Insights Gained From Extrasolar Planetary Systems

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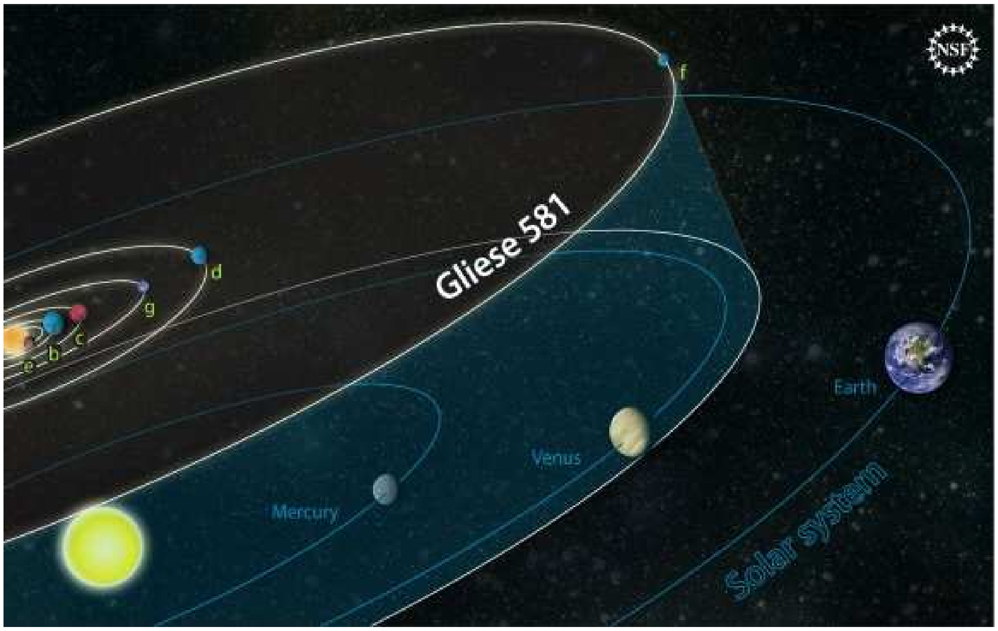


A comparison of the Gliese 581 system with the inner solar system Image 1
Zina Deretsky, NSF

Introduction

It could be said that the seeking out of extrasolar planetary systems and all of their oddities and similarities to our own solar system, all the planetary surveys being undertaken, all of the new instruments and techniques being developed to detect even lower radial velocities (Vr) of stars that we suspect of hosting orbiting planets, all of this is being done to answer one simple question that has been on the minds of humans since we first looked up into the starry sky: Are we alone? It can be argued that this is the most important basic question in all of science, even in all of philosophy. If examined in detail, one finds that there are several important basic questions here: are there other planets that can support life? Are there other planets that support simple microbial life? And finally, are there other planets that harbor intelligent life? As exciting and thought provoking as these questions are, they are not the prime focus of this paper. They are the ultimate big questions that astronomers as people are striving to answer. However, in order to get to the answers of these profound questions there are some intermediate milestones that we must meet first.

This paper will explore what we have learned about extrasolar planetary systems in general; how they are similar to and different from our own solar system, and what has surprised us and made us take a closer look at what we thought we knew about planets. When one considers that it has only been eighteen years since the first extrasolar planet was discovered, and only fifteen since the first extrasolar planet orbiting a sun-like star was discovered, we have learned a tremendous amount about planets and how they form in a very short period of time. (Schneider 2010) But, what have we learned in those fifteen years and how does that helps us to answer those big questions posed above?

From the very start, the discovery of extrasolar planets has been upsetting--upsetting to the formerly held theories of how and where planets formed. In 1991, Penn State professor of Astronomy and Astrophysics, Alexander Wolszczan, using the Arecibo radio telescope, discovered the first planets known to exist outside of our solar system when he found three planets orbiting the pulsar PSR +1257+12 in the constellation Virgo. (Web 4) Wolszczan found three small planets orbiting a rapidly rotating neutron star over 300 pc from the Sun. Two of these planets had masses similar to that of the Earth, while the third had a smaller mass similar to that of the Moon. When the discovery was announced, the world greeted the news with disbelief. To find Planets orbiting a neutron star was totally unexpected. But, it taught those seeking extrasolar planets that nature held the right to make the rules regarding where planets could possibly be. And, it set the stage for future discoveries and urged astronomers to expect the unexpected.

Since the distance between stars is so great and the light of a parent star is so overwhelmingly bright compared to any orbiting planets, extrasolar planets cannot be seen directly. At optical wavelengths stars are typically 10^9 times brighter than even the largest orbiting planets. (Beatty, et al. 1999) And, until recently, they were not able to be seen or imaged directly. At infrared wavelengths, the situation is improved somewhat, but even at infrared wavelengths, stars typically far outshine their orbiting planets. In fact, it wasn't until 2005 when an extrasolar planet was actually imaged. And, this was done in the infrared and done with the one of the largest telescopes in the world and using a Hubble Space Telescope (HST) image to help confirm the planet itself. (Web 5) Since 2005, there has been progress in obtaining optical images of several extrasolar planets, but it requires the largest and most sophisticated instruments astronomers have at their disposal. As a result, special methods have been developed to detect faint and distant extrasolar planets. Currently there are six methods that have detected extrasolar planets: the Radial Velocity method (V_r), the Planetary Transit method, the Timing method, the Direct Imaging method, the gravitational microlensing method, and the astrometry method. Out of the six methods listed above, two have proven to be the most reliable and repeatable and have so far, captured the majority of the discovered extrasolar planets. The Radial Velocity and the Planetary Transit methods will be briefly described below.

At the end of November 2010, as this paper is being written, 504 extrasolar planets have been discovered in 422 planetary systems, with 52 of those systems containing more than one planet. Of the 52 multiple planet systems, thirty-four have been found to contain two (2) planets, thirteen systems have been found to contain three (3) planets, three systems have been found to contain four (4) planets, one system has been found to contain five (5) planets, and one system has been found to contain six (6) planets. (Schneider 2010) This is compared to our own solar system's eight major planets. By far, most of the planets have been detected using the "radial velocity technique," where the spectrum of a star with a planet or planets orbiting it, changes it radial velocity toward or away from Earth. When the planet is behind the star and its gravity is trying to pull the star away from Earth, the star's V_r is very slightly red-shifted. Then, as the planet continues in its orbit about the star it finds itself between the star and the Earth and the planet tries to tug the parent star toward the Earth. This results in the star's spectrum being slightly blue-shifted. The magnitude of the star's spectral shift is dependent on the mass of the star, the mass of the planet, and the distance at which the planet orbits the star. As mentioned above, the magnitude of the spectral shift ($\Delta\lambda$) is given as a function of the relative velocities between the Earth and the target star. And, they are very small. The new wavelength that has been modified by the gravitational tug of the much less massive orbiting planet $\lambda' = \lambda_0 (1 + v/c)$, where λ_0 is the rest wavelength, v is the radial velocity of the star and c is the speed of light. Currently, the minimum detectable V_r is approximately 1 m^{s-1}, according to Dr. Debra Fischer, of Yale University's Astronomy Department. She was quick to point out that new instrumentation that will allow even smaller V_rs to be detected and measured are being developed. (Fischer Oct. 2010, personal communication)

The V_r method has detected 469 planets in 395 systems. (Schneider 2010) It is the most successful technique for detecting massive planets that orbit relatively close to their parent stars that are in the F, G, K, and M spectral classes. If the stars selected are too massive, as the O, B, and A classes are, then the influence of even massive planetary companions will not be adequate to cause a change in the Vr large enough for our present instrumentation to detect.

The second most successful extrasolar planet detection method is the planetary transit method. This method has detected some 107 planets in 105 systems. (Schneider 2010) This method takes advantage of a chance alignment of the extrasolar planet, its parent star and the Earth. If such an alignment exists, and if a waiting astronomer is trained on the star that is thought to have an orbiting planet, when the planet passes in front of its parent star, it eclipses or transits and the star's light is temporarily reduced while the planet is in the way. Then, as the planet moves off of the star's disc, the light level of the star returns to its normal level. In principle it is simple; in actual practice, it is much more difficult. A serious drawback of this method is that only about 10% of the planetary systems will be correctly aligned for us to see their transits. Some advantages of the Planetary Transit method are that it is able to yield the planet's diameter with considerable accuracy. Furthermore, the length of time between successive transits can give astronomers the period of revolution of the planet around its star. With that known, the planet's mass can be calculated using the Newton's form of Kepler's third law of planetary motion: $p^2 = [4\pi^2 / G(m_1+m_2)]\ a^3$ And, following the determination of the planet's mass, the density ($d = m/4/3\pi\ r^3$) can be calculated to determine whether the planet is a gas giant or a denser, rockier world. And, while not an easy measurement to make, as the planet is transiting, its atmosphere can be sampled spectroscopically. In 2001, measurements were taken of the atmosphere of the large planet (HD209458b) orbiting the star, HD209458, during three transits of the planet across the star. The results, published in 2003, revealed that neutral Na as well as atomic H were present in the atmosphere of an exoplanet that hinted that the planet was so close to its star that its atmosphere was literally being boiled away by the high temperature. (Vidal-Madjar 2003) As recently as December 2, 2010, it was announced in the journal, Nature that a super-Earth planet orbiting the star GJ 1214 had its atmosphere analyzed. Presently a number of other transiting planets are having their atmospheres studied, and in so doing, an entirely new field of astronomy is being born.

At the brink of 2011, astronomy stands at the beginning of a new golden era in planetary astronomy. Perhaps it is more appropriate to call it comparative extrasolar planetology. The instrumentation, software, computer power, and the methodology now exist for the first time to actually search with the real expectation of determining whether or not a planet is present orbiting a given star. If there is a planet present, we can determine what kind of planet it actually is. It is now possible to make reasonably accurate determinations of its atmospheric composition and to make at least a first order estimate of whether that particular planet has the right ingredients for life. In less than twenty years time, this is rapid progress and makes one even more hopeful for the next major step forward in understanding the intricacies of extrasolar planets.

What We Thought We Knew

As late as the early 1990s, before the existence of any extrasolar planets had been confirmed, it was difficult to know how accurate our ideas and theories of how, where and how frequently planets formed actually were. When one has only a single example of something that one is trying to improve one's knowledge about, learning proceeds slowly. With only one example of a planetary system to work with, our own, it was difficult to know what else might truly be possible. Before the first system was confirmed in 1992, that is exactly the situation that the astronomical community faced as it looked outward into the galaxy and into the future.

To understand how astronomers developed their theories and ideas of how our solar system formed, we must go all the way back to 1755, when the Prussian Philosopher, Immanuel Kant first came up with the concept of a solar nebula that contained dust and gas. Although Kant did not provide the supporting mathematics for this notion, he did provide a remarkably accurate account of how we believe our solar system formed. Kant's solar nebula was large and gravitationally unstable and over time, this regional, gravitational instability succumbed to a slow and steady collapse. One facet that Kant apparently got right was that these gravitational instabilities slowly rotated and as they collapsed, they rotated faster and faster and eventually flattened out into a disk. It is out of one such disk that our Sun and the planets formed from. (Beatty, et al. 1999) This collapsed, flat disk of rotating gas and dust fit nicely with what astronomers of the time were seeing as they began to observe solar system objects with optical aid from 1609 – into the 1900s. They saw the planets orbit a central Sun in the same direction and roughly in the same plane, in elliptical, but neat, nearly circular stable orbits. The solar system was well-behaved—or at least it appeared to be.

Once astronomers understood how stars produced energy and they discovered the excess infrared radiation around certain stars, they discovered that around many of these stars was an accompaniment of copious amounts of dust that would absorb the energy emitted by the stars and then reradiate it longer wavelengths, further supporting the dusty origin for stars and planetary systems that lie beyond the solar system. As the twentieth century went on, it became expected that other planetary systems, should they exist, would also be stable and as well-behaved as the planets in our solar system were, and apparently always have been. As mentioned above, with only one planetary system to go by, it became natural to assume that all solar systems would look pretty much like our own, with small, rocky terrestrial planets close to the central star, while the large, puffy gas giants formed much further out from the star; beyond the snow line where volatiles could condense and form the cores and outer layers of larger, gas giants.

As the Space Age dawned and the sixties raged on, astronomers began to have access to high quality, high resolution images of the inner planets and the Moon and noticed a multitude of craters. As NASA's manned lunar program progressed and the time came to pick out landing sites that our spacecraft could safely land in, geologists and planetary astronomers found themselves in the midst of a landscape littered with craters. For a time, they did not know for sure whether the craters were volcanic or impact-related. There was one certainty; there were a lot of them; far too many to be the result of volcanoes. That left impacts as the origin for the violent surface of the Moon. As probes returned images form Mercury, Mars, and the Moon, it became clear that our solar system had a very violent past and perhaps was not as well-behaved as we first thought. This line of thinking opened up new possibilities and introduced chaos into the equation in the history of the solar system. During the 1960s and 70s, scenarios like the late heavy bombardment and chaos theory and the Earth being provided with water and other volatiles from outside; maybe even life itself was brought to Earth from other worlds. These scenarios were well-founded and some remain with us today. But, it finally prepared astronomers for an other than peaceful and orderly birth for our solar system.

In 1975 Dr, William Hartmann published a paper in *Icarus* that put forth the giant impact theory to explain the origin of the Moon. (Hartmann 1975) This theory gained popularity and is now the leading theory to explain the origin of the Moon. It brought to light at least the possibility that the solar system has been shaped throughout its history, by impacts and was not as orderly as we had once thought. That impacts have shaped and heavily influenced our solar system is now, and has been since the mid-1970s, a part of our "givens" in terms of how our solar system and probably how others formed as well. It would be difficult to argue that other planetary systems could form without small, leftover planetesimals or small chunks that were not assimilated into the larger major planets. With that extra small-scale material remaining, collisions are bound to occur in many other systems. This is something that we should expect to find evidence of as we study new, multi-planet systems.

