2). This planet has an orbital period of 4.2 days and a $M_{\sin i}$ of 0.45 M♃. Unfortunately Doppler detection techniques alone are unable to determine the inclination of the planet's orbit with respect to our line of sight. As a result, we currently do not have a definitive mass for this EGP. While the actual mass is likely around 0.6 M♃, other methods are required to help obtain a definitive mass and firmly establish the substellar nature of 51 Pegasi B.

Theoretical models of the tidal evolution of the orbit of 51 Pegasi B suggest that it is likely below the 80 M♃ boundary dividing self-luminous red dwarfs from their nonstellar EGP cousins (47). A large companion orbiting a star produces a tidal bulge on that star. If the companion's orbital period is shorter than its sun's period of rotation, this bulge will lag behind the orbiting body and act as a brake. The larger the body and the smaller its orbit, the more quickly it will slow and spiral in towards a destructive encounter with its sun. A small star in the orbit of 51 Pegasi B would stay in orbit for less than the main sequence lifetime of a solar-type star. If 51 Pegasi B were of Jovian proportions, its orbit would still decay but its life would exceed ten billion years and outlast its sun.

Other indirect means have yielded still lower mass limits for 51 Pegasi B. It is generally assumed that the plane of a solar system's orbits lies approximately in the equatorial plane of its sun. Recent measurements of the line of sight component of the rotational velocity of 51 Pegasi A indicate that it is 2.3 to 2.5 kilometers per second (3). This suggests that 51 Pegasi B is not only sub-stellar but also marginally smaller than Jupiter with a mass between 0.45 and 0.70 M♃. Independent measurements of the spectral line shapes by Artie Hatzes and his colleagues at the McDonald Observatory give a similar value of 2.35 kilometers per second for the projected rotational velocity of this star (4). Their measurements also show that low-order nonradial pulsations in 51 Pegasi A cannot be responsible for the observed radial velocity measurements thus adding additional weight to the EGP interpretation for the observations to date. Future measurements of various types should help refine the mass estimate for 51 Pegasi B further.

After it was discovered, some astronomers felt that 51 Pegasi B was a rare freak of nature. But it did not remain alone in this class for long. Early in 1996, Geoff Marcy and Paul Butler began to process the data from the second half of their radial velocity survey of 120 nearby, predominantly sun-like stars. The first 60 stars in their survey netted two EGPs and it was likely that a couple more substellar companions remained to be discovered in the balance of their data.

On April 11, 1996, while lecturing at the University of Maryland, Butler announced the discovery of a near twin of 51 Pegasi B orbiting the star $\rho^1$ Cancri (5). This star is a G8V type about 44 light years away with a luminosity of about 0.66 $L_{\odot}$ (6). This star is also accompanied by a small M4 red dwarf called Giclas 47-9 which is at least 1,100 AU away from its primary. The new planet was detected using Doppler shift measurements that indicated a radial velocity modulation with a magnitude of 72 meters per second and a period of 14.76 days. The likely mass of this new discovery is about 1 M♃ and it orbits only 0.11 AU from its sun.

The new planet found orbiting $\rho^1$ Cancri is likely to be similar to 51 Pegasi B in appearance and its properties. It probably has a Jovian-like atmosphere dominated by hydrogen and helium with a temperature of about 700 K (7). Because of its slightly cooler temperature and greater mass, $\rho^1$ Cancri B probably has a radius slightly smaller than 51 Pegasi B but still a respectable 1.2 R♃. This planet is close enough to its sun to have its rotation tidally synchronized with its orbital period over the course of about a billion years. So, like 51 Pegasi B, $\rho^1$ Cancri B would have its day equal to its year of 14.76 Earth days.

