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HIGH-RESOLUTION SPECTROSCOPY OF THE PLANETARY HOST HD 13189: HIGHLY EVOLVED AND METAL-POOR[1]

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ABSTRACT

We report on the abundances of 13 elements in the planetary host HD 13189, a massive giant star. Abundances are found to be subsolar, with [Fe/H] = −0.58 ± 0.04; HD 13189 is one of the most metal-poor planetary hosts yet discovered. Abundance ratios relative to Fe show no peculiarities with respect to random field stars. A census of metallicities of the seven currently known planet-harboring giants results in a distribution that is more metal-poor than the well-known metal-rich distribution of main-sequence (MS) planetary hosts. This finding is discussed in terms of accretion of H-depleted material, one of the possible mechanisms responsible for the high-metallicity distribution of MS stars with planets. We estimate the mass of the HD 13189 progenitor to be 3.5 $M_\odot$ but cannot constrain this value to better than 2–6 $M_\odot$. A stellar mass of 3.5 $M_\odot$ implies a planetary mass of $m \sin i = 14.0 M_J \pm 0.8 M_J$, placing the companion at the planet/brown dwarf boundary. Given its physical characteristics, the HD 13189 system is potentially unique among planetary systems, and its continued investigation should provide invaluable data to extrasolar planetary research.

Subject headings: planetary systems — stars: abundances — stars: atmospheres — stars: early-type — stars: fundamental parameters — stars: individual (HD 13189)

Online material: machine-readable table

1. INTRODUCTION

Ascertaining the physical properties of planetary host stars, the chemical abundances thereof in particular, is a critical component of understanding the formation and evolution of extrasolar planetary systems. Of the approximately 131 stars presently known to harbor planets, Fe abundances have been derived for no fewer than 117, with the abundances of numerous other elements having been determined for many. The results of these abundance analyses have led to the now well-known discovery that stars with planets tend to be metal-rich compared to random field stars (e.g., Fischer & Valenti 2005; Santos et al. 2005). Two hypotheses have emerged as possible explanations of the planet-metallicity correlation: accretion of H-depleted, rocky material by planetary hosts and preferential planet formation in high-metallicity, protoplanetary disks. Both of these propositions are discussed extensively in the pertinent literature (e.g., Gonzalez 1997; Ida & Lin 2004; Fischer & Valenti 2005).

An interesting consequence of the radial velocity (RV) method used currently to detect extrasolar planets is the limited range of stellar spectral types of stars chosen as targets. Planet searches generally focus on older, main-sequence (MS) late F, G, and K dwarfs because it is these stars that are bright enough to obtain high signal-to-noise ratio (S/N), high-resolution spectra, have an ample number of usable spectral lines for the RV analyses, and have rotation rates and activity levels that facilitate the detection of planets. Furthermore, there is potentially great sociological significance in finding planets around stars like our Sun. While unique challenges exist for finding planets around younger stars and stars of earlier and later spectral types (e.g., Setiawan et al. 2003; Paulson et al. 2004), the paucity of known planets in orbits around these "other" stars prohibits a full elucidation of extrasolar planet formation and evolution.

Recognizing the importance of filling the gaps of the currently known planetary host sample, a handful of groups have initiated dedicated surveys of low-mass stars (Endl et al. 2003) and evolved G and K giants, the progenitors of which were massive early-type MS dwarfs (Hatzes et al. 2003). Most recently, the Tautenburg Observatory Planet Search (TOPS) program, using the Alfred-Jensch 2 m telescope at the Thüringer Landessternwarte Tautenburg (TLS) with follow-up observations with the 2.7 m Harlan J. Smith and Hobby Eberly (HET) telescopes at The McDonald Observatory, has announced the discovery of a giant planet orbiting the K2 II giant HD 13189 (Hatzes et al. 2005, hereafter Paper I). Based on an estimated luminosity of 3.6 $L_\odot$ and the evolutionary tracks of Girardi et al. (1996), Paper I estimated a mass range of 2–7 $M_\odot$ for the MS progenitor of HD 13189. Thus, HD 13189 may be the most massive star known to harbor a planet. Here we present the results of our abundance analysis of this potentially unique planetary host.

2. OBSERVATIONS AND DATA ANALYSIS

Our abundance analysis makes use of two template spectra (spectra taken without an iodine cell) obtained as part of the TOPS program on 2002 December 19 using the Alfred-Jensch 2 m telescope and the high-resolution coudé echelle spectrometer at TLS, located in Tautenburg, Germany. The spectrometer consists of an echelle grating with 31.6 g mm^{-1} and a cross-dispersing grism; the VISUAL grism has been used, along with a single 2048 × 2048 CCD detector with 15 μm pixels, providing a wavelength coverage of 4660–7410 Å. Each spectrum has a resolution of $R = 67,000$ and a typical S/N of ~115. A standard data reduction process, which includes bias subtrac-

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TABLE 1
EQUIVALENT WIDTHS AND ABUNDANCES

Species	λ (Å)	χ (eV)	log gf	$EW_\odot$ (mÅ)	log $N_\odot$	EW (mÅ)	log N
Fe I	5633.95	4.99	−0.27	82.4	7.59	95.1	6.97
	5705.47	4.30	−1.57	40.1	7.60	82.7	7.14
	5720.90	4.55	−1.95	20.1	7.77	46.4	7.30
	5731.77	4.26	−1.19	59.7	7.54	97.1	6.92
	5732.30	4.99	−1.50	16.9	7.63	31.7	7.16

NOTE.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

tion, flat-fielding, scattered light removal, extraction, and wavelength calibration, using the usual routines within the IRAF facility has been applied to the spectra.

The two individual HD 13189 spectra were co-added into a single, higher S/N (S/N ≈ 160) spectrum, and equivalent widths (EWs) were measured by fitting lines with Gaussian or Voigt profiles using the one-dimensional spectrum analysis package SPECTRE (Fitzpatrick & Sneden 1987). Spectral line selection was aided by the collection of Thevenin (1990); only lines labeled as "case a"—lines with estimated internal uncertainties of ≤0.05 dex in oscillator strengths (log gf) and presumably free from blends in the solar spectrum—were considered. The list was culled further by examining each line in the spectrum of HD 13189 and eliminating those that were deemed to be blended or otherwise unmeasurable. Our final line list, along with the measured EWs for both HD 13189 and the Sun, is presented in Table 1. Solar EWs have been measured in a high-quality (R = 60,000 and S/N = 1000) spectrum of the daytime sky obtained with the 2.7 m Harlan J. Smith telescope at the McDonald Observatory (Schuler et al. 2005b).

Stellar parameters have been determined spectroscopically via an iterative process. The T_{eff} and ξ are determined by adjusting their values until there are no correlations between line-by-line [Fe/H][5] abundances (as derived from Fe I lines) and excitation potential (χ) and reduced EW (log EW/λ), respectively. This method for determining T_{eff} and ξ is used often, but care must be taken to ensure that there is no ab initio correlation between excitation potential and reduced EW, which can lead to degenerate solutions. This is the case with our Fe I list, which consists of 86 lines. The list was trimmed until the correlation between excitation potential and reduced EW was eliminated; this left 47 Fe I lines with a satisfactory range of excitation potentials (0.91 eV ≤ χ ≤ 4.99 eV). Uncertainties in T_{eff} and ξ (1 σ) are determined by adjusting the parameters until the corresponding correlation coefficient has a 1 σ significance. Finally, log g is fixed by forcing Fe abundances derived from Fe I and Fe II lines into agreement; the uncertainty in log g is based on the uncertainty in the difference of the Fe I and Fe II abundances. The final stellar parameters and uncertainties are given in Table 2. We note that our derived log g value supports the finding of Paper I that HD 13189 is a highly evolved giant.

Abundances have been derived using the LTE stellar line analysis package MOOG (Sneden 1973; C. Sneden 2004, private communication). The abfind driver was used to force-fit abundances to the line-by-line EWs for all elements except O. We have used the blends driver to derive the abundance of O from the [O I] λ6300 line, taking care to account for the non-

[5] The bracket notation is used to denote abundances relative to solar values, e.g., [Fe/H] = log [N(Fe)/N(H)]$_*$ − log [N(Fe)/N(H)]$_\odot$, where log N(H) = 12.0.

TABLE 2
FINAL RESULTS

Parameter	Value	σ
T_{eff} (K)	4180	77
log g	1.07	0.19
ξ (km s^{-1})	2.12	0.22
[Fe/H]	−0.58	0.04
[O/H]	−0.22	0.08
[Na/H]	−0.31	0.06
[Mg/H]	−0.21	0.05
[Al/H]	−0.23	0.06
[Si/H]	−0.36	0.07
[Ca/H]	−0.49	0.07
[Sc/H]	−0.52	0.07
[Ti/H]	−0.42	0.07
[V/H]	−0.38	0.12
[Cr/H]	−0.47	0.09
[Mn/H]	−0.58	0.09
[Ni/H]	−0.57	0.04

negligible contribution to the feature by an Ni I blend (e.g., Allende Prieto et al. 2001). The specifics of our O analysis follow that of Schuler et al. (2005a), which should be consulted for details. Model atmospheres with the convective overshoot approximation for HD 13189 and the Sun have been interpolated from the ATLAS9 grids of Kurucz; the solar parameters T_{eff} = 5777 K, log g = 4.44, and ξ = 1.25 were adopted. Atomic parameters for all transitions are from Thevenin (1990), except for those of Mg, which are from the VALD database (Piskunov et al. 1995; Kupka et al. 1999; Ryabchikova et al. 1999), and that of [O I] λ6300, which is from Allende Prieto et al. (2001).

Final absolute abundances for HD 13189 and the Sun are given in Table 1, and the final stellar parameters, relative abundances, and uncertainties for HD 13189 are presented in Table 2. The Fe I abundances are derived with the complete list of 86 lines. Relative abundances are the mean of a line-by-line comparison with solar values, thus limiting the impact of possibly inaccurate gf-values. Final abundance uncertainties are the quadratic sum of the uncertainties related to the adopted stellar parameters, based on sensitivities to arbitrary changes in T_{eff}, log g, and ξ (Table 3), and uncertainties in the mean abundances. For Mn and O abundances, which are based on a single feature, the final uncertainties incorporate uncertainties in the solar abundances. Sensitivities to the adopted C (important for molecular equilibrium calculations, primarily related to CO) and Ni abundances are also included in the final O abundance uncertainty. The final abundance uncer-

TABLE 3
ABUNDANCE SENSITIVITIES

Species	ΔT_{eff} ($\pm$150 K)	Δ log g ($\pm$0.25 dex)	$\Delta\xi$ ($\pm$0.30 km s^{-1})
Fe I	+0.04 / +0.02	±0.05	∓0.09
Fe II	∓0.25	±0.15	∓0.06
O I	±0.01	±0.08	∓0.02
Na I	±0.15	+0.01 / +0.02	∓0.09
Mg I	±0.03	±0.02	∓0.09
Al I	±0.13	±0.00	∓0.07
Si I	∓0.12	±0.07	∓0.04
Ca I	±0.18	0.00	∓0.10
Sc II	∓0.04	±0.11	∓0.06
Ti I	±0.23	0.00	∓0.09
V I	±0.26	±0.02	∓0.15
Cr I	±0.12	±0.01	∓0.08
Mn I	±0.09	±0.03	∓0.02
Ni I	±0.02	±0.07	∓0.10

FIG. 1.—Relative Fe abundances of giants (*red circles*) and dwarfs with planetary companions vs. T_{eff}. The sources of the giant abundances and T_{eff} other than those for HD 13189 are given in the text. Dwarf abundances are from Fischer & Valenti (2005; *black circles*), Santos et al. (2004; *black squares*), and Santos et al. (2005; *black triangles*). The horizontal line represents the mean Fe abundance ([Fe/H] = +0.13) of the dwarf sample.

tainties are on the order of 0.05–0.10 dex, but larger uncertainties due to systematic errors, e.g., related to relative differences in the atmospheric models, cannot be ruled out.

3. DISCUSSION

The derived Fe abundance, [Fe/H] = -0.58 ± 0.04, places HD 13189 in the lower envelope of the planetary host metallicity distribution and makes HD 13189 one of the most metal-poor planetary hosts yet discovered. Furthermore, with a semi-major axis in the range 1.5–2.2 AU (Paper I), the planetary companion of HD 13189 is the only one known to have a semimajor axis >1.0 AU and orbit a star with a metallicity <-0.40, a combination that is potentially important to understanding giant planet formation (Rice & Armitage 2005). Abundances of other elements considered here are subsolar, and the [*m*/Fe] ratios are unspectacular when compared to the general field population (e.g., Edvardsson et al. 1993; Fulbright 2002). The planet-metallicity correlation is one of the most scrutinized results to emerge from extrasolar planet studies. Fischer & Valenti (2005) offer the most thorough investigation of the correlation to date; their conclusion, based on a uniform analysis of 850 stars with and without planets, is that gas giant planets preferentially form in high-metallicity environments. Various groups have also argued for this "primordial" scenario (e.g., Pinsonneault et al. 2001; Santos et al. 2003), and there are two main pieces of evidence given in support. First, there is no correlation between convection zone (CZ) depth and metallicity of planetary hosts, an effect that is expected if accretion of H-depleted rocky material has occurred. Second, the metallicity distribution of planet-harboring subgiant stars does not differ from that of dwarfs; the deepening CZ of a subgiant should dilute any accretion signatures that might have occurred.

Despite the substantial evidence pointing to the primordial

scenario for planetary formation, data in support of the accretion of H-depleted rocky material hypothesis also exist, albeit they are more sparse. Gonzalez (1997) was the first to report on the supersolar metallicities of planetary hosts and to suggest that the correlation may be a result of accretion. Shortly thereafter, Israelian et al. (2001) detected ^{6}Li in the metal-rich planetary host HD 82943; ^{6}Li is a volatile species that should be destroyed beyond the level of observability in the atmospheres of solar-type stars during pre-MS evolution (e.g., Proffitt & Michaud 1989). Israelian et al. (2001) interpreted the presence of ^{6}Li, which should be preserved in giant planets, in HD 82943 as possible evidence of accretion; the possibility of heightened ^{6}Li abundances in the atmospheres of stars that have engulfed rocky material was later confirmed by Montalbán & Rebolo (2002). The ^{6}Li detection was subsequently challenged by Reddy et al. (2002), who questioned the atomic data used by Israelian et al. (2001). In response, Israelian et al. (2003) reanalyzed ^{6}Li in HD 82943 using updated atomic data and confirmed their original detection. Further evidence for the accretion hypothesis comes from the study of Smith et al. (2001), who found a trend of increasing abundance for elements with increasing condensation temperatures (T_c) for a small subsample of planetary hosts. If accretion of rocky material has occurred, one might expect the material to be rich in high-T_c, refractory elements compared to low-T_c, volatile elements (Gonzalez 1997). However, similar T_c-dependent abundance trends in planetary hosts have not been found by others (e.g., Sadakane et al. 2002).

Additional support for the accretion hypothesis may be emerging from the discovery and analyses of giant stars with planetary companions. As of this writing, planets are known to orbit two G-type and five K-type giants (including HD 13189), and their metallicity distribution is not similar to that of planet-hosting dwarfs. In Figure 1 we plot relative Fe abundances versus T_{eff} for the seven giants (*red circles*) and for planet-hosting dwarfs from Fischer & Valenti (2005; *black circles*), from Santos et al. (2004; *black squares*), excluding duplicates with Fischer & Valenti (2005), and from Santos et al. (2005; *black triangles*), again excluding duplicates. The horizontal line represents the mean [Fe/H] abundance of the combined, 126 dwarf sample. The giant data for HD 47536, HD 59686, HD 137759, and HD 219449 are from Sadakane et al. (2005), and data for HD 11977 and HD 104985 are from Setiawan et al. (2005) and Sato et al. (2003), respectively. In the combined dwarf sample, 41.3% have derived [Fe/H] abundances higher than +0.20 dex, and if the giants follow the same metallicity distribution, we would expect approximately three to have [Fe/H] abundances higher than +0.20 dex (see also Sadakane et al. 2005), which is clearly not seen. If the dwarf and giant samples are drawn from the same parent population, there is only a 0.6% probability of obtaining the observed metallicity distributions according to a two-sided Kolmogorov-Smirnov test.

While the sample of giant stars with planetary companions is not statistically significant, the indication of a metallicity distribution that possibly differs from that of dwarfs is intriguing. One possible explanation for the difference is that the planet-metallicity correlation found for the dwarfs is a result of accretion, and the giants have sufficiently diluted their atmospheres via evolution-induced mixing. This conclusion, however, would be difficult to reconcile with current results for subgiants (e.g., Fischer & Valenti 2005). Alternatively, planet formation may be sensitive to the mass of the host star, independent of metallicity. The progenitors of G and K giants

are early-type MS dwarfs and would be more massive than the F, G, and K dwarfs known to have planets. Thus, the current results for giants with planets would support a mass-dependent planetary formation scenario. Furthermore, Fischer & Valenti (2005) showed that the occurrence of planets around stars increases linearly with stellar mass. However, they also found a correlation of rising metallicity with increasing planetary host mass and argued that the increased occurrence of planets around more massive stars is most likely spurious. A larger number of planets orbiting subgiant and giant stars need to be analyzed in order to determine if either of these explanations is plausible, or if the difference in metallicity distributions is due to other effects, such as different planetary formation mechanisms (e.g., Chauvin et al. 2005). Including more evolved stars in RV surveys is highly encouraged.

Our analysis provides the opportunity to place further constraints on the mass of HD 13189 from Paper I. The tracks of Girardi et al. (2000) are plotted in the $T_{\rm eff}$–$\log g$ plane in Figure 2; the position of HD 13189 is marked by the open star. From our derived stellar parameters, we find a mass of $M_\star = 3.5\ M_\odot$ for HD 13189. Unfortunately, the range of possible masses, $M_\star = 2$–$6\ M_\odot$, is not well constrained due to the uncertainty in the $\log g$ value and is not a significant improvement over that given by Paper I. Adopting a stellar mass of $3.5\ M_\odot$, we find a minimum companion mass of $14.0 M_{\rm J} \pm 0.8 M_{\rm J}$, placing the companion at the planet/brown dwarf boundary. HD 13189 and its companion are a potentially unique system among planetary systems known today. The star has one of the lowest metallicities and possibly the highest mass of all planetary hosts, and the companion likely lies on the planet/brown dwarf boundary and has the largest semimajor axis for a planet orbiting a significantly metal-poor star. Further investigation of the HD 13189 system is needed to place more stringent constraints on the mass of the two objects and should provide unparalleled data in the effort to understand the formation and evolution of planetary systems.
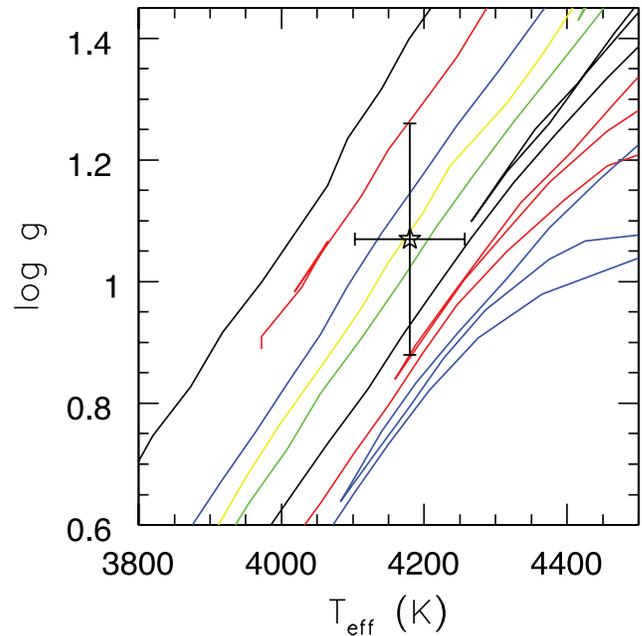
FIG. 2.—Evolutionary tracks of Girardi et al. (2000) for (*top left to bottom right*) $M_\star = 1.5, 2.0, 3.0, 3.5, 4.0, 5.0, 6.0$, and $7.0\ M_\odot$. The tracks are characterized by a metallicity of [Fe/H] $= -0.50$ or $Z \approx 0.008$. The open star with error bars marks the location of HD 13189 in the $T_{\rm eff}$–$\log g$ plane.

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