In summary of what we thought we knew about the formation and evolution of planetary systems, astronomers theorized that our solar system formed and condensed from the solar nebula approximately 4.6 billion years ago. In this cold molecular cloud there were mass concentrations that fragmented and began to contract under their own gravity. As gas and dust from the nebula continued to fall in on the protosun, its mass increased and along with it, so did its gravity, which enabled it to more effectively attract more material. It was assumed that there was some small, slow rotation that accompanied this process and as the protosun continued to contract, the rotational rate increased. This, in turn caused the contracting cloud to flatten to a rotating disk. Within the disk, other mass concentration began to accumulate material. These much smaller condensations became the planets. Since the cloud, and later, the disk was denser closest to the protosun, this massive, central condensation accreted more rapidly and gathered the majority of the material. The protoplanets acquired material more slowly and depleted their orbital regions eventually. As the future Sun continued to contract and warm, its core eventually reached the ignition temperature and pressure required for hydrogen fusion to occur, at approximately 15.6 X 10^6K with a density at its core of approximately 151g/cm^3. (Beatty, et al. 1999)

Because all of the planets formed from the same cloud and disk complex at the same time, they all revolve around the Sun in the same direction and roughly in the same plane. When the infant Sun ignited and began fusing hydrogen into helium, the inner solar system was blown free of volatile material and dust and for all practical purposes this ended the accretion of the inner, terrestrial worlds. Because the lighter material was blown outward from the inner solar system, all that remained was denser, heavier material. And, because these young planets were still molten, they differentiated and their heavier components sunk to the center to become their cores. This accounts for our terrestrial planets occupying the inner solar system. At greater distances from the young Sun, beyond the snow line, what were to become our gas giants already had small cores. Because the further from the central condensation the lighter the disk material was and this material was swept up and captured by Jupiter, Saturn, Uranus, and Neptune. Because in this region water and ice were at least ten times more abundant by volume than the denser, heavier silicates that formed the terrestrials was. This lighter material was added to the already formed cores of Jupiter and Saturn, which mainly formed from the original solar nebula due to their higher mass, they were able to form cores that more closely resembled the Sun, with layers of water and ammonia on top, along with trace amounts of other substances such as sulfur and phosphorus. (Beatty, et al. 1999)

Beyond the extent of Neptune's orbit, the density in the thinning disk, which consisted of mainly of ices, namely water and ammonia, contained some, but very little silicate material. Since the disk at this distance, was so thin, only very small bodies formed in this region. Here we find comets and Kuiper belt objects to finish off the formal extent of the solar system. From beginning to end this process, though not totally understood, is thought to take approximately 10 million years. Throughout that time period, the mass of the disk is diminishing as planets accrete material from it and add it to their own mass. Planet-planet scattering and mean-motion resonance conditions also develop and add small, but definite oscillations in the eccentricities of the affected planets, which can dramatically destabilize the delicate orbital and gravitational balance, especially in packed planetary systems. (Web 2) Additionally, during this time the larger, gas giants are capturing smaller icy planetesimals and gravitationally scattering comets into the outer reaches of the solar system into what we now call the Oort cloud. To explain and account for the multitude of impact craters that dot nearly all planetary surfaces in our solar system, including the surfaces of most of the satellites, gravitational interaction between the larger planets and smaller planetesimals that may have been in eccentric or inclined orbits due to previous encounters with more massive solar system objects. This action tended to eliminate small bodies that were on eccentric or inclined orbits, while it tended to preserve bodies that were on nearly circular orbits that were more stable and freer from destructive collisions.

Essentially this is it. Very briefly this summarizes how we think our solar system formed and evolved over an approximately 10 million year span of time. It does not account for all that we see in our solar system, but it does explain the more obvious features. By the time the first extrasolar planets were found and confirmed in 1992, astronomers knew enough about the solar system to realize that there would be some differences between our solar system and others if they did exist. But, what astronomers were not prepared for was just how different other, yet to be discovered systems would actually be, beginning with the very first set of three extrasolar planets to be discovered; the three planets that orbited pulsar 1257+12. As mentioned above, this system contains three small planets; two roughly 4 times the mass of the Earth and the third with a mass approximately twice the mass of our Moon. These three worlds all orbit 1257 +12 inside of 0.46 AU. (Schneider 2010) From these two pieces of information, nothing seems out of place. Again, what surprised astronomers so much about this system was that these planets orbited a neutron star. And orbiting so close, astronomers would have expected the planets to be destroyed.

Early Expectations for Extrasolar Planetary Systems

Expectations Vs what was discovered – Dr. Bill Cochrane, UT Astronomy/McDonald Observatory (Cochrane 2006, 2010 personal communication)

As a part of my research on extrasolar planets, I contacted Dr. Bill Cochrane, of the University of Texas' McDonald Observatory, and inquired about the expectations of astronomers in the field of extrasolar planet research, both before and after the onslaught of discoveries of the last ten years or so. What follows is a list of the expectations that the astronomical community had before extrasolar planets were discovered on the left side of the page and the reality, or what was *really* discovered on the right side of the page. It should be noted that the quest is far from over. Even though hundreds of stars have been examined to determine whether or not they have an accompanying system of planets, there are thousands more that have not yet, but scrutinized and still await the gaze of the extrasolar planetary astronomer.

Expectations	**Reality**
Planetary Systems are common	**So far, about 4% of main-sequence stars have detectable planets * (23%) from recent work by (Howard, Marcy, et al.)**
There are many planets per system.	**Several (Many *) systems of multiple planets have been found**
Jupiter is the prototype giant planet	**Many objects are more massive than Jupiter. The transiting planets indicated these are true giant planet like Jupiter**
***a* > 5AU for gas giants**	**There is a very wide range of semi major axes. How did "hot" Jupiters get so close to their parents?**
Nearly circular orbits.	**Many highly eccentric orbits**
Terrestrial planets in the inner regions	**Terrestrial planets not yet detectable** *** Terrestrials just now being detected in close-in orbits. (Howard, Marcy, et al. 2010)**

*** Not taken from Dr. Bill Cochrane information. (Howard, Marcy 2010)**

Expectations Vs Reality

In this section our expectations will be compared to the reality of what has been found to date. **Are planetary systems common?** Well, that depends on how "common" is defined. Estimates of the number of stars in the Milky Way range from 100 – 400 billion. Utilizing a somewhat conservative number of 200 billion, let us calculate the number of stars with at least one planet that reside in the Milky Way. Some 90 % of the stars in our galaxy are main sequence stars in the spectral classes F – M. This gives us approximately 180 billion main sequence stars in our galaxy alone. If we take Howard and Marcys' most recent work as an accurate estimate of the prevalence of planets estimate above, that 23 % of main sequence stars have planets, this yields approximately 41.4 billion planetary systems in the Milky Way. (Web 6) & (Howard, Marcy 2010) It should be noted that the 23 % is a very conservative number as the Howard and Marcy findings are only interested in close-in planets in a mass range between 0.5 – 5 Earth masses. Thus, the density of planet bearing stars is higher

