Extrasolar Planets and Chemical Abundance

Intermediate Graduate Physics Seminar

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Abstract

Over 200 extrasolar planets have been discovered since the first confirmed observation in 1995. Most of these turn out to be Jupiter-class objects, orbiting their host stars at very small semimajor axes, with corresponding orbital periods of less than a year. Various planetary formation and migration models have been proposed to explain the discrepancy between observed extrasolar planetary systems and our own Solar System. The most successful among these appears to be the Core Instability Accretion hypothesis which adequately describes the formation of giant planets. Migration of these planets inwards due to angular momentum transfer through the protoplanetary disk then explains the observed orbital distribution. Another interesting feature of the extrasolar planet population appears to be the positive correlation between metallicity of the host star and the presence of Jupiter-class planets. The source for the high mean metallicity of planet hosts is likely to be primordial, requiring a metal-rich protoplanetary nebula. Finally, the presence of giant planets may not necessarily imply the existence of terrestrial planets in the same planetary system.

1 Introduction

The very first planet discovered outside our own solar system was found to be orbiting around a dead star. Wolsczan and Frail observed an Earth-sized companion around the 6.2 millisecond pulsar PSR 1257+12 in 1992. This was quickly followed by the first detection of a Jupiter-sized object in orbit around the main-sequence star 51 Pegasi by Mayor and Queloz in 1995. Since then, nearly 230 planets have been discovered, at an impressive rate of nearly two a month. Most of these planets are Jupiter-sized objects in close orbit around their stars. This, of course, is in stark contrast to our own Solar System, where the inner-most planets are terrestrial in nature and size, while the gas and ice giants dominate the outer solar system.

Explaining this discrepancy requires an understanding of planetary system formation and subsequent evolution. This paper presents an overview of the efforts to reconcile the observations of the known extrasolar planetary systems with theoretical models of planet origin, formation, and migration. Section 2 is an introduction to some useful physical and chemical concepts used in this field. The concept of metallicity is introduced as an important factor in star formation and evolution.

Section 3 goes over some of the properties of extrasolar planets, as well as some of the detection methods in use today. Section 4 presents evidence that the prevalence of giant Jupiter-class planets is tied to the metallicity of the host star, and explains how this observation prefers a certain planetary formation model. Finally, Section 5 outlines some of the effects that metallicity and presence of giant planets might have on terrestrial (Earth-sized) planets.

2 Chemical Abundance and Metallicity

Of the visible matter in the universe, roughly 75% is hydrogen (in atomic, ionized, and molecular forms) and about 25% is helium. All of the other elements are a tiny fraction of the total composition of the universe; on the order of 0.01%. Hydrogen and helium are two of the primordial elements, having formed in the initial stages of the Big Bang. Heavier elements result from fusion reactions in the cores and envelopes of stars. Examples of these elements include carbon, silicon, and oxygen. Still heavier elements such as iron and much of the radioactive series are formed in energetic reactions following supernovae.

The typical star, therefore, is composed mostly of hydrogen and helium, with a trace amount of other elements present. The mass fractions of elements in stars depend on several factors; the most important of which happen to be when and where the star was formed. If stellar formation takes place early in the age of the universe, the interstellar medium will be devoid of heavier metals, and the mass fraction of hydrogen and helium in the star will be proportionately larger. If the star is formed after several epochs of star formation have already taken place, it will have a higher proportion of heavy elements. Similarly, if the star forms in a heavy element-rich region of the galaxy, it will end up with a higher heavy element fraction.

Astronomical convention defines anything heavier than hydrogen and helium as a *metal*. The total mass fraction of a star equals 1.0, and can be written as

$$X + Y + Z = 1.0 \tag{1}$$

where X, Y, and Z are mass fractions of hydrogen, helium, and metals respectively. The typical values of these are $\sim$0.7, $\sim$0.3, and $\sim$0.005–0.05 respectively. The mass fraction Z is referred to as the *metallicity* of the object in question, and is usually measured as the ratio $Z/Z_{\odot}$, where $Z_{\odot} = 0.02$ is the metal mass fraction of the Sun.

The metallicity and abundances of various chemicals present in astronomical objects are determined by taking spectra. Absorption and emission lines in the spectrum have different shapes and strengths which are affected by the presence of metallic species as well as the structure of the star. Fitting chemical-sensitive lines to stellar atmosphere models gives us a good estimate of the relative chemical abundance. Other fitted lines provide the surface temperature $T_{\rm eff}$, as well as the $\log g$ measure of the star. These two parameters allow us to determine the structure, and in some cases, the age of the star. A high $T_{\rm eff}$ and a high $\log g$ indicate that the star is small and hot; most likely an evolved white dwarf. A low $T_{\rm eff}$ and a low $\log g$ are the characteristics of a giant star. Intermediate values may indicate a main-sequence star.

Most chemical abundance measurements are carried using the absorption lines of the element iron, because they are easy to pick out among the literal forest of spectral lines generally observed. We can define a measure of the metallicity of a star:

$$[Fe/H] = log\left[\frac{n(Fe)}{n(H)}\right]_{*} - log\left[\frac{n(Fe)}{n(H)}\right]_{\odot} \tag{2}$$

where $[Fe/H]$ is the metallicity of the star expressed as a log ratio between the relative abundance of iron seen in the star (first term), and the relative abundance of iron in the Sun (second term). This ratio is a convenient way to compare the metallicities of different stellar populations. $[Fe/H]$ ratios generally range from -3.00 (very metal poor) to +2.00 (very metal rich). The Sun's $[Fe/H]$ is taken by convention to be 0.00.

The effect of changing metallicity on a star can be gauged by its effect on the luminosity of the star. The luminosity of a star depends on many factors, including the temperature and the pressure in the stellar interior. The ideal gas equation of state governs these factors:

$$P = \frac{\rho}{\mu} RT \tag{3}$$

where P is the pressure at the center of the star, ρ is the density of the gas, μ is the mean molecular weight, and T is the temperature. Varying the metallicity of the star most directly changes the value of the mean molecular weight. As μ changes, the temperature and pressure must also change to compensate. This, therefore, changes the luminosity of the star. Other effects arise due to a change in radiative opacity in the stellar interior, owing to a change in the mean molecular weight. On the whole, a star is redder when its metallicity is high, and bluer if its metal fraction is low.

We see, therefore, that changing the metallicity of a star can lead to considerable changes in its radiative properties. These changes, in turn, govern its evolution over its lifetime, and also influence the fate of any planetary companions.

3 Extrasolar Planets

Nearly 230 extrasolar planets have been found since the first one was discovered in 1992. Two groups, one based in the United States, and one based in Europe have been at the forefront of discoveries in this area. G. Marcy and his collaborators in California, and M. Mayor's group at Geneva have been responsible for most of the extrasolar planets discovered so far.

Both groups have utilized precision spectroscopy in order to find these planets. They have used Doppler measurements of the radial velocity of the host stars, in which a small perturbation indicates the presence of a planetary companion, to find most of their candidates. Both of the searches have focused on mostly FGKM dwarf stars, owing to their stability and well-known stellar parameters. The *reflex velocity* of a star induced by a planetary companion is given by:

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{m_p \sin i}{(m_s + m_p)^{2/3}} \frac{1}{(1-e^2)^{1/2}} \tag{4}$$

where K is the reflex velocity, P is the orbital period of the companion, $m_p \sin i$ is the minimum mass of the planetary companion, m_s is the mass of the star, i is the inclination of the orbit with respect to the plane of the sky, and e is the eccentricity of the orbit.

We see that the measured reflex velocity is directly proportional to the minimum mass of the planet, and inversely proportional to the period of the orbit. There is, therefore, a bias towards high mass, and small period planets when using this method. Indeed, most of the planets discovered by the radial velocity method are large Jupiter-class giant planets orbiting close to their stars. This bias should decrease, however, as more precise measurements of the reflex velocity allow us to reach the terrestrial regime in planet mass and semimajor axis.

Another successful method in the hunt for the extrasolar planets has been to simply look for transits across the face of the host star. This requires the inclination of the planetary system to be nearly edge-on with respect to the observer. Despite the rarity of such an occurence, nearly 20 planets have been discovered by observing a characteristic dip in the light curve from a candidate host star. We can extract more information about the planet using this method, because we can obtain the ratio of the radii of the planet and the star by looking at the depth of the transit in the light curve. Furthermore, spectroscopy enables us to probe the atmospheres of planets discovered in this way, and obtain information on their chemical composition.

The radial velocity and transit detection methods have provided us with most of our extrasolar planet candidates so far. Taking their respective biases into account, the picture of planetary systems that emerges is much different from our own Solar System. We have found many planets that are Jupiter-like, but orbit at semimajor axes less than 1 AU from their host stars. Another worrying tendency is the large range in orbital eccentricities encountered thus far. There have been some multiple planet systems detected, but even these look nothing like our familiar Solar System. To explain the discrepancy between the observed extrasolar planet systems and our Solar System, we turn to models of the formation of planetary systems, and giant planets in particular. There are two competing hypotheses: the Core Instability Accretion model, and the Disk Gravitational Instability model.

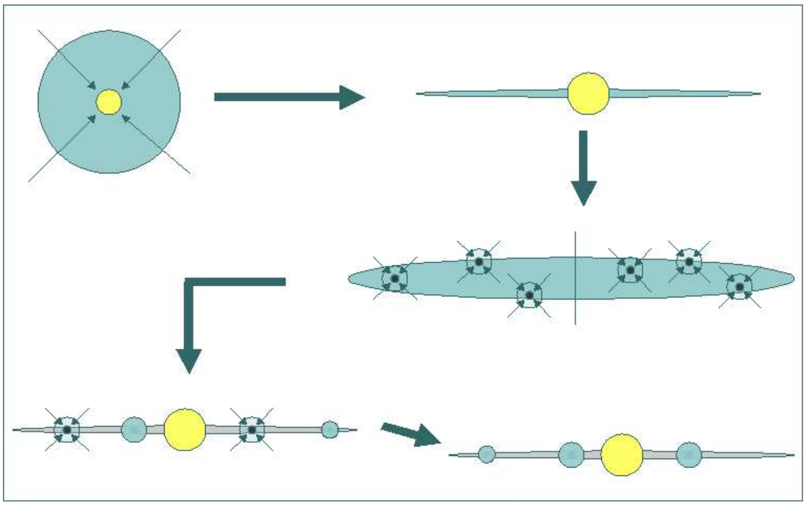

Figure 1: Core Instability Accretion Model of Giant Planet Formation

A schematic of the Core Instability Accretion model is shown in Figure 1. After the initial collapse of the protostellar nebula takes place, the remaining material settles into a planar orbit around the young star. Random collisions of dust grains in regions of this planar disk cause accretion and formation of small planetesimals. This slow growth via gravitational interaction continues until a critical point is reached in the size and mass of the planetesimals (usually 10 km in radius). Once they are sufficiently massive, the planetesimals begin to interact via long range gravitational interactions, and sweep up all remaining material present in their orbital path. After about 10^6 years of evolution, these planetary embryos grow to about 10 $M_\oplus$ in mass and a runaway gas accretion phase sets in. These giant planet cores then rapidly accrete much of the remaining disk gas, and finally become giant Jupiter-class planets. Thus, we end up with giant planets in a time-frame of order 10 Myr.

In contrast, the Disk Gravitational Instability model (Figure 2) does not require as much time as the previous model. As the protoplanetary disk cools, it dissipates heat via radiative and convective processes. Small parts of the disk become gravitationally unstable; as the local radiation pressure can no longer stand against self-gravitation, and form local fragments of mass on the order of 10–20 $M_\oplus$. This process can take as little as 10^3 years. These small fragments of the disk then proceed to form giant planets via runaway gas accretion. We, therefore, can expect fully formed giant planets in about 1 Myr. We will see in Section 4 which of these two formation models is more likely to explain the giant planets we see today.

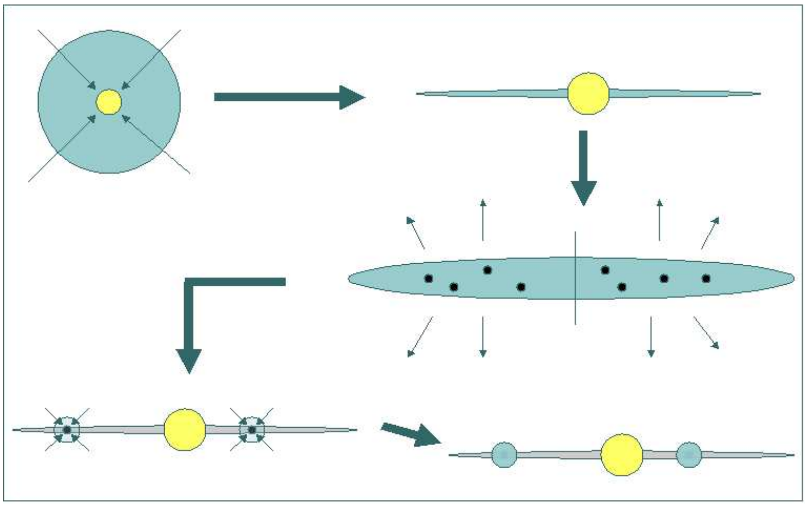

Figure 2: Disk Gravitational Instability Model of Giant Planet Formation

Both formation models predict Jupiter-sized planets at orbital radii of several AU from their host stars. We have to invoke the process of planetary migration to explain why so many giant planets are found so close to their host stars (even after taking the observational bias into account.) Planetary migration occurs when the disk gas and dust have not yet fully dissipated. Gas drag from the disk acts on the forming planetesimals, and causes the transfer of angular momentum outward, hence decreasing the orbital radius. This can have a significant effect on both accretion of gas onto giant planets, as well as the formation of any planetesimals inside the orbital radius of the migrating protoplanetary core.

Giant planet migration, therefore, is a plausible explanation for why we observe giant planets with small orbital semimajor axes. These planets cannot have formed where we see them today, because the stellar radiation field would have destroyed them long ago. One difficulty with the planet migration hypothesis is making it stop in time for the giant planets to survive. We still do not know why the migration process stops where it does; however, several explanations have been put forward. If the gas in the protoplanetary disk is removed, either by planetary or stellar accretion, or by radiative pressure blowout, the gas drag disappears, and inward moving planetary cores will presumably halt their migration. Another possibility is the interaction of the stellar magnetic field with the disk, which causes angular momentum transfer that also halts inward migration.

4 Metallicity and Giant Planets

In 1997, Gonzalez noticed an interesting trend when he measured the metallicity of the first few known planet host stars. He found that these stars had higher metallicity on average than stars in the field, which were known not to have any planetary companions. He proposed that this was due to a connection between the presence of planetary companions and stellar evolution of their hosts.

After the detection of more than two hundred extrasolar planets since then, we now have confirmation that the metallicity of giant planet-hosting stars is indeed, on average, higher than that of stars without such companions. The two leading planet-hunting groups have obtained high resolution spectra of all stars in their respective surveys, enabling them to obtain detailed information about their chemical abundances, effective temperatures and surface gravity. These include both planet-host stars as well as stars without planets. A meaningful comparision between the spectral properties of the two populations is thus possible.

Fischer and Valenti obtained spectra for 1,040 FGKM stars selected for the survey carried out by Marcy et al. in 2005. They then fit the spectra of these stars to stellar atmosphere models, and calculated the $[Fe/H]$ ratio, $T_{\rm eff}$ and $\log g$ values for each specimen. They reproduced Gonzalez's results from 1997; planet-hosting stars do have higher metallicities than stars without planets in a uniform magnitude limited sample. Moreover, the incidence of stars with planets seems to rise with increasing metallicity. Figure 3 shows this trend clearly.

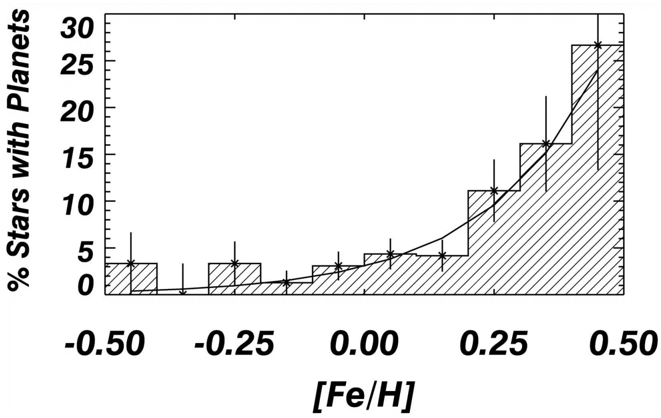

Figure 3: Incidence of Stars with Planets as a Function of Metallicity (Fischer & Valenti 2005)

Note that the probability of finding a star with a planet is a nearly flat function starting from a $[Fe/H]$ value of -0.5 to about solar metallicity. Thereafter, it rises as a relatively steep function of metallicity. Fischer and Valenti characterize this distribution with the following relation:

$$P(planet) = 0.03 \times 10^{2.0[Fe/H]} \tag{5}$$

which may be rewritten as:

$$P(planet) = 0.03 \left[\frac{(n_{Fe}/n_H)_{star}}{(n_{Fe}/n_H)_{\odot}} \right]^2 \tag{6}$$

The probability of finding a giant planet around a star with a certain metallicity, therefore, is proportional to the square of the number of the iron atoms observed in that star. Given the large number of stars in this sample, this relation is likely to be statistically significant, and should hold in the range of metallicities that Fischer and Valenti looked at.

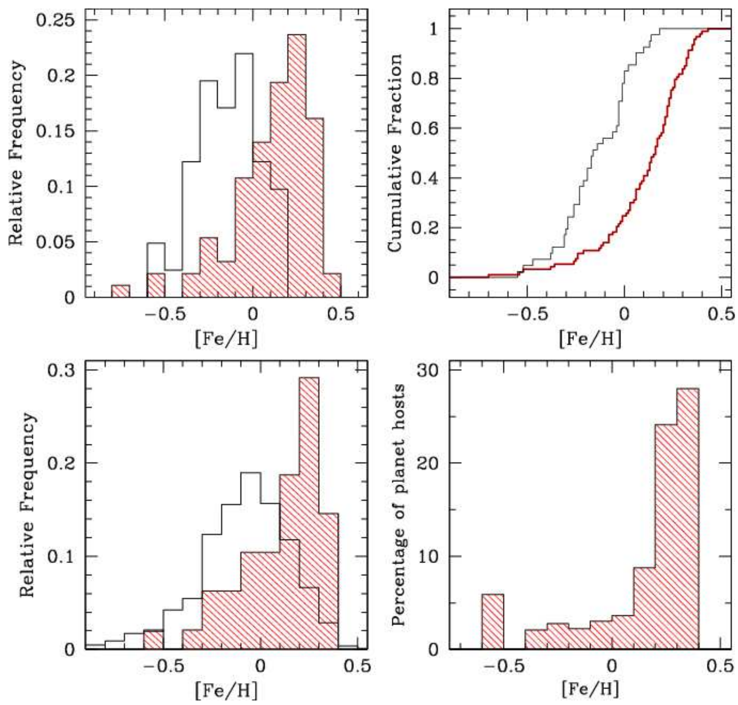

Figure 4: Giant Planet Incidence as a Function of Metallicity (Santos et al. 2004)

Santos, Israelian, and Mayor carried out a similar analysis on nearly 150 stars in 2004. Of these, 98 were planet hosts, and 41 were stars without planets. They conclude that nearly 25% of stars with $[Fe/H]$ of about +0.5 have giant planet companions (Figure 4). The shaded population in the figure represents all stars with planets, and can be seen to have comparatively higher metallicity than the stellar population without planetary companions. Using Fischer and

Valenti's relation (Equation 5) for stars with $[Fe/H] = +0.5$, we obtain a planet-hosting fraction of 0.3. This is in reasonable agreement with Santos et al., even though there are considerable systematic differences between the two surveys. The metallicity-planet hosting trend is, therefore, very likely to be real.

Two possible explanations have put forward for this trend. The first is that the planet hosting star has high metallicity due to its continual accretion of metal-rich planetary fragments that have migrated inward during the course of evolution of the protoplanetary disk. The metals end up in a layer of the photosphere close to the surface of the star. The leftover planetesimals end up in close orbits around the star and thus form the building blocks of giant planets. The second explanation holds that the origin of the high metallicity in planet hosting stars is primordial. The stars that end up with planetary companions must have formed out of a metal-rich nebula. A metal-rich protostellar nebula has a higher surface density, and thus forms planetesimals out of metal-rich dust grains readily. The process then follows the Core Instability Accretion model as well as the planetary migration model outlined in Section 3.

To distinguish between these two competing explanations for the metallicity trend, Fischer and Valenti looked at various properties of their sample which contained both stars with planets, as well as stars without planets. They first looked at how surface temperature varied with metallicity of stars. The effective surface temperature of a star may be used as an analogue for its spectral type. Thus, hotter stars, for example F dwarfs, have higher surface temperatures than cooler stars, such as G dwarfs. If the origin of the high metallicity in planet hosts is due to the accretion of metal-rich planetary cores, then these metals must end up in the convective zone in the outer envelope of such stars.

The depth of the convective zone is inversely proportional to surface temperature, i.e. F dwarfs have shallower convective zones than G dwarfs. Stars with shallower convective zones do not recycle their accreted materials as much as stars with deeper convective zones. Therefore, if the high metallicity of planet hosts is related to accretion and eventual deposition of metals in the convective zones of stars, higher metallicity must be correlated with higher surface temperature (and shallower convective zones). Figure 5 shows that this trend does not exist in Fischer and Valenti's sample of main sequence dwarfs from their 1,040 FGKM stars.

A similar experiment can be carried out on giant stars. Although there are few giant star planet hosts, they follow the same metallicity/planet-host incidence relationship as their dwarf counterparts. As stars evolve towards the red giant branch, they become more convective; the radiative efficiency decreases because of increased opacity in the stellar interior. As the depth of the convective zone in such stars increases, any accreted matter should be mixed and diluted, this decreasing the metallicity observed in stars further along the red giant branch (i.e. redder in color, and with lower surface temperature.) Figure 6 shows a plot of the effective temperature of giant stars in the Fischer-Valenti sample (serving as a proxy for color), and the metallicity observed in such stars. Once again, no trend can be discerned from the data.

One final piece of evidence leads us to believe that the high metallicity

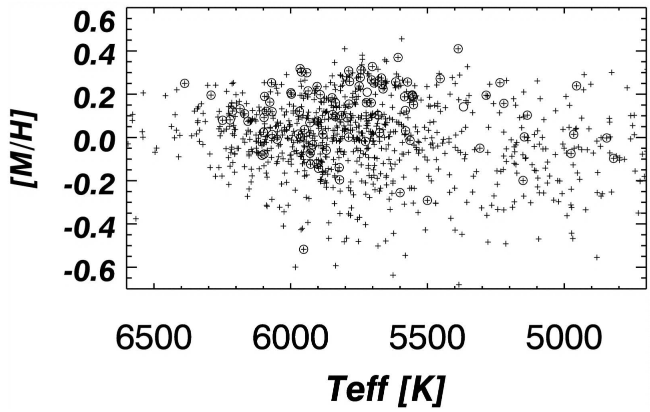

Figure 5: $T_{\rm eff}$ and Metallicity Relationship for Main Sequence Dwarfs (Fischer & Valenti 2005)

in planet hosts cannot be due to accretion of metal-rich planetary fragments. Figure 7 shows the relationship between the mass of stars and their metallicity. This time, a trend is clearly observable within the data; higher mass stars tend to be more metal-rich. The solid line in the figure is the best fit for stars without planets, and the dashed line is the best fit for stars with planets. Both best fit lines appear to be parallel to each other, with the line for stars with planets having a nearly constant +0.12 dex metallicity offset from the line for stars without planets. If the origin of high metallicity in planet hosts is due to accretion, stars with lower metallicities but higher masses could start forming planets, and the two lines would no longer be parallel. Stars with initially low metallicities would be enriched by accreting planetesimals, thus skewing the line for stars with planets downward. We do not see this behavior, leading us to believe that the accretion hypothesis for the origin of high metallicity in planet hosts must be incorrect. The high metallicity in planet hosts must therefore have a primordial origin; the protostellar nebula is metal-rich to begin with.

The primordial origin of metallicity in planet hosts also appears to prefer one of the planetary system formation models discussed in Section 3. The Core Instability Accretion model of planetary formation prefers higher metallicities in the protoplanetary disk. Increased metal content in the disk leads to a higher condensation temperature for matter, as well as a higher surface density of solid matter. This allows the disk to form protoplanetary cores quickly, which then accrete by gravitational interaction, and finally enter the runaway gas accretion phase, where they form gas giant planets. This process is reasonably fast, and can happen before the gas in the disk dissipates or is blown out of the system by radiation pressure.

On the other hand, the formation of giant planets via the Disk Gravitational Instability model appears to be hampered by the presence of high metal content

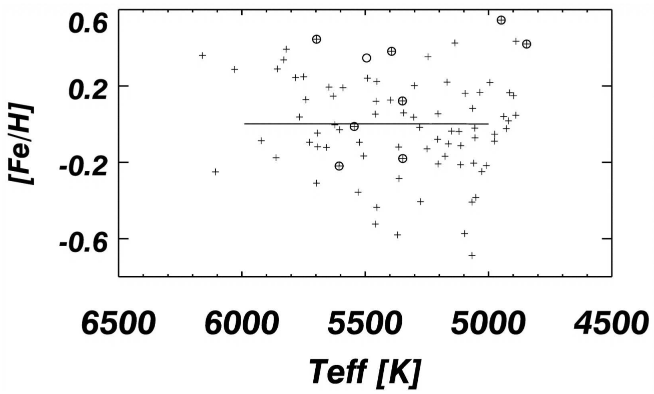

Figure 6: T_{eff} and Metallicity Relationship for Giants (Fischer & Valenti 2005)

in the protoplanetary disk. A higher metallicity leads to a higher radiative opacity, which decreases the rate of cooling, and the disk cannot condense to form planetesimals easily. This in turn reduces the rate of formation of giant planets from these planetesimals. Since observational evidence points to the fact that higher metallicity actually leads to a higher incidence of giant planets, this model cannot be used to correctly explain the formation of giant planets. The fact that the protostellar nebula is metal-rich to begin with, therefore, leads us to believe that giant planet formation can be explained by the Core Instability Accretion model, and that the subsequent migration inward (via gas drag) deposits these newly formed planets into tight orbits around their host stars.

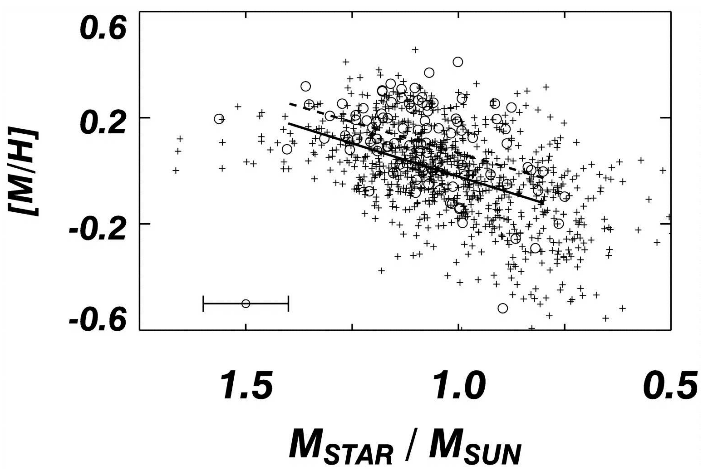

Figure 7: Metallicity-Mass Relationship for All Sample Stars (Fischer & Valenti 2005)

5 Metallicity and Terrestrial Planets

We have seen so far that the formation of giant planets is closely related to the metallicity of the host star. We may conclude that, in general, planets form more readily if there are more metals available. This statement may be true for giant planets, but it may not necessarily apply to terrestrial planets, like the Earth in our own Solar System. Although our ability to detect these smaller planets is limited due to the restrictions imposed by distance and precision, we still see a startling lack of Earth-like planets in our surveys so far.

Given the results of the metallicity-giant planet correlation, we would be tempted to conclude that metal-poor stars cannot form giant planets with the frequency seen in their metal-rich cousins. If we compare the metallicity of our Sun to that of the population of stars with extrasolar planets, we see that it lies on the 'metal-poor' end of the metallicity distribution. Is it possible that the incidence of terrestrial planets is independent of that of giant planets, and uncorrelated with the metallicity of planet host stars?

A partial answer to this question is provided by the work of Greaves, Fischer, and Wyatt, who carried out a survey of metal-poor (but Sun-like) stars in 2006. They compared this population to the population of stars known to have giant extrasolar planet companions. They found that metal-poor stars tended to form debris disks more readily than metal-rich stars. Debris disks, therefore, appear to be characteristic of many Sun-like but metal-poor stars. The amount of matter in such disks is much lower than what would be required to form several giant planets, like those seen in metal-rich planetary hosts.

If our own Sun is relatively metal-poor, yet has four terrestrial-type planets;

this would suggest that the formation of planets such as these is decoupled from the dependence on metallicity seen for giant planets. In fact, the metal-rich nature of the stars surveyed so far might even act to hinder the formation of terrestrial planets. The high surface density of a metal-rich disk might lead to several giant planets being formed, thus starving the smaller terrestrial planetary cores of much needed material. The inward migration of giant planets would further disrupt the accretion of smaller terrestrial planets being formed in orbits closer to the star.

One other important factor related to metallicity must be taken into account when considering its influence upon possible terrestrial planets. We must remember that the Galaxy itself exhibits a metallicity gradient. Near the Center of the Galaxy, the average metallicity increases due to the depth of the potential well. We might, therefore, expect increased giant planet formation in protostellar nebulae close to the Galactic Center. This is balanced, however, by the fact that much of the star formation in the Galaxy takes place in the Spiral Arms. Thus, we might expect there to be a *Galactic Habitable Zone* where the metallicity of the interstellar medium is favorable towards terrestrial planet formation.

6 Conclusion

Observations of Jupiter-mass planets found in radial-velocity surveys show that their host stars tend to be more metal-rich than comparable stars of the same mass and luminosity that have no planetary companions. The probability of finding a giant planet around a star in the population observed so far is a relatively steep function of metallicity starting from about the solar value of $[Fe/H] = 0.00$. The most likely explanation for this dependence is that these stars are formed from metal-enriched protostellar nebulae. Planetary accretion into host stars is ruled out as a significant source of this high metallicity value.

The primordial origin of the high metallicity seen in planet hosts also lends support to the Core Instability Accretion model of planetary formation. This holds that the giant planets are formed by runaway accretion of leftover gas in the later stages of protoplanetary disk evolution. Gravitational interactions between planetesimals are thought to play a major role in the formation of giant planet cores, which then accrete massive amounts of gas to end up as the giant planets observed today. The close orbits of these planets around their host stars can be explained by inward migration via gas drag from the protoplanetary disk.

Finally, the presence of giant planets around a given star may not be necessarily conducive to the formation of terrestrial planets in the same system. Indeed, it appears that low mass planets can form around stars with low metallicities more readily than they can form around high metallicity stars. The Solar System is an excellent example of this independence from the general trend of high metallicity leading to an increased incidence of giant planets.

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