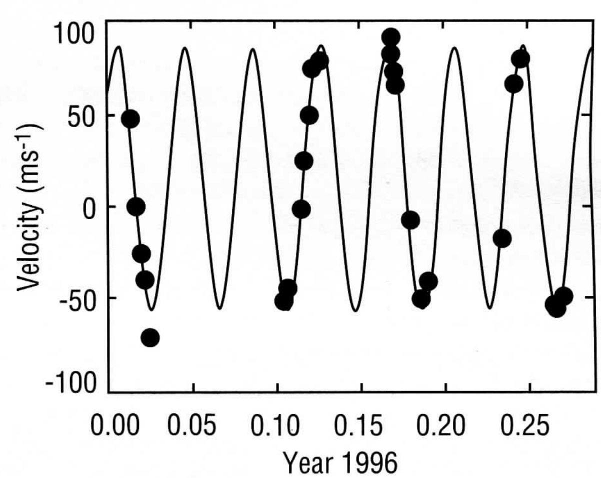


**Figure 1:** *This plot shows how the radial velocity of $\rho^1$ Cancri varied during the first quarter of 1996 under the influence of its newly discovered Bellerophon-class companion. (Courtesy of Marcy and Butler)*

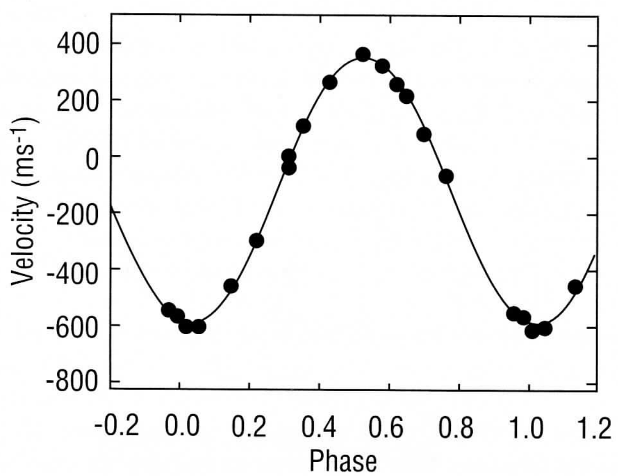


**Figure 2:** *In this graph we see how the radial velocity of τ Bootis changes over the course of one orbit of its newly confirmed companion's orbit. The RMS of the residuals from the fitted orbit amounts to 14.5 meters per second. (Courtesy of Marcy and Butler)*

In June of 1996, Marcy announced at the Workshop on Planetary Formation in the Binary Environment that he and his team had found indications of yet another EGP in this system. After the effects of the Bellerophon-class EGP are taken into account, residual velocity variations hint at the presence of a 5 $M_{♃}$ EGP in a 15 to 20 year orbit (8). Circling between 6 and 8 AU from its primary, it is where previous theories of planet formation had placed worlds of this sort. At least another decade's worth of radial velocity data in combination with astrometric measurements with milliarc second accuracy will be required before a definitive orbit and mass could be derived. With this arrangement of planets and stars, the sun-like primary could still have habitable planets in stable orbits. Assuming that the formation of a Bellerophon-class EGP does not destroy terrestrial planets in the inner solar system, the $\rho^1$ Cancri system has a SETI rating of about 0.48 (9, 10).

At the same workshop in Stony Brook, New York, Marcy announced the "discovery" of yet another Bellerophon-class planet. In reality it was a confirmation of a suspected companion discovered in 1991 by Antonie Duquennoy and his colleague Michel Mayor. As part of their systematic search for radial velocity standards using the CORAVEL spectrometer, Duquennoy and Mayor made 33 measurements of the sun-like star in the τ Bootis binary system. Taken over 15 years, the data showed a radial velocity variation with a period of 3.312 days (11). Marcy and Butler's more precise observations of τ Bootis A made over 1.3 years showed a radial velocity variation of the same period with an amplitude of 468 meters per second. While the exact nature of this companion is not known due to the uncertainties in the orientation of the orbit, an EGP with a $M_{\sin i}$ of 3.87 $M_{♃}$ and a probable mass of 5 $M_{♃}$ is the likely culprit.

The primary star of this system, τ Bootis A, is a spectral type F7V with a luminosity of about 5 $L_{\odot}$ (6) and is some 62 light-years from our solar system (12). Because this new EGP is only 0.046 AU from its much brighter sun, its conditions are even more extreme than those previously seen in this class. This planet's surface temperature likely exceeds 1,700 K and its radius is probably about 1.2 $R_{♃}$ (7). Like the other members of this class, τ Bootis C would have its rotation tidally locked in less than 10 million years yielding a period of rotation equal to its year.

