Chemical Abundances in the Universe:
Connecting First Stars to Planets
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Metallicity and Planet Formation – Observations

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Abstract. Early abundance measurements established that stars known to host giant planets are metal rich compared to the Sun. More extensive abundance measurements then showed that giant planet hosts are metal rich compared to the parent sample in planet searches. Stars spanning a range of convection zone depths all show the same metallicity effect, ruling out significant abundance enhancements due to selective accretion. Most known planets migrated inwards from the snow line, but subsamples closer to and further from the star have similar iron abundances, so the stopping point of migration does not depend on metallicity. Stars recently discovered to host Neptune mass planets may be metal poor compared to the Sun, particularly if one focusses on stars that do not also host higher mass planets. This would be consistent with core-accretion models of planet formation. Before drawing physical conclusions, it will be necessary to check for metallicity bias in the subsample of stars around which Neptune mass planets could have been found. M dwarf abundances are currently too uncertain to relate planet frequency and host star metallicity, due mainly to missing or incorrect molecular line data.

Keywords. planetary systems, planetary systems: formation, stars: abundances, stars: late-type

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1. Introduction

Chemical abundances in the photospheres of cool main-sequence stars provide a fossil record of the composition of the parent molecular core and the initial composition of the circumstellar disk. Exceptions may occur, for example when light elements fuse at the base of the convection zone or when a star preferentially accretes specific elements from a an evolved stellar companion or perhaps an evolved circumstellar disk. Nonetheless, the dependence of planet formation on disk abundances can be observationally constrained by studying the frequency of observed planets as a function of photospheric abundance.

2. F, G, and K Star Abundances

Gonzalez (1997) noted that the first four stars known to host an exoplanet were all metal rich compared to the Sun. As more planet hosts were discovered, Gonzalez and others showed that known planet hosts tended to be metal rich compared to the Sun. Figure 1 compares abundances from the SPOCS catalog (Valenti & Fischer 2005) with other published results for stars in common. Small systematic differences are apparent, but all studies agree that giant planet hosts are metal rich, relative to the Sun.

Before drawing physical conclusions about planet formation, it was necessary to check whether the much larger planet search samples were themselves biased in favor of high metallicity. Santos, Israelian, & Mayor (2004) and Valenti & Fischer (2005) demonstrated that giant planet hosts are indeed metal rich compared to the parent sample in planet searches.

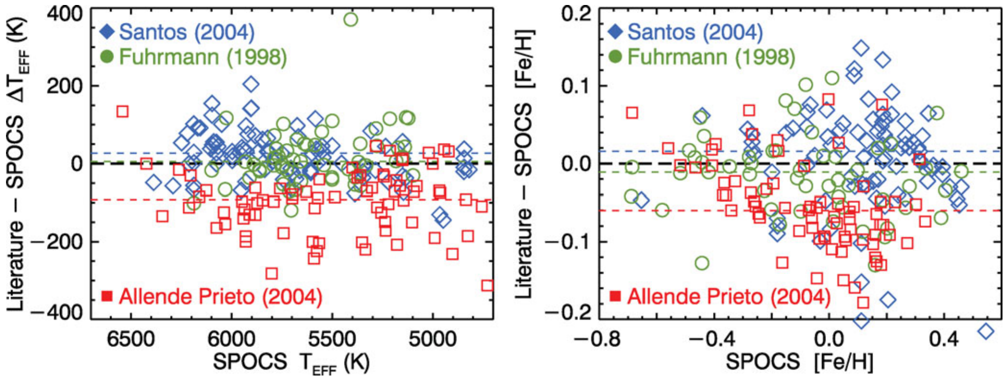

Figure 1. Comparison of effective temperatures *(left panel)* and iron abundances *(right panel)* from Fuhrmann (1998), Allende Prieto *et al.* (2004), Santos, Israelian, & Mayor (2004), relative to values from the SPOCS catalog (Valenti & Fischer 2005). Systematic difference are evident.

3. Frequency of Giant Planets

Fig. 2 shows iron abundance distributions for all stars in the Fischer & Valenti (2005) sample and also the subset with uniformly detectable giant planets. The ratio of these two distributions gives the probability of a star in the sample having a known giant planet, as a function of stellar iron abundance. Planet detectability rises quickly with iron abundance for stars more metal rich than the Sun.

Valenti & Fischer (2005) determined stellar parameters by fitting spectra using SME (Valenti & Piskunov 1996). Santos, Israelian, & Mayor (2004) studied a different sample of stars, using a different spectrograph, different spectral lines, and a different radiative transfer code. They fitted equivalent widths rather than line profiles and adopted a different gravity constraint. Despite these differences, Fig. 2 shows that the two studies find a similar relationship between planet detectability and host star metallicity.