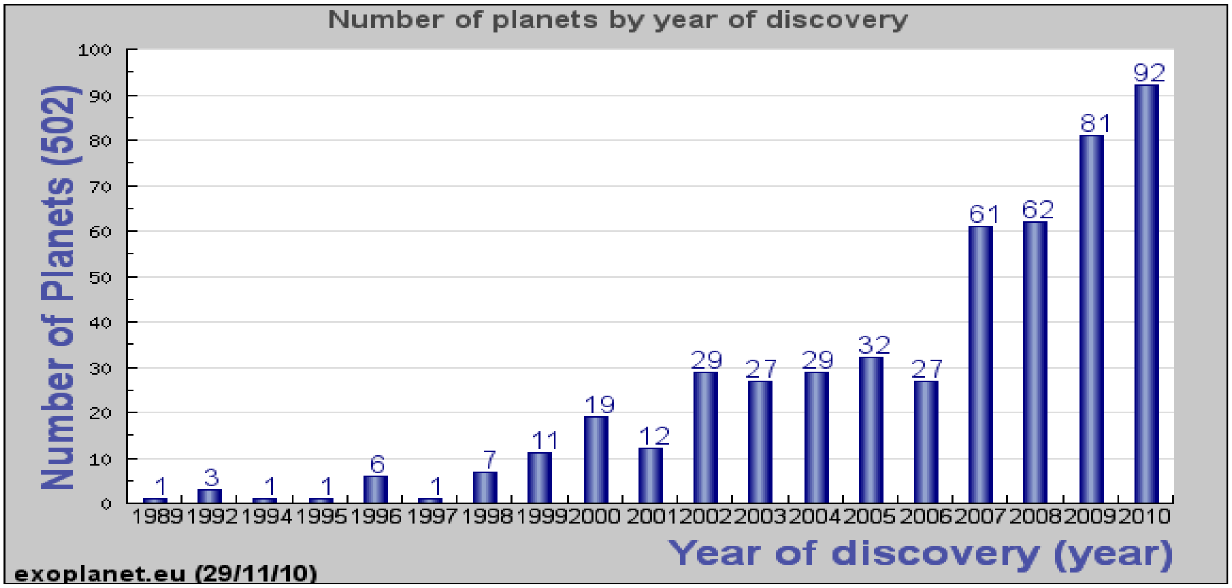
Making some rough calculations for the dimensions and volume of the Milky Way, we find that its approximate volume is πr^2 x T, where r is the radius at ~50,000 ly and T is its average thickness at about 6,000 ly. Thus, the approximate volume of the Milky Way galaxy is some 4.71 x 10^{13} ly^3 (Web 6) This rough calculation suggests that for every 1,138 ly^3 of space, there will be a star with at least one planet. Does this mean that the expectation above, that planetary systems are common, matches the reality of what we have found so far? Perhaps, but the expectation was vague in the first place, so it is difficult, if not impossible to determine whether or not our expectations were correct. This density of planetary systems puts direct communication with an intelligent alien species well beyond a human lifetime. Perhaps this indicates that our expectations were not met. On the other hand, 41.4 billion is a big number and it is likely to end up much higher.

This is surely not the final word on the prevalence of extrasolar planets. The core accretion model of planetary formation calls for the growth of planets to begin in a disk of dust and gas. As time goes on, the small planetesimals grow, not only through the accretion of dust and gas, but also from the impact with other planetesimals, both large and small. These impacts, occurring over hundreds of thousands, if not millions of years, generate a very large quantity of dust. All of this dust, radiates strongly in the infrared (specifically at 24μ and 70μ). This can be detected utilizing the Spitzer Space telescope. (Trilling, Bryden 2008) Observations have shown that systems with extrasolar planets present emit strongly in these wavelengths. Additionally, there are many “suspect” stars that have not yet been found to host planets, but are in the FGKM spectral classes and have the characteristic higher metallicity levels that will soon be discussed. It is probable that in the next 1 – 2 years the 23% of FGKM stars that host planets will increase significantly. (Fischer Oct. 2010, personal communication)

As a part of my research, I spoke to Dr. Francesco Pepe of the Observatoire Astronomique in Switzerland. Dr. Pepe explained that searching for and studying extrasolar planets is an exciting, but complex undertaking and that no one has all of the answers. He and his colleagues believe that as many as 30% of Sun-like stars have Neptune-mass planets, to say nothing of smaller Earth-mass planets that are below the limit of detection utilizing the V_r method. (Pepe Oct. 2010, personal communication)

Before proceeding any further, it is important to confront a bias that our current methods for planet detection introduce into our efforts to detect planets. Both the V_r and Planetary Transit methods favor the detection of large, massive planets that orbit close to their parent stars. Additionally, since we are still in our early stages of development in detecting planets, we were bound to find the planets that were easiest to find first. And, that is exactly what we have done and are still doing presently. It is quite possible and probably very likely that any star that has one planet also has several more that are currently below our limit of detection. If alien astronomers with the same technology within a few hundred ly were taking V_r measurements on the Sun for about as long as we have, they might have detected Jupiter, for its influence on the Sun is sizeable at 12.5m s^{-1}. (Lissauer, Marcy 2000) They would not have been observing long enough to detect Saturn with its twenty- nine year period and its much weaker 2.7m s^{-1} V_r effect on the Sun. Detecting Earth would be out of the question as it induces only a 10 cm s^{-1} V_r signal on the Sun due to its very low mass.

Figure 1 below, is a histogram plot from the Extrasolar Planet Encyclodaedia. It plots the number of planets discovered per year all the way up through November 28, 2010.



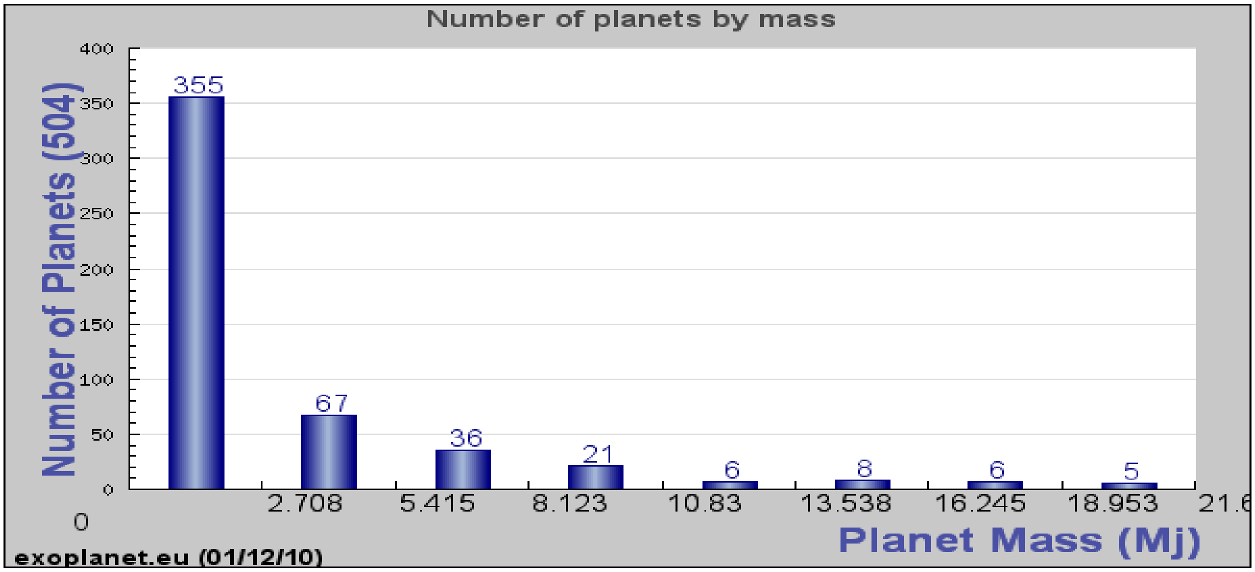
(Schneider 2010) Figure 1

While histograms are typically not used for predicting what might happen, if figure 1 is examined carefully, the dramatic jump in the number of planets discovered in 2007 is quite striking. As better equipment is developed and put into operation, along with a similar improvement in data reduction, analysis software and computing power, we can expect the trend of an increasing number of planets being found each year for the foreseeable future because there are so many candidate stars that have yet to be examined. Utilizing the telescope facilities at the ESO, La Silla Observatory in Chile (HARPS) or the W.M. Keck facility in Hawaii

(HiRES), the V_r level of detection is currently at or just under 1 ms$^{-1.}$ Utilizing the next generation of instrumentation, Earth-mass planets orbiting very close to its parent star will be detected and the number of planet discoveries is likely to explode. (Web 7) & (web 8) & (Howard, Marcy 2010)