Mayor and his colleagues have calculated that the primary's period of rotation is equal to about 3.9 days, which is almost exactly the orbital period of the new companion (13). These two bodies may be the first example of a planet and its sun with synchronous rotations and orbits. The chances that some sort of rotational effect in the primary is mimicking the radial velocity signature of an EGP is unlikely given that the star is photometrically stable to the millimagnitude level (14) and that the velocity modulation has kept its phase over the past score of years (13). This apparent rotational synchronization could also indicate that the EGP is actually of marginally stellar proportions but there is only a 0.1% chance of this being the case given a random orbit orientation. As with the other members of this class of EGP, direct imaging of this component or astrometric measurements of the wobble it induces in its primary will be needed to derive a definitive mass.

In addition to the sun-like primary and its close EGP companion, this system also contains a distant M2 red dwarf with a luminosity of 0.08 $L_{\odot}$ (6). It is in a lazy centuries-long orbit that at the present time places the dim companion no closer than about 100 AU from its primary. With the presently known arrangement of this system, potentially habitable planets could have stable orbits around the sun-like primary. Because of this and its relative closeness, the τ Bootis system has a SETI rating of 0.72 and it ranks among the 50 best potential SETI targets (9, 10).

Finally, on June 23, at the annual meeting of the Astronomical Society of the Pacific, Marcy announced the discovery of still another Bellerophon-class planet circling υ Andromedae (48). Their measurements show a radial velocity modulation with a period of 4.61 days and an amplitude of 75 meters per second (49). This would be caused by a planet with a semimajor axis of 0.054 AU and a $M_{\sin i}$ of 0.6 $M_{♃}$. This EGP would have a probable mass of 0.8 $M_{♃}$, a radius around 1.2 $R_{♃}$, and a surface temperature of about 1,600 K (7). It is a virtual twin of 51 Pegasi B.

The star υ Andromedae is a spectral type F8V with a luminosity of 5 $L_{\odot}$ and a distance of 53 light years from our solar system (6). There are some citations in professional literature indicating that this star also has an additional spectroscopic component of stellar proportions in an orbit with a period of 197.7 days (50). If true, this could have profound consequences on the theory that this class of planet originally formed much further out and migrated in towards its present position. The configuration of this system will have to be better determined before its prospects as a SETI target can be properly ascertained.

## The Eccentric Planets

Two EGPs have been discovered to date that Marcy and Butler have designated "eccentric planets" (15). This class of EGP is defined as a body with a mass between 5 and 15 $M_{♃}$. While the lower limit is somewhat arbitrary, the upper limit is near the minimum mass needed for a brown dwarf to briefly fuse its limited stores of deuterium during its formative phases. This class of EGP also have orbital eccentricities of 0.2 or greater and the examples found to date possess orbital radii of only a fraction of an AU. Unlike the Bellerophons, the eccentric planets are distant enough to escape significant tidal interactions with their primary that would circularize their orbits or lock their rotation rates.

The first EGP in this class was discovered circling HD114761 by David Latham and his colleagues in 1989 (16). Later observations by William Cochran and his team at the McDonald Observatory

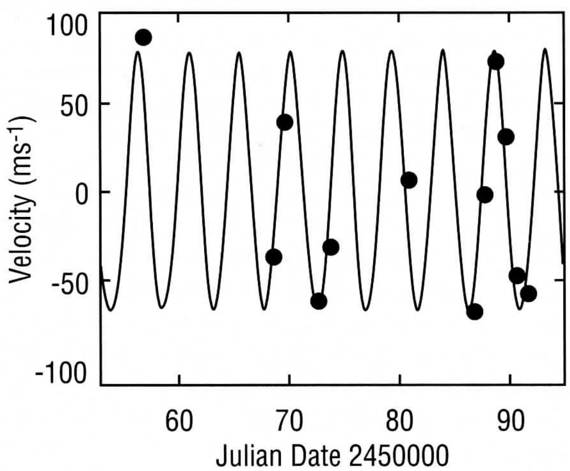


**Figure 3:** *This is a plot showing the radial velocity variations of υ Andromedae from late December 1995 to early January 1996 caused by its newly discovered companion. The small vertical lines indicate the uncertainty in each measurement. (Courtesy of Marcy and Butler)*

published in 1991 confirmed and refined the original Doppler velocity measurements (17). However there were indications that this system was being viewed nearly pole-on and therefore the calculated mass of the companion was dangerously close to the 80 M♃ upper mass limit for brown dwarfs. Recent reviews of the data used to constrain the orientation of this system have put this pessimistic interpretation in doubt (15). With the discovery of a similar body orbiting 70 Virginis, it seems likely that the companion of HD114762 is substellar and a member of a new class of EGP.

As part of his research for his masters thesis, Eric Williams of San Francisco State University worked on Marcy and Butler's team to obtain new data on HD114762. The results from William's Doppler velocity measurements released in March of 1996 confirmed the earlier findings that HD114762 displayed a 618 meter per second radial velocity modulation with a period of 84.02 days. An EGP with a $M_{sin}i$ of 10 M♃ and a probable mass of 13 M♃ is needed to produce such a variation. The non-sinusoidal nature of the radial velocity curve indicates that its orbit is oval with an eccentricity of 0.33 (18). Much uncertainty still exists in the physical parameters of this system making it difficult to determine if it could possess habitable terrestrial planets. Assuming that it proves to be possible, this system has a relatively low SETI rating of no more than about 0.1 mainly due to its distance (9, 10).

The discovery of a second member of this new class of EGP in the 70 Virginis system was announced by Marcy and Butler in January of 1996 (15). The one major dispute surrounding 70 Virginis that seems to have been finally settled is its distance from our solar system. Previously published estimates of the distance ranged over a factor of almost three making it difficult to pin down this star's basic properties. Recently released analysis of the astrometric measurements made by the European Space Agency's Hipparcos satellite have finally settled the issue and show that 70 Virginis is 59 light-years from us (19). These same measurements were unable to detect the wobble caused by the EGP but when combined with the available radial velocity measurements, they do place an upper mass limit on 70 Virginis B of 38-65 M♃ thus confirming its substellar status.

This definitive distance measurement has allowed the true nature of the 70 Virginis system to be determined. The type G4V (20) central star has a luminosity of about 2.9 $L_\odot$ (6) and a radius of about 1.9 $R_\odot$ (21). The star is about 9 billion years old and there are indications that it is beginning to leave the main sequence (22). Based on this information and a new mass estimate for the primary, the $M_{sin}i$ for 70 Virginis B is now estimated to be 7.4 M♃ with a probable mass of over 9 M♃ (23). This new mass would place the EGP in an orbit with a semimajor of 0.47 AU. Receiving over a dozen times the sunlight the Earth does, it is impossible for this EGP or any large moons that may be present to support life as we know it.

With the Habitable Zone (HZ) currently ranging from about 1.6 to possibly as far as 2.9 AU (24), there could be terrestrial planets in stable orbits in this system despite the presence of 70 Virginis B (25). But if 70 Virginis A is leaving the main sequence, its HZ would have originally been much closer so that only the inner part of the current HZ would have been continuously habitable over most of the life of the system. Optimistically the SETI Rating for the 70 Virginis system would be no more than about 0.3 given what is currently known about the system (9, 10).

At this time there is much disagreement whether "eccentric planets" are really a new class of planet with a unique style of formation or if they represent the low mass end of the star formation process and should therefore be considered brown dwarfs. At the Fifth International Conference on Bioastronomy, Mayor announced the discovery of six bodies in eccentric orbits with masses in the range of 16 to 40 M♃ that he classifies as brown dwarfs (51). Additional observations and theoretical work will be required to determine the dividing line between planets and brown dwarfs and whether there are other methods of producing "eccentric planets" such as the merger of closely spaced gas giants (52), large protoplanets feeding off streamers in the protoplanetary disk (53) or some other unknown process.

## The "Jovian" Planets

This class of EGP is typified by the planets Jupiter and Saturn in our own solar system. They are the Jupiter-size worlds in distant, nearly circular orbits that previous theoretical work on planet formation had predicted would commonly exist in other solar systems. Unlike the previous classes of EGP, these objects require a decade or more of observations to detect and determine their orbits. The 5 M♃ EGP suspected to be in the $\rho^1$ Cancri discussed earlier is a likely addition to this class. The first firm discovery in this class outside our solar system was 47 Ursae Majoris B with a probable mass estimated to be about 3 M♃ (26). Recently released analysis of Hipparcos astrometric measurements failed to detect any wobble in the motion of the primary star of this system placing an upper mass limit of 7 to 22 M♃ on this EGP thus confirming its nonstellar nature (19).

The discovery of at least one and possibly two or more new Jovian-class planets was announced on June 11, 1996, at the 188th meeting of the American Astronomical Society held in Madison, Wisconsin. George Gatewood of the University of Pittsburgh presented the results of a long-term astrometric program on the nearby star known as Lalande 21185 (27). Using 8.5 years worth of data obtained using the Multichannel Astrometric Photometer (MAP) on the Thaw Refractor at the Allegheny Observatory, Gatewood detected a 2.2 milliarc second wobble with a period of 5.8 years. This wobble is consistent with the presence of an EGP with a mass of 0.9 M♃ and an orbital distance of about 2.4 AU. Such a body

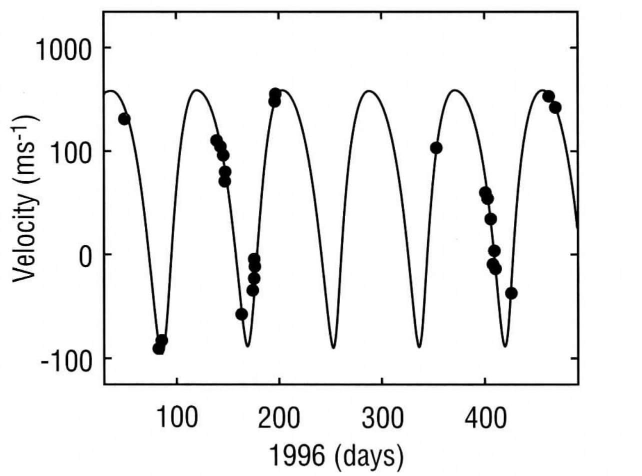


**Figure 4:** *This plot shows the improved radial velocity data gathered during 1995 and early 1996 by Eric Williams that confirmed the existence of a companion orbiting HD 114762. The RMS of the deviation from the fitted eccentric orbit is 19 meters per second. (Courtesy of Williams)*

would be a near-twin of Jupiter in our solar system.

This was not the first announcement of a planetary discovery in this system. Lalande 21185 is a M2V red dwarf with a luminosity of only 0.025 $L_\odot$ (6) located 8.25 light years from our system (28). Being so close to us and having a mass of about 0.4 $M_\odot$, it is one of the best candidates for the detection of an EGP using astrometry and has been diligently observed by several observatories for over two thirds of a century. Over the years there have been several EGP discovery claims in this system' the best known of which was made by Peter van de Kamp and Sarah Lippincott of the Sproul Observatory (29). Their measurements indicated the possible presence of a 10 $M_♃$ EGP with a period of 8 years. Subsequent reanalysis of their data (30) and independent work by other astronomers, including Gatewood (28, 31), failed to support the claim.

While this new discovery remains to be confirmed, it seems to be on a much firmer footing than the previous claims for this system. In addition to the 0.9 $M_♃$ EGP, there are indications of additional, more distant planets in this system (27). Using photographic astrometric data taken at the Allegheny Observatory starting in 1930 in combination with the newer high accuracy MAP measurements, Gatewood found indications of another EGP with a mass of about 1.5 $M_♃$ in an orbit with a period of about 30 years yielding a semimajor axis of around 7 AU. There is evidence of additional perturbations in the motion of Lalande 21185 hinting at the possible existence of still more distant EGPs (27, 32).

Lalande 21185 also happens to be on the Marcy and Butler survey list and almost a decade's worth of radial velocity measurements are available. With an apparent orbit inclination of 30 degrees, each EGP found by Gatewood should produce a radial velocity modulation of about 13 meters per second with a period equal to their respective orbital periods (33). Unfortunately this is near the detection limit for the 7.5 V magnitude star and the Bay Area Astronomers so far have inconclusive evidence for the existence of these new bodies (32). Additional, more sensitive radial velocity measurements and independent astrometric observations will be required to confirm the orbits of these new EGPs. Gatewood is also planning on using an improved version of MAP on one of the twin 10-meter Keck Telescopes to obtain even more accurate astrometry of this and other systems to help resolve the issue (34). With angular separations at maximum elongation of 0.9 and 2.8 arc seconds and visual magnitudes of about 27 to 30, these planets are good candidates for detection by new direct imaging techniques that could confirm their existence more quickly.

## Latest information on Gliese 229B

While technically not a planet, new information on the brown dwarf Gliese 229B not only supports the substellar nature of this dim companion but also potentially gives additional insight into the natures of its less massive EGP cousins. New measurements made by the Mount Palomar Observatory team that discovered this body as well as a new look at their original data has let them estimate the bolometric luminosity of this body to be around $6.4 \times 10^{-6}$ $L_\odot$ and its temperature to be about 900 K (35). While the mass of this object has yet to be determined directly, two independent teams of scientists using the latest data on Gliese 229B have developed models that have allowed them to estimate its mass to be somewhere between 30 and 50 $M_♃$ (36, 37).

New models and data on Gliese 229B also lead astronomers to believe that it does not have a global, homogeneous cloud deck (38). If it does have any clouds, their distribution would be patchy at best and spectra indicate that we can observe deep into its atmosphere where temperatures can reach at least 1,640 K (35). Models predict that if clouds do form they would likely be composed of refractory compounds such as sulfides of zinc, potassium, sodium and manganese as well as ammonium hydrogen orthophosphate (37). It is likely that the torrid atmospheres of the Bellerophon-class EGPs possess clouds of similar composition.

By far the most interesting new data on this brown dwarf is its spectrum. T.R. Gabelle and his team in Hawaii used the United Kingdom Infrared Telescope located on Mount Hilo to obtain a medium resolution spectrum in the 1.0 to 2.5 micron region of the infrared band (39). In addition to the methane detected by earlier, lower resolution spectra (40), unmistakable absorption bands attributable to high temperature water vapor were detected. Other as yet unidentified absorption features were also seen. The rich spectrum of Gliese 229B is more reminiscent of the organic chemical-laden atmosphere of the Saturnian moon Titan than the Jovian planets in our solar system. This hints that the chemistry taking place in the atmospheres of EGPs is potentially more dynamic than what we see in our solar system.

## More Discoveries to Come

The new discoveries and data discussed so far are only the beginning of a veritable torrent that is currently rushing through the astronomical lines of communication. Almost monthly there seems to be news of additional discoveries. At the time of this writing, Mayor and his team have plans to announce the discovery of another Bellerophon-class planet (51). They are continuing their radial velocity survey of 142 sun-like stars which promises to make more discoveries in the future as well as give an opportunity to independently confirm the radial velocity measurements of 70 Virginis and 47 Ursae Majoris. They will also soon be moving to a dedicated telescope at the European Southern Observatory which could allow them to expand their survey (55).

Marcy and Butler are continuing their survey of 120 nearby stars to refine their present findings as well as detect more distant (and likely more numerous) EGP companions that may inhabit other systems. In the first pass through their data, they could confidently detect EGPs with the mass of Jupiter within 2 AU of their sun. They are currently in the process of developing improved data reduction algorithms that should lower this threshold further, making it possible to find still more planets in the data taken to date (41). Marcy and Butler doubt they will be making any more discovery announcements for the rest of 1996 and they believe that the rate of announcements will decrease to just a few per year (54). Starting in 1997, the Lick Observatory team will begin a more sensitive survey of an additional 300 stars using the Keck Telescope on top of Mauna Kea in Hawaii (42, 55). It is quite likely that at least another dozen or so EGPs will be discovered before the end of the century by this expanded effort.

While the European and San Francisco-based teams have been responsible for most of the EGP discoveries made to date using Doppler velocity measurement techniques, other groups are also busy doing the same. An international collaboration of astronomers is using the 1.4 meter Auxiliary Telescope (CAT) at the European Southern Observatory (ESO) for an independent search in the southern sky known as the ESO Planet Search (ESOPS) (43). Their survey consists of 26 nearby sun-like stars and early analysis of their data indicates the presence of EGPs in Jovian-class orbits around three of them. While none of these suspected companions have been observed through an entire orbit, the measurements hint at an EGP circling κ Fornacis with a mass of at least 30 $M_{♃}$ with a period of about four years, one with a minimum mass of 20 $M_{♃}$ circling HR 3677 in a similar size orbit, and another with a minimum mass of 14 $M_{♃}$ circling HR 2400 with a period in excess of four years. Another two to four years of data will be needed before reliable orbits and masses can be determined that will allow these possible new companions to be categorized.

Nor are discoveries limited to the indirect means of radial velocity measurements and astrometry. An international network of astronomers at observatories scattered around the world have been monitoring the brightness of the small eclipsing binary known as CM Draconis as part of the Transits of Extrasolar Planets (TEPS) program. The reasoning behind this campaign is that any planets in this system will likely be orbiting in the same plane as the pair of M5V stars that periodically eclipse each other during their 1.268 day orbital period. As a result, as any planet in this system transits the pair, an easily observed decrease in the system's brightness would result. Planets as small as 2.6 times the radius of the Earth could be detected in this way (44).

A Villanova University team using the Four College Consortium 0.8 meter APT noted a 80 milli-magnitude drop in the brightness of this system on June 1, 1996, indicating the possible presence of a planet with a size of 0.85 $R_{♃}$ (45). Photometric observations with the IAC80 telescope at the Teide Observatory made on May 27, 1994, showed a similar dip in brightness (46). While it is premature to label these observations as a true discovery, it may indicate the presence of an EGP in a 735 day orbit. Additional observations of this system will be required to determine the presence of this or any other planet in this system.

The findings discussed here are just a small sample of all the extrasolar planet search programs currently taking place. With additional programs waiting to come on line, the rate of extrasolar planet discoveries is sure to increase allowing astronomers additional insights into the planet formation process and the prospects of finding suitable terrestrial planets.

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33) At the time of this writing, it has been frequently and misleadingly stated in the press and on the Net that the $V_{sin}\, i$ for the Lalande 21185 B alone would be about 28 meters/second. The correct value given here is calculated as follows:

$$V_{sin} i = (2\pi G/P)^{(1/3)} (m_{p\ sin} i)/(M+m_p)^{(2/3)}$$

where $V_{sin} i$ is in meters per second, G is the gravitational constant, P is the orbital period, M is the mass of the primary and $m_p$ is the mass of the planet. Taking $G = 6.67X10^{-11}$ newtons-meter$^2$/kg$^2$, P = 5.8 years = $1.8X10^8$ seconds, $m_p = 0.9\ M_{♃} = 1.7X10^{27}$ kilograms, $M = 0.4\ M_{\odot} = 8.0X10^{29}$ kilograms, and $_{sin} i = \sin(30°) = 0.5$, then $V_{sin} i = 13$ meters/second. For Lalande 21185 C with P = 30 years = $9X10^8$ seconds and $m_p = 1.5\ M_{♃} = 3X10^{27}$ kilograms, $V_{sin} i = 13$ meters per second also. Over the course of about three decades (about three times longer than the period of time Marcy and Butler have been observing Lalande 21185), the combined $V_{sin} i$ for both planets would have a *maximum* value of about that commonly quoted.

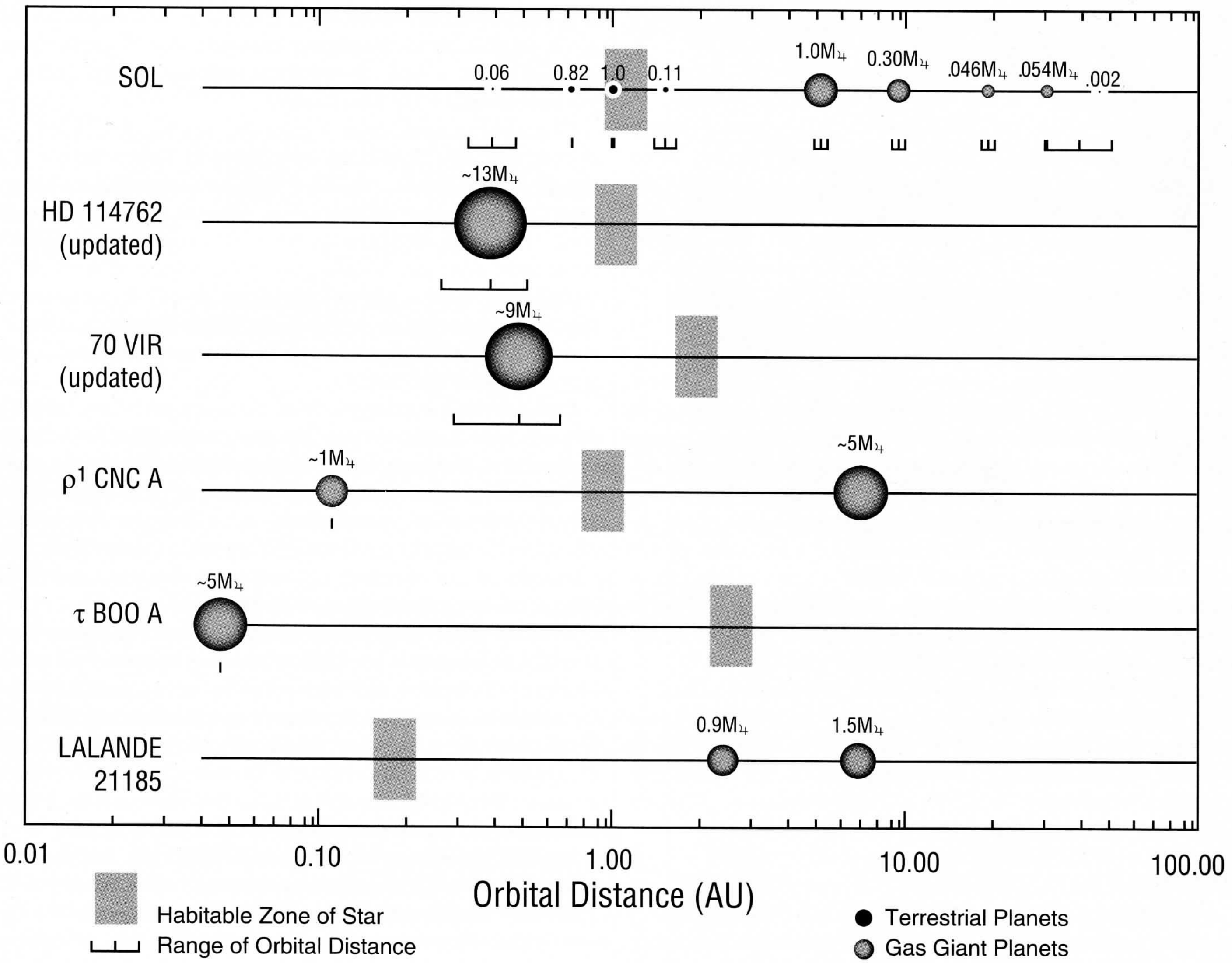


**Figure 5:** *This diagram shows the three newly discovered solar systems and improved parameters for two previously announced discoveries compared to our solar system. Gas giants, like Jupiter, are represented by gradient circles while terrestrial planets, like the Earth, are shown as filled circles. The size of each symbol is proportional to the cube root of the planet's mass. The actual mass values are given above each planet symbol. Typically, terrestrial planet masses are given in units of Earth masses while gas giants are given in Jupiter masses or M♃. The small line with three tick marks under each planet gives the range of it orbital distance due to its eccentricity. This symbol is excluded if the orbital eccentricity is unknown. Finally, the gray region in each solar system indicates the extent of that system's Habitable Zone (HZ). Any terrestrial planet or large satellite in this zone is potentially habitable. (Chart courtesy of the author)*

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