Giant planets are believed to form far enough from the star that condensed volatiles (rather than diffuse gas) can be accreted onto a rocky core. Most known planets migrated inwards from where they formed. Livio & Pringle (2003) suggested that inward migration could be enhanced in metal-rich disks, but as yet this effect has not been observed. The

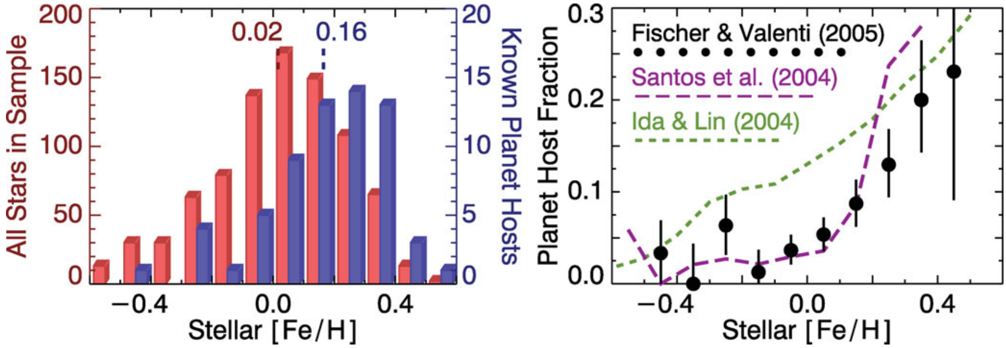

Figure 2. *Left:* Distribution of iron abundances in a uniform planet search sample (Fischer & Valenti 2005), for all stars *(left bins)* and for stars known to host giant planets *(right bins)*. *Right:* The fraction of stars known to host giant planets increases dramatically with increasing iron abundance. Fischer & Valenti (2005) and Santos, Israelian, & Mayor (2004) obtain similar results, despite different samples, spectrographs, and analysis techniques. A model by Ida & Lin (2004) shows similar behavior.

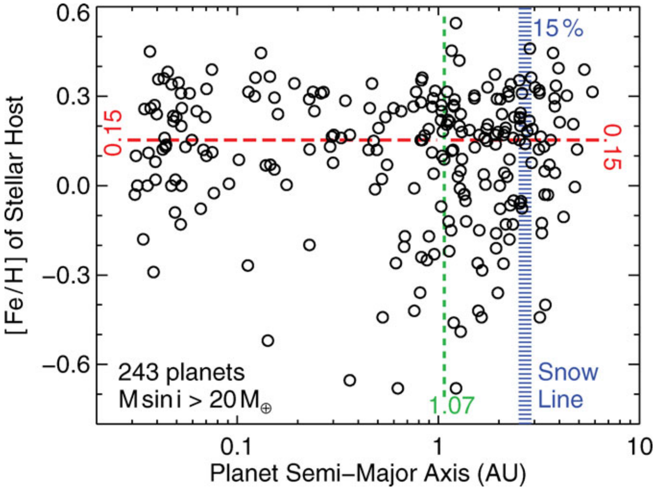

Figure 3. Iron abundances of stars known to host planets more massive than $20\,M_\oplus$. At least 85% of these planets have migrated inwards from beyond the snow line. The median semi-major axis of known planets is 1.07 AU. The median iron abundance on both sides of this boundary is 0.15, so there is no evidence that abundance affects the stopping point of inward migration.

median separation between known planets and their host star is 1.07 AU. Fig. 3 shows that subsamples of known planets closer to and further from the star have similar iron abundances, so the stopping point of migration does not depend on metallicity.

4. Frequency of Neptune Mass Planets

Preliminary results from the HARPS spectrograph suggest that F, G, and K stars known to host planets less massive than $20\,M_\oplus$ are *not* metal rich, relative to the Sun (Mayor 2009). If this result is confirmed, one interpretation would be that planet mass depends on how soon envelope accretion begins and that metal-rich disks form rocky cores faster than metal-poor disks.

Fig. 4 shows iron abundance versus $M \sin i$ for published planets. Each host star appears only once per panel, either at the position of least massive known planet *(left panel)* or the position of the most massive known planet *(right panel)* in the system. Using $M \sin i$ for the least massive (or for all) planets in a system improves the statistics for low mass planets, but potentially obscures the physics. To test the hypothesis that metal-poor disks cannot form high-mass planets, one should focus on the maximum $M \sin i$ in a system. To illustrate this point, note that all four metal-rich stars with published planets less massive the Neptune also have another planet more massive than Neptune. Similarly, the six planet hosts that do *not* have a planet more massive than Neptune are all metal-poor relative to the Sun (though one of the M dwarfs may be metal-rich, see next section).

Despite sparse statistics, it seems clear that stars with published planets less massive Neptune and no planets more massive than Neptune are metal poor. However, before interpreting these results physically, it is important to check for metallicity bias in the subsample of stars around which Neptune mass planets could have been found. Santos, Israelian, & Mayor (2004) and Fischer & Valenti (2005) performed analogous tests for giant planets after Gonzalez (1997) noted that published planet hosts were all metal rich. In this case, Neptunes might only be detectable around stars with low intrinsic velocity

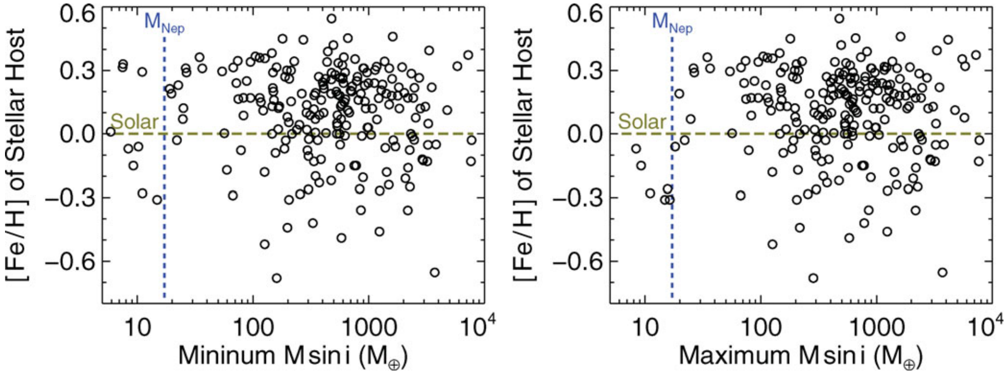

Figure 4. Iron abundance of known planet hosts as a function of the least massive *(left panel)* and most massive *(right panel)* known planet in the system. The maximum $M \sin i$ plot addresses more directly whether stars with lower iron abundance than the Sun are able to form planets less massive than Neptune, despite an observed dearth of more massive planets.

variations, which might imply low activity, old age, and hence low metallicity. These detectability issues are best evaluated by the planet search team.

5. M Dwarf Abundances

M dwarfs are useful targets in the search for low mass planets because observed velocities are inversely proportional to stellar mass. However, M dwarf abundances are difficult to measure spectroscopically due to inaccurate or missing molecular line data. Improved line data are desperately needed, especially for TiO.

An alternate approach is to use broad-band photometric indexes that are calibrated using binaries, where the primary is warm enough to obtain a reliable spectroscopic abundance. Using binaries, Johnson & Apps (2009) have redetermined the photometric

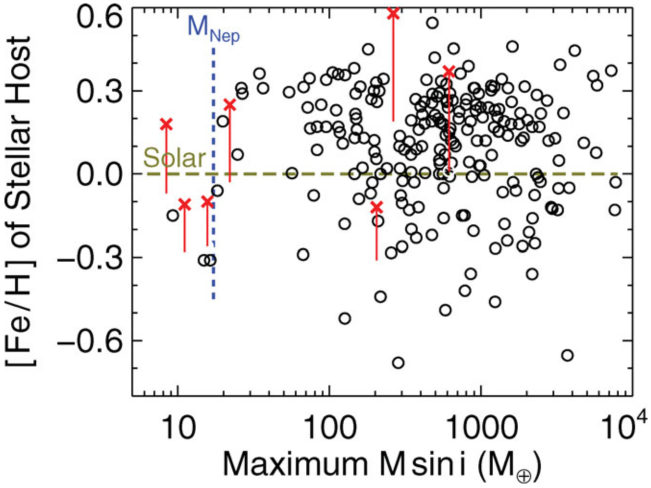

Figure 5. Similar to Fig. 4, but with iron abundances for M dwarfs in Johnson & Apps (2009) adjusted upwards (× *symbols*). Even after this correction, 5 of 6 planet hosts that do not have a known planet more massive than Neptune tend to have lower iron abundance than the Sun. More work is required to characterize sample and detection biases in searches for systems that only have planets less massive than Neptune.

abundance scale for metal-rich M dwarfs, finding a significant increases in abundance. Fig. 5 shows the impact of this change. Three of the six planet hosts with only sub-Neptune mass planets are M dwarfs. One of these planet hosts becomes slightly metal-rich, but the mean is still metal poor relative to the Sun

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