A PLANETARY SYSTEM AROUND HD 155358: THE LOWEST METALLICITY PLANET HOST STAR

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ABSTRACT

We report the detection of two planetary mass companions to the solar-type star HD 155358. The two planets have orbital periods of 195.0 and 530.3 days, with eccentricities of 0.11 and 0.18. The minimum masses for these planets are 0.89 and 0.50 M_J, respectively. The orbits are close enough to each other, and the planets are sufficiently massive, that the planets are gravitationally interacting with each other, with their eccentricities and arguments of periastron varying with periods of 2300–2700 yr. While large uncertainties remain in the orbital eccentricities, our orbital integration calculations indicate that our derived orbits would be dynamically stable for at least 10^8 yr. With a metallicity [Fe/H] of −0.68, HD 155358 is tied with the K1 III giant planet host star HD 47536 for the lowest metallicity of any planet host star yet found. Thus, a star with only 21% of the heavy-element content of our Sun was still able to form a system of at least two Jovian-mass planets and have their orbits evolve to semimajor axes of 0.6–1.2 AU.

Subject headings: planetary systems — stars: individual (HD 155358) — techniques: radial velocities

Online material: color figures

1. INTRODUCTION

There is now strongly compelling evidence that planetary companions to main-sequence stars are found preferentially around metal-rich stars. Gonzalez (1997, 1998a, 1998b, 1999) was the first to do a detailed comparison of the chemical abundances of stars with and without planets, and to conclude that there was a significant difference in these samples. This finding has subsequently been supported by a large number of investigations, several of which included carefully selected control samples (e.g., Reid 2002; Heiter & Luck 2003; Santos et al. 2005; Fischer & Valenti 2005; Grether & Lineweaver 2007). Much of the early work in this area concentrated on determining the direction of causality in the observed correlation. That is, does the presence of planets pollute the stellar convective region causing an apparent increase in photospheric metallicity, or does the physics of planet formation significantly favor a metal-rich environment? This issue has been addressed by searching for patterns of elemental enhancement in planet host stellar photospheres that might result from the metal-rich (or H- and He-poor) detritus of planet formation. So far, there is little compelling evidence that post-formation stellar photospheric self-enrichment is responsible for the observed correlation; a primordial explanation is most likely (Gonzalez 2006). Thus, searching for planets around stars with relatively low metallicity is extremely important for our understanding of the physics of planet formation. We need to find the lowest metallicity stars around which planets are able to form. The radial velocity survey of Sozzetti et al. (2006) was the first to specifically target low-metallicity stars in order to understand in detail the low-Z end of the dependence of planetary system and formation on metallicity.

We present here the discovery of two planetary companions to the star HD 155358. This is one of the sample of low-metallicity stars that were included in our Hobby-Eberly Telescope planet survey (Cochran et al. 2004) in order to begin to explore the low-metallicity tail of the heavy-element distribution of stars with planets. Details of the observations are given in § 2. Orbital solutions for the planets are given in §§ 3.1 and 3.2. Section 3.3 describes our use of a genetic algorithm to achieve a complete exploration of possible orbital solutions. The dynamical stability of our preferred orbital solution is explored in § 3.4. Detailed parameters of the host star are given in § 4, and the implications of this fascinating system for planet formation theories are given in § 5.

2. OBSERVATIONS

All observations of HD 155358 were made in queue scheduled mode using the High Resolution Spectrometer (Tull 1998) of the 9.2 m Hobby-Eberly Telescope (HET; Ramsey et al. 1998). A 400 μm optical fiber that subtends 2.0″ on the sky tracks the star across the focal plane of the telescope. Starlight then passes through a molecular iodine absorption cell stabilized at a temperature of 70°C. The dense, narrow I_2 spectrum that is superimposed on the stellar spectrum enables us to model the instrumental point-spread function (Valenti et al. 1995) and provides the velocity metric for precise radial velocity measurement (Butler et al. 1996; Endl et al. 2000). A 250 μm spectrograph entrance slit then gives a spectral resolving power of R = λ/δλ = 60,000. The spectrum is recorded on a mosaic of two 2048 × 4100 pixel E2V CCDs, which sample the spectrum at ≈4 pixels per resolution element. The cross-disperser is set to obtain the spectrum between 4076 and 7838 Å. A small gap between the two CCDs falls at 5936 Å, allowing most of the I_2 absorption spectrum to be recorded on the “blue” CCD chip.

We obtained a total of 71 high signal-to-noise ratio radial velocity observations of HD 155358 between 2001 June and 2007 March. All spectra were processed using standard IRAF routines, and velocities were computed using our high-precision radial velocity code. Table 1 gives the relative radial velocities for HD 155358. The observation times and velocities have been corrected to the solar system barycenter. The uncertainty σ for each velocity in the table is an internal error computed from the
A periodogram of the HET velocities of HD 155358 shows a very strong peak at \( \sim 195 \) days, with substantial additional power in the 300–500 day range. The Scargle (1982) false-alarm probability of this 195 day signal is \( 4.5 \times 10^{-10} \). We first fit a Keplerian orbit to the data using the GaussFit generalized least-squares software of Jefferys et al. (1988). This planet, with a period of 193.8 days, eccentricity of 0.16, and K velocity of 31.0 m s\(^{-1}\), has a minimum mass of \( M \sin i = 0.79 M_\odot \) and a semimajