Stellar Chemistry in Stars with Planets as a Probe of Planetary Formation and Planetary-System Architecture

White Paper in Response to the Solicitation by the Gemini Observatory for High-Resolution Optical Spectroscopy

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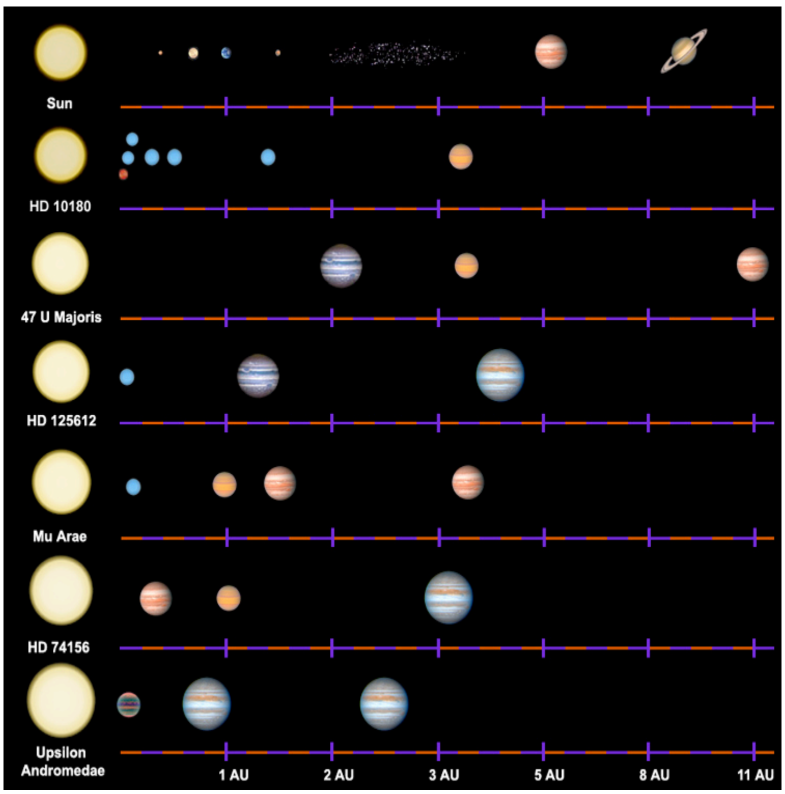

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Executive Summary

Detailed analyses of the chemical abundances in exo-planet hosting stars, in comparison to stars which do not harbor known planets, has revealed intriguing differences in their respective chemical make-ups. These chemical signatures provide clues to how planets form, how the parent star's properties affect the type of planetary system that forms, and even yield insights into past interactions between proto-planetary disks and young planets with their parent stars. Precise and detailed chemical abundance studies of the ever increasing number of known planet hosting stars will require high-resolution spectroscopy over a broad range in wavelength.

Introduction

The number of known exoplanets discovered to-date is approaching 500, half of which have been detected in the last 3 years. This number does not include the ~700 Kepler transiting targets released in June 2010 (Borucki et al. 2010, Science, 327, 977), since these have not yet been confirmed as planetary transits beyond the Kepler data; these systems were discovered from only the first 43 days of Kepler observations, with the mission continuing over the next 3 years. In addition, 400 more Kepler targets will be released in January 2011. The majority of confirmed exoplanets identified so far have been discovered via radial-velocity measurements, with the next largest number discovered from planetary transits of the hosting star. In the coming decade, the number of known transiting planetary systems will grow enormously (due to Kepler's continuing mission, CoROT, as well as a number of ground-based surveys). Radial-velocity surveys will also continue to uncover new systems and, with longer time baselines coupled with improved precision, will reach ever-longer period systems with larger orbital separations, as well as smaller and smaller planetary masses. With the launch of JWST in 2014 and its extreme sensitivity in the mid- and far-IR, the detection of direct radiation from certain types of planets will open additional windows into the ways into which exo-planetary systems can be probed.

All of the various exo-planetary detection methods have different selection biases and a proper overall understanding of how exo-planetary systems form and evolve will require follow-up scrutiny by a variety of observations and analyses. One important follow-up analysis will be the precise determination of key host-star characteristics, such as T_{eff}, age, mass, and detailed chemical abundances from high-resolution spectroscopy.