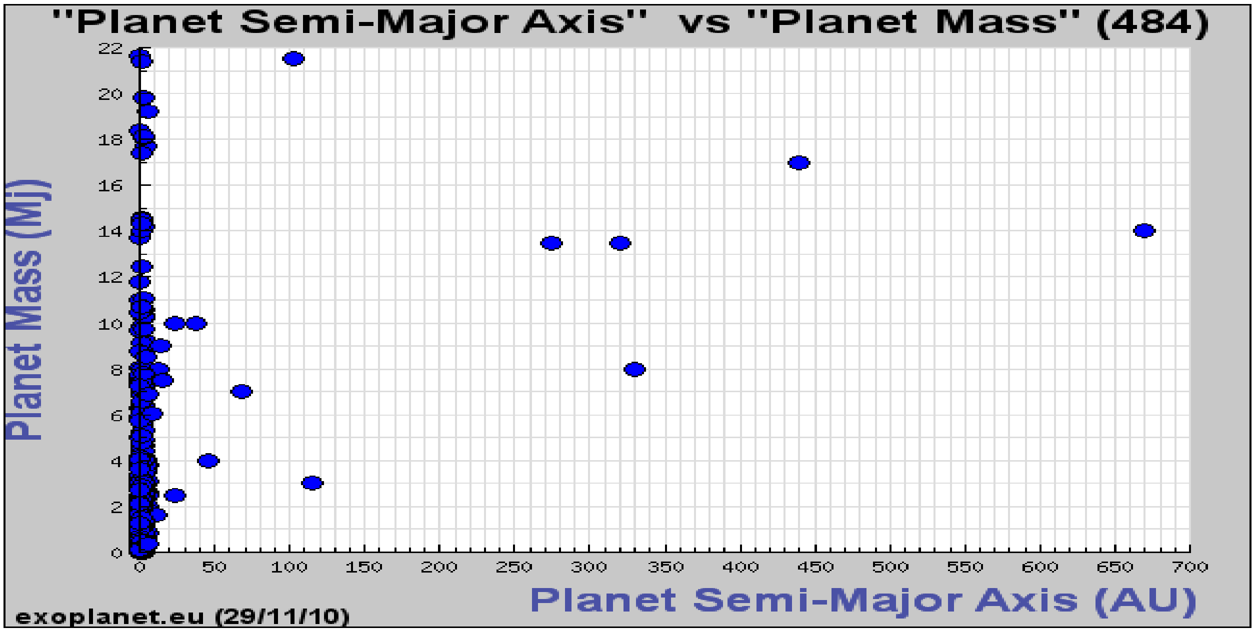
The next expectation was that **astronomers expected many planets per system**. How do the results stack up in this area? As was mentioned in the introduction, so far 504 planets have been detected in 422 systems. 52 of those systems have been found to contain more than one planet, or about 12.3%. Strictly by the numbers with only 12.3% of the planetary systems having more than one planet and of those 12.3%, 34 of the 52 multiple planet systems have been detected to have just two planets. This hardly fulfils our expectation of many planets per system. However, all is not lost. While the numbers above report the planets that have been detected and verified. Many more await confirmation and announcement. In a recent article published in *Science* that describes work done by astronomers at UC, Berkley, CalTech, Yale University, the STScI, and others, the number of extrasolar planets confirmed and even more importantly, the number of small, Earth-mass planets (with masses of between 0.5 and 2 Earth masses) may soon be dramatically revised upwards. It is reported by this team that small planets are common in close-in orbits, just as is found for large, massive, gas giant planets. The group also suspects that Earth-mass planets will also be found at greater distances than the 50d orbital period that they were searching for. However, at this increased distance, the gravitational tug imposed by these low-mass planets on their parent stars will be much more difficult to detect. These planets will definitely require improved detection methods before they are easily confirmed. This may boost the average number of planets per system and put our expectations on par with reality in the next 1 – 2 years.

Jupiter as the prototype giant planet—If we allow some flexibility and consider planets with up to three times Jupiter's mass, a Jupiter-like planet, then as can be seen from figure 2 below, a total of 422 planets fall into this category. This accounts for nearly 84% of the extrasolar planets discovered to date. While the majority of the planets discovered so far are indeed gas giant worlds similar to Jupiter and Saturn in mass, there are other key attributes where they differ from the gas giants in our solar system.



(Schneider 2010) Figure 2

In our solar system, the semi-major axis of all of the outer gas giant planets are large; beginning with Jupiter at 5.2 AU and ending with Neptune at a distant 30 AU. As can be seen in the correlation diagram in figure 3, that plots the semi-major axis Vs planetary mass of the discovered extrasolar planets. Not only are most of these alien worlds much more massive than the gas giants of our solar system, but they tend to orbit in very tight orbits. This was one of the major surprises as planets began to be discovered. Planetary systems in this configuration were definitely unexpected.

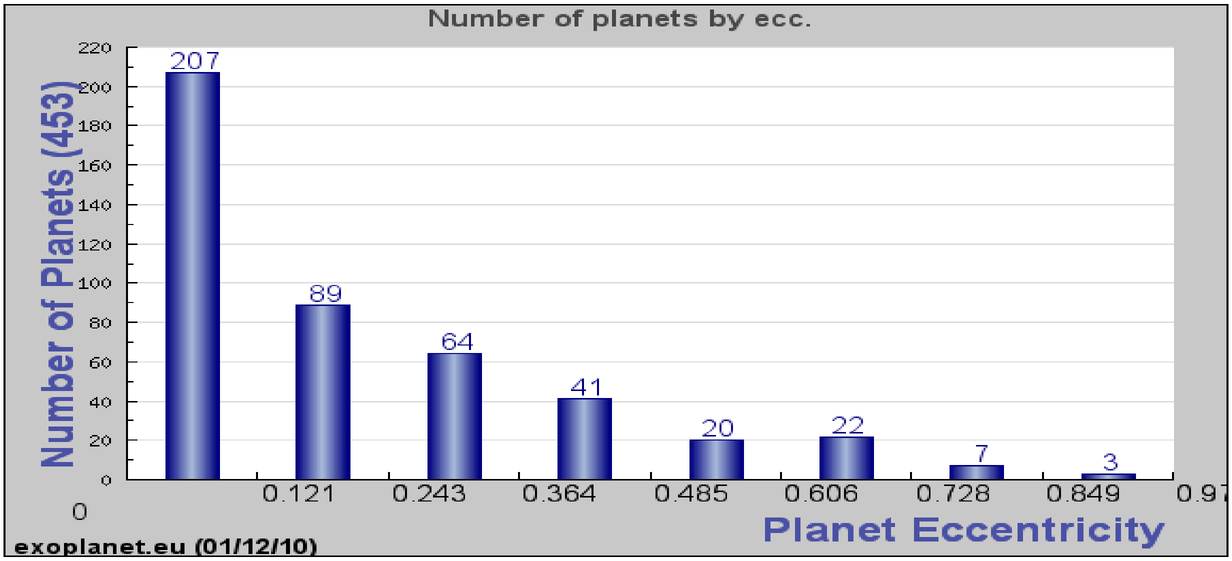


(Schneider 2010) Figure 3

As a result of this major difference, astronomers worked to come up with theoretical models that could explain this very different planetary layout. Because our core accretion models did not allow for the formation of gas giants so close to the parent star, astronomers devised various theories to explain how the giants in many other planetary systems got there. Our models held that the gas giants formed out beyond the "snow line" where the volatiles and ices could condense out and form cores and outer gas layers of the Jovian worlds. (Kraus, Covey 2010) But, with so many giant planets much more massive than Jupiter, where did they get the light, raw materials in such a hot and hellish environment?

Planetary migration was turned to as a way for giant planets to form out where our models predict they should, but provides a way for them to fall in toward the central star. In the dusty and gaseous disks believed to be conducive for growing planets, the planet is acted upon by the disk material as a gravitational torque is applied to the planet that robs it of angular momentum and causes it to migrate inwards toward the star. If this disk remains intact nearly all the way in to the star, the planet will continue to lose orbital speed and spiral into the star. (Matssumura, Pudritz 2009) However, if the planet either clears a gap or encounters a gap, the migration will stop. This type of migration is referred to as type I orbital migration. (Armitage 2008) Because of the vast complexity of planetary systems and because there are so many variables, every system is different. So, some planets will stop their inward migration before they are at risk of spiraling into the star and some will not. This leaves us with a very diverse population of planetary systems. (Armitage, Rice 2005) & (Armitage 2008)

The eccentricities and the orbital inclinations of the orbits of many giant extrasolar planets presented astronomers with additional surprises. Astronomers expected to find orbits with low eccentricities and inclinations just as we find in the orbits within our solar system. After all, if the orbits of the planets are highly elliptical and highly inclined, this can lead to intersecting planetary orbits which means the frequent gravitational perturbations would induce considerable chaos and reduce stability of the entire planetary system. In our solar system any eccentric or highly inclined orbits that may have been present early in the solar system's history have lead to the ejection or destruction of the planet(s) that possessed those orbital characteristics. As can be seen in figures 4 & 5 below, there are a large number of planets with eccentricities and inclinations far higher than any in our solar system. Mercury has the most eccentric orbit of any of the planets in our solar system (e = 0.206). And, although Pluto has now been moved to the dwarf planet category, most are familiar with its high orbital inclination of approximately 17°. The rest of the planetary orbits are nearly circular and in the same plane, with little chance for collisions between the major planets.



(Schneider 2010) Figure 4

How do we explain the high number of eccentric orbits and highly inclined orbits in the Extrasolar Planet Encyclopaedia depicted in figures 4 & 5? As these were unexpected, modifications to existing theories and models were required. (Takeda, Rasio 2005) As Takeda and Rasio state in their 2005 paper that a possible contributor to eccentric orbits in some systems is referred to as the Kozai mechanism, whereby a distant binary companion can induce oscillations in the eccentricities of even distant planetary orbits. They describe that this distant companion could even be a distant massive planet. “The Kozai mechanism is effective at very long range and its amplitude is purely dependent on the relative orbital inclination.” (Takeda, Rasio 2005) Based on their work, they believe that the Kozai mechanism can produce many highly eccentric orbits. At the time this paper was published there were ~150 known extrasolar planets; their median eccentricity was 0.28, which is higher than any planet in our solar system. In the vicinity of the Sun, roughly half of the stars have companions. It is quite possible that some of the unseen and undiscovered companions are brown dwarfs that could, by their gravitational influence at a great distance, be inducing highly eccentric orbits in some planetary systems.

A detailed look at three selected systems

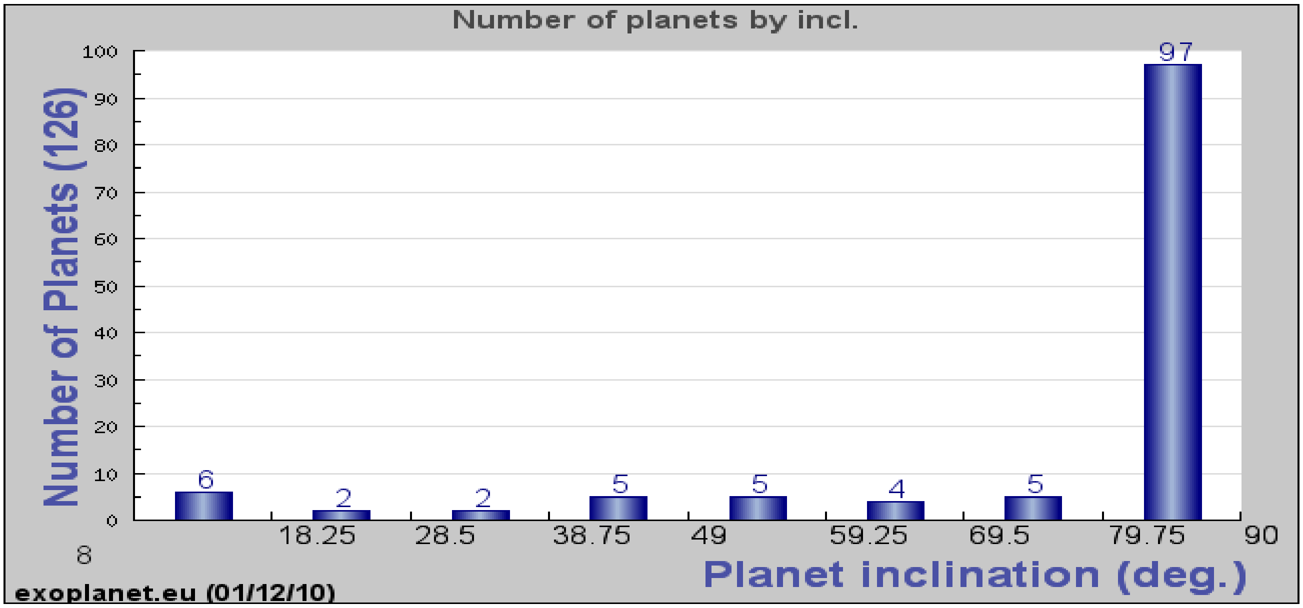
A closer examination of three selected extrasolar planetary system follows. As can be seen in table 1, the members of each planetary system are listed along with key attributes of the system: planetary mass, radius*, period of revolution, the semi-major axis, eccentricity, and orbital inclination. Planetary radius, year of discovery and the parent star’s metallicity are also listed. As a point of comparison, the gas giants of our solar system, along with Earth are also listed. Before the discovery of the first extrasolar planet orbiting a Sun-like star in 1995, our planetary model was all we were familiar with. And, it is often the first thing researchers and even the general public do is to compare a newly discovered planet or system with ours.

PLANET	M. (M_{Jup}) - stats	Radius (R_{Jup}) *	PERIOD (days)	SEM-MAJ AXIS (AU) - stats	ECC.	INCL. (deg)	DISCOV. (year)	DIST. (pc)	[Fe/H]
55 Cnc e	0.024	-	2.82	0.038	0.07	-	2004	13.02	0.29
55 Cnc b	0.824	-	14.65	0.115	0.014	-	1996		
55 Cnc c	0.169	-	44.34	0.24	0.086	-	2002		
55 Cnc f	0.144	-	260.00	0.781	0.2	-	2007		
55 Cnc d	3.835	-	5218.00	5.77	0.025	-	2002		
GJ 581 e	0.006	-	3.15	0.03	0	-	2009	6.26	-0.33
GJ 581 b	0.049	-	5.37	0.041	0	-	2005		
GJ 581 c	0.017	-	12.93	0.07	0.17	-	2007		
GJ 581 d	0.022	-		0.22	0.38	-	2007		
HD 10180 c	0.041	-	5.76	0.064	0.045	-	-	40	0.08
HD 10180 d	0.037	-	16.36	0.129	0.088	-	-		
HD 10180 e	0.079	-	49.75	0.270	0.026	-	2010		
HD 10180 f	0.075	-	122.76	0.493	0.135	-	2010		
HD 10180 g	0.067	-	601.2	1.422	0.19	-	2010		
HD 10180 h	0.203	-	2222	3.4	0.08	-	2010		
Jupiter	1.000	1.000	4332	5.200	0.048	1.300			0
Saturn	0.299	0.843	10760	9.550	0.053	2.480			
Uranus	0.046	0.358	30718	19.200	0.043	0.770	1781		
Neptune	0.054	0.346	60215	30.100	0.010	1.770	1846		
Earth	0.003	0.089	365.25	1.000	0.017	0.000			

Table 1 provides a tool to easily compare the selected systems with our solar system. Table 1

* Only when an extrasolar planet transits its star can accurate radius measurement be made. These planets do not transit.

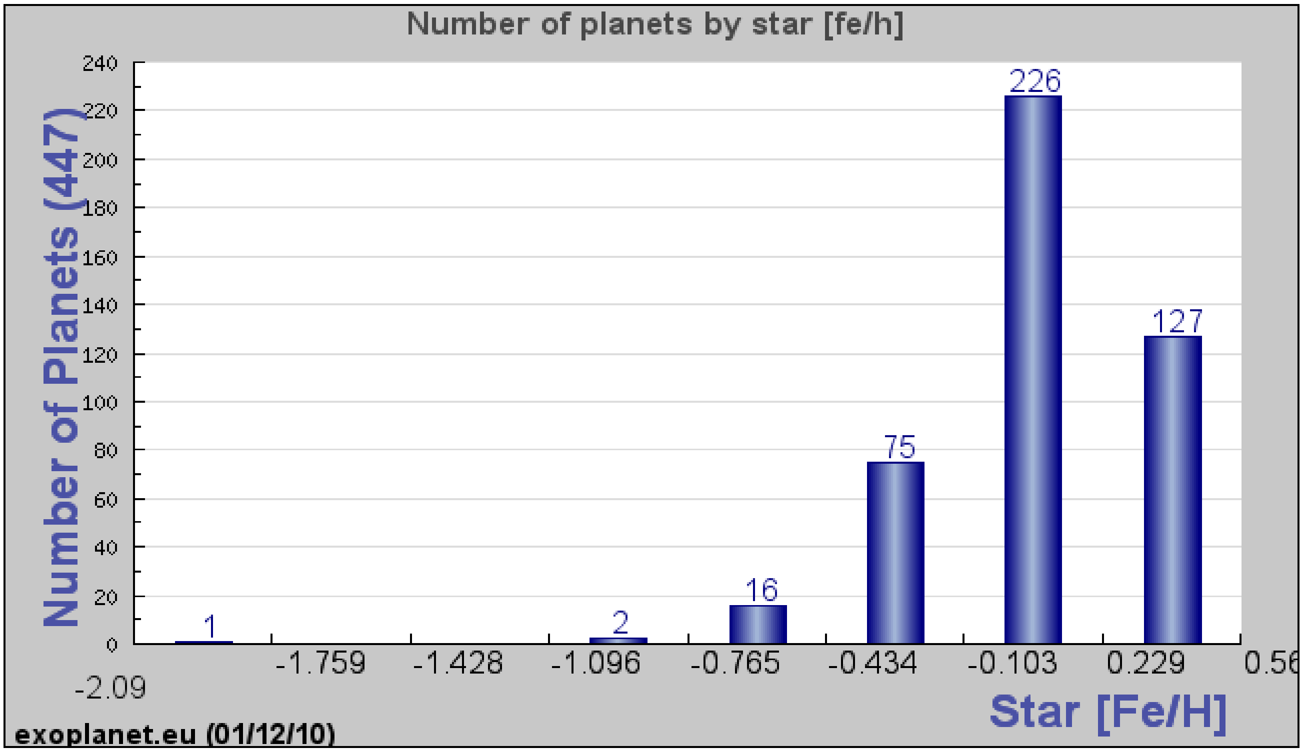
The high orbital inclinations as is illustrated in Figure 5 with data from the Extrasolar Planet Encyclopaedia were very unexpected. The sample systems selected for comparison in this paper have not had their inclinations determined as yet. In our own solar system, none of the major planets show high inclinations. However, one of the ways the inclination of a planet's orbit can be affected is through gravitational influence resulting from a close encounter with another object, or possibly through the Kozai cycles mentioned earlier. If our understanding of the various types of planetary migration is correct, it is likely that many systems have experienced major disruption induced by planet-planet scattering. (Winn, Fabrycky 2010)



(Schneider 2010) Figure 5

Stellar Metallicity

In terms of stellar astrophysics, Iron is the most frequently measured element in nearby stars. The star's Fe/H ratio is the ratio its iron to hydrogen by mass. (Robles, et al. 2008) In the years following 1995, astronomers began noticing that stars with high metallicities tended to host planetary systems. This trend is well-illustrated in Figure 6, which plots the Fe/H ratios for the known extrasolar planets. In this histogram, the Sun's Fe/H would be 0. 353 out of the 504 planets discovered to date have metallicities close to that of the Sun. The Sun's metallicity is approximately 1.8% by mass. This provides a basis of comparison with other stars with planetary systems. Again, as can be seen in Figure 6 below a Fe/H threshold of ~ -0.765, there are very few planet hosting stars, which provides astronomers with a powerful tool in searching out which stars should be examined in closer detail when looking for planetary systems.



(Schneider 2010) Figure 6

A Comparison of Three Extrasolar Planetary Systems to Our Solar System

Since the two most successful methods for detecting extrasolar planets bias us toward our detecting large planets around FGKM stars, our views on which stars actually do host planets are still skewed at this time. That being said, that does not prevent us from comparing and contrasting the known systems. The systems selected here are all multiple planet systems that contain many planets. Our solar system contains eight major planets and a host of smaller planetary satellites, comets, dwarf planets, asteroids, and a considerable amount of dust that is left over from its formation, has been released comets, or released from the numerous impacts that have occurred over the past 4.6 billion years. Because of the immense distance that separates even the closest stars, we do not as yet have the familiarity with any of the other systems that we do with our own solar system. Progress is being made by astronomers as they begin to search for satellites of transiting planets.

A comparison of the four stars in the comparison group is shown below in Table 2. All of the stars are in the FGKM spectral classes mentioned above.

A COMPARISON OF PARENT STARS

	distance (pc)	spectral class	T eff (K)	Age (Gyrs)	Fe/H	Radius Sun radius	Mass Sun mass
The Sun	**0**	**G2**	**5800**	**4.65**	**0.00**	**1.00**	**1.00**
55 Cnc	**13.20**	**G8V**	**5240**	**5.50**	**0.29**	**1.15**	**1.03**
GJ581	**6.26**	**M3**	**3480**	**8.00**	**-0.33**	**0.38**	**0.31**
HD10180	**40.00**	**G1V**	**5911**	**7.30**	**0.08**	**1.20**	**1.06**
data from (Schneider 2010) & (Freedman, Kaufmann 2008)							

Table 2

The 55 Cnc System has an interesting history since its first planet was discovered by Paul Butler in 1997. Then, in 2002, Geoff Marcy discovered a third planet that orbited 55 Cnc in ~ 14 yr. Its minimum mass (M sin*i*) was found to be = 4 M_{jup}. At the time of its discovery, this planet was the first large planet to be found orbiting at a distance very close to Jupiter's 5.2 AU making this system a possible analogue to our own. Then, in the same year a third planet was found orbiting very close in at only 0.25 AU. (Fischer, et al. 2008) As additional planets were found in this system, it became the first system known to have four planets. Utilizing the Fine Guidance Sensor on the HST, researchers at the University of Texas found that the fourth planet orbited at a very high inclination of some 53° +/-6.8°. (Cochrane, et al. 2004) The discovery of the fourth planet in this system seemed to leave a large gap that was later filled when 55 Cnc f was discovered in 2007. (Fischer, et al. 2008). It is very interesting to note that in this system, unlike in our solar system, there is an M-class star orbiting at ~1000AU. This is very type of long-range gravitational influence that has been invoked to possibly oscillations in inclination and eccentricity through the Kozai mechanism.

55 Cnc has one of the highest metallicities of any star within 25pc of the Sun. (Fischer, et al. 2008) It is not surprising that it now is known to contain five planets compared to our eight. Unfortunately this system is not aligned so that its planets transit. If it did, it would allow us to measure the diameters of these planets to determine their densities. This would allow the determination whether these worlds were gas giants like Jupiter, ice giants like Neptune, or perhaps large terrestrial planets. This planetary system will continue to be watched closely as there is still a large gap between 55 Cnc d & f.

The Gliese 581 System made the headlines in September, 2010, when researcher Steven Vogt published a paper in Astro-ph that claimed that a fifth and sixth planet (GJ 581f and GJ 58g) had been detected. This would be the second system known to contain six planets. The noteworthy point of this announcement was that GJ

581g has a minimum mass of only 3.1 Earth's, one of the lowest mass planets yet detected. This planet is said to orbit the star in 36.6 days at an average distance of 0.146 AU. For this M3 class star, this is in the middle of its habitable zone (HZ). (Vogt, et al. 2010) As can be seen from Table 1, these planets have not yet been added to the Extrasolar Planet encyclopaedia because they have not been confirmed. In fact there is a debate raging between two competing planet-searching camps on whether or not these two "new" planets really exist. Vogt and his team from UC Santa Cruz combined data they had obtained using the Keck HiRES spectrograph and data from the ESO's HARPS spectrograph. When I contacted Dr. Francesco Pepe, a member of the Swiss team that has also been utilizing ESO's HARPS spectrograph, he was very open about the importance of this discovery and that extreme care needed to be exercised when publishing results. But the Vogt team is a dedicated and very experienced team, with the discovery of many extrasolar planets to their credit. Although the final verdict is still out, it is likely that these two planets will soon be confirmed and a new debate will take the center stage. This is the way science works. Because the Swiss team had already announced two Super-Earths in this system at the edge of the GJ581's HZ in 2007, and 2009, they were particularly sensitive to being "scooped." (Pepe 2010, personal communication) Because this star is an M class star, its Habitable zone (HZ) is much closer in, where at least two planets reside. As mentioned in the introduction, being the first to discover and announce a confirmed Earth-mass planet orbiting its star in its HZ would garner a tremendous amount of satisfaction, publicity and down the road, much-needed funding. A discovery such as this is described by astronomers themselves as finding the "Holy Grail of Astronomy." (Vogt, et al.2010) It would also point to a large number of smaller, Earth-mass planets just as in our own solar system. If GJ581f and g are confirmed, that would give this system more planets in its habitable zone than the Sun has. That is something to think about. Gliese 581a possibly has six planets orbiting it. This ties it with HD10180 as the system having the most planets yet discovered. Our solar system has eight; with our detection limits still quite high, it is very likely that many more systems already known to have planets will have their planet counts increased in the coming months and years.

The HD 10180 System is a rich planetary system orbiting a star that is very similar to our Sun. As shown in Table 2, this star's mass, radius, and effective temperature are very close to the Sun's. In addition to the star's similarity to our own, there are six confirmed Neptune-mass planets, with a suspected 1.4 Earth-mass orbiting only 0.02 AU out. The fact that there are so many Neptune-mass, or ice-giant-mass planets makes this system remarkably similar to our solar system. The detection of so light a planet despite its proximity to its star represents the intense efforts being made by Astronomers utilizing the ESO's HARPS spectrograph on the 3.6m telescope at the La Silla Observatory in Chile. This small planet is only inducing a V_r of 2km hr^{-1}, which is about walking speed. Again, as is the case for 55 Cnc, HD10180a is a metal rich star containing slightly more heavy elements that the Sun. (Lovis, et al. 2010)

The planetary layout in the HD10180 system seems to have all of its planets orbiting at a semi-major axis distance of only 3.4 AU. Certainly a star this massive, could have several, more distant planets that are as yet undetected. If we apply the core accretion and gravitational instability theories to this system, one might even say with certainty that more planets await discovery. It just so happens that this gap lies in the HZ of this star. And, since they have so far resisted discovery, they could be between Earth-mass and Neptune-mass planets. If one examines the semi-major axis of the planets, it is very clear that this system is stacked densely with close-in planets. Despite this close spacing compared to our solar system, the Lovis team, utilizing the HARPS spectrograph is convinced that the system is dynamically stable over long periods of time. They have estimated the system's age at roughly 4.3 Gyrs, which differs from the age of the parent star listed in the Extrasolar Planet Encyclopaeda.

If the eccentricities of the planets in this system are examined, it is easy to see that they also closely match up to the eccentricities of the planets in our solar system. This is another strong point of comparison arguing the dramatic similarity to the Sun's family of planets. But, while this system shows similarity to ours, it does illustrate the dramatic diversity of the known extrasolar systems display to us. HD10180 does contain close in planets as many other systems do, but it has no Jupiter-mass giants.

Conclusion

It is evident from the presentation of the material in this paper, the field of extrasolar planetary astronomy is exciting, fascinating and still immature. Considering that the first system was discovered only eighteen years ago, much has been learned. Just before submitting this paper, I checked the Extrasolar Planetary Encyclopaedia one more time and found that yet another planet, number 505, had been entered. As more research teams join in the search and the hardware and software continue to improve, the planet count will continue increase every month.

With the Kepler and COROT spacecraft keeping a vigil from aloft on suspect stars, this will bring about an exponential increase in the numbers of planets and systems we are aware of. That influx of data is just starting to arrive. These space-based platforms have already added systems to the growing list of known systems and they are expected to continue this exploration for several years more before being replaced by even more advanced platforms.

It would appear that the universe holds as much diversity in stellar and planetary systems as Nature here on Earth does for life. Perhaps we will soon find, as many suspect already, that life in the universe is as diverse as it is on Earth, just on a far grander scale, if that were possible. As the late Dr. Carl Sagan said in his wonderfully successful *Cosmos* series and book, it is a wonderful time to be alive as we wade out into the cosmic ocean. The researches I spoke to researching this project certainly seemed to think so.

It seems we live in a solar system that is in the company of many others throughout the galaxy and probably well beyond; some are very similar and some are very different. We have a firm understanding of how stars and their systems of planets form and evolve over time. Our theories of core accretion and inward planetary migration seem to explain the systems we are now discovering. But we have much yet to learn. We still do not know if Earth-like worlds are rare or if they are common. We think in the end, we will find many of them as our equipment and techniques mature and develop. We still do not know if life is rare or common. We still do not know whether or not complicated or intelligent life has arisen elsewhere. These are the questions that continue to drive scientists of all disciplines to probe even further into these matters. Perhaps it is these very questions that drive all of science.

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Image Credit:

Image 1 A depiction of the Gliese 581 system compared with our solar system, Zina Deretsky, NSF

Figure 1 Histogram plotting planets discovered per year (Schneider 2010)

Figure 2 Histogram plotting planet mass (Schneider 2010)

Figure 3 Correlation Diagram—planetary mass Vs. semi major axis (Schneider 2010)

Figure 4 Histogram plotting planet eccentricity (Schneider 2010)

Figure 5 Histogram plotting planet orbital inclination (Schneider 2010)

Figure 6 Histogram plotting stellar metallicities ((Schneider 2010)