Chemical Abundance Signatures in Planet-Hosting Stars

Stellar Metallicity and Its Effect on Planetary Masses:

Early-on it was recognized that the stars that were discovered to host planets from the radial-velocity (RV) surveys tended to have rather large metallicities (e.g., Gonzalez 1997, MNRAS, 285, 403). With the ever increasing sample size of RV-selected exo-planetary systems, it has been shown by a number of studies that the shift in metallicity (usually characterized by [Fe/H]) between planet-hosting FGK dwarf and subgiant stars, when compared to FGK dwarfs and subgiants known not to host closely orbiting giant planets, is a statistically significant difference. Most studies agree (e.g., Fischer &

Valenti 2005, ApJ, 622, 1102) that in the majority of cases, the metal-rich nature of the planet-hosting stars is intrinsic to the star itself, and this suggests that planets, at least giant planets of the type that are found most easily in RV surveys, are preferentially formed in a metal-rich environment.

In a recent homogeneous abundance analysis of 117 FGK planet-hosting main-sequence stars when compared to 145 similar-type stars which are RV stable (with $\sigma_{RV} < 30$ m/s), Ghezzi et al. (2010, ApJ, 720,1290) found that the planet-hosting stars were more metal rich, on average, by [Fe/H]=+0.15 dex. More interestingly, Ghezzi et al. noted that stars which hosted Jovian-mass planets tended to be more metal-rich than those stars which have only Neptunian-mass planets. This result suggests that metallicity plays a role not just in the formation of giant planets, but may also influence the distribution of planetary masses within exo-solar sytems. The shift in values of [Fe/H] between stars with Jovian- versus Neptunian-mass planets is shown in Figure 1. Probing this effect in detail, which will test planetary system formation mechanisms, will require much larger samples.

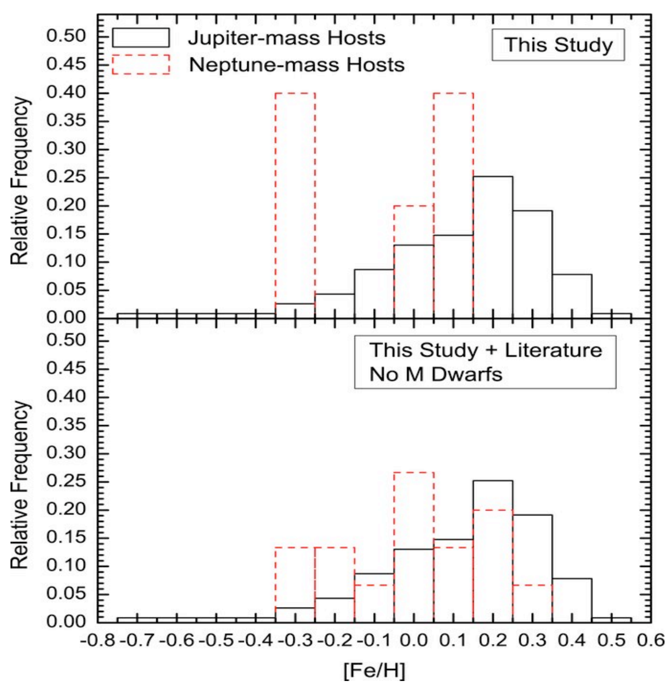

Figure 1: The top panel shows [Fe/H] distributions from Ghezzi et al. (2010), with the black histogram representing planet-hosting stars which contain at least one Jovian-mass planet, while the red dashed histogram represents the sample of stars hosting only planets with Neptune-like masses. The shift towards lower Fe abundances for the Neptunian-hosting stars is significant. The bottom panel is the same as the top with the addition of all abundances from the literature and the shift between the two samples remains.

Parent-Star Masses and the Formation of Planets:

Extending the abundance studies of planet-hosting stars beyond the main-sequence and subgiant branches to giant stars which host planets reveals new details about the interplay between planets, stars, and metallicity. Contrary to the observation that main-sequence and subgiant planet-hosting stars are more metal-rich than stars without known planets, Schuler et al. 2005, ApJ, 632, L131), Pasquini et al. (2007, A&A, 473, 979) and Ghezzi et al. (2010, ApJ, submitted, [arxiv:1008.3539]) have found that this planetary-metallicity correlation does not extend to evolved giant stars; giants with planets tend to be more metal-poor than both their main-sequence and subgiant counterparts. A key point about the samples of the various stellar types probed is that the giant stars that have been discovered to host planets are more massive than the main-sequence and subgiant planet-hosting stars. This result that the average metallicity of planet-hosting stars is related to the average mass within the stellar sample, with giants representing the more massive but lower metallicity population, is taken as an observational signature of core-accretion as the main mechanism for planet formation, at least for planets which form relatively close to their parent stars. Since higher-mass stars tend to have more massive disks with more total mass of metals available for planet formation through core accretion, the higher masses of the giant stars compensates for lower metallicites.

On the Possibility of Using Abundances to Identify Systems with Terrestrial Planet-Like Architectures:

Using a technique in which spectral lines in stars with very similar stellar parameters to those of the Sun (solar twins) are compared in a careful differential abundance analysis, Melendez et al. (2009, ApJ, 704, L66) found that the chemical composition of the Sun is anomalous with respect to most (85%) solar twins, which are stars with physical parameters similar to the Sun. Compared to its twins, the Sun exhibits a deficiency of refractory elements (those with high condensation temperatures T_{cond}) relative to volatile elements (those with low T_{cond}), as shown in Figure 2. This finding is speculated to be a signature of the planet formation that occurred more efficiently around the Sun compared with the majority of solar twins. Furthermore, within this scenario, it seems more likely that the abundance patterns found are specifically related to the formation of terrestrial planets, as while refractory material is missing in the Sun, those dust-forming elements are over-abundant in meteorites and terrestrial planets. If correct this is an exciting result, as it points the way to using chemical abundance distributions to infer the existence of inner terrestrial-type planetary architectures.

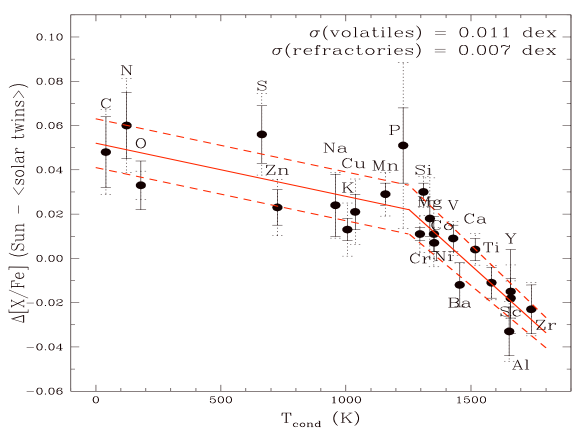

Figure 2: Differences between [X/Fe] of the Sun and the mean values in the solar twins as a function of T_{cond}. The abundance pattern shows a break at T_{cond} ~1200 K. The solid lines are fits to the abundance pattern, while the dashed lines represent the standard deviation from the fits. The low element-to-element scatter from the fits for the refractory (σ= 0.007 dex) and volatile (σ= 0.011 dex). The zero-point for the differences in relative chemical abundances depends on the adopted reference element, which here is Fe.

Follow-up studies using independent samples have confirmed the findings of Melendez et al. (2009), showing that indeed the Sun is anomalous when compared to most nearby solar twin stars (Ramirez et al. 2009, A&A, 508, L17; Gonzalez et al. 2010, MNRAS, 407, 314; Ramirez et al. 2010, A&A, in press [arxiv:1008.3161]). If the chemical signature found in the Sun is indeed due to the formation of terrestrial planets, then the study of metal-rich solar analogs and F dwarfs can provide further clues to planet formation mechanisms (Ramirez et al. 2010).

Large Samples of Precise Chemical Abundances in Stars with and without Planets from Radial-Velocity and Transit Surveys

The above mentioned studies have demonstrated that there are subtle, but fascinating patterns in the chemical abundance distributions of the parent stars of exo-planetary systems that have significance beyond a simple empirical shift towards higher metallicities. The interplay between stellar parameters, such as mass or age, and the chemical compositions may hold clues to the underlying mass distributions of planets, or even the architecture of the planetary system itself. The possibility that ground-based spectroscopy will help in categorizing exo-planetary systems is an exciting prospect for the coming decades.

Further progress in this field requires, at its core, high-resolution, high-S/N spectra of all of the planet-hosting stars being discovered, with the majority being found by both RV and transit surveys. The science proposed here ties in very well with other extra-solar planet projects currently being pursued on both sites at Gemini Observatory, thus helping solidify the observatory's leadership in this field.

Overarching Instrument Requirements for a Gemini Optical Echelle Spectrograph

Because several thousand planet-hosting stars are expected to be discovered over the next few years, follow-up high-resolution spectroscopy is an important observational capability. Target densities will be low, with the stars spread over the entire sky, so a single-object spectrograph is well-matched to this program. Many of the transiting systems will be faint (V>16), so pushing to the largest samples will be challenging even for an 8-m class telescope, as high-S/N is necessary.

A spectrograph with minimum R=30,000 and wavelength coverage from 3900-10000A is feasible as a Gemini Cassegrain-mounted instrument. The geometrical relations between slit width, telescope aperture, and grating size suggest a collimated beam size of ~14 cm. The input parameters are very similar to those of the Magellan instrument MIKE (Bernstein et al. 2003 SPIE 4841 1694). With folding of the optical path, a design similar to MIKE would fit into the Gemini instrument envelope. MIKE has demonstrated that the high throughput and large wavelength coverage required for optimum performance on Gemini are possible in a physically compact package. For brighter targets, a higher resolution mode (minimum R~45,000) using a smaller slit should also be incorporated as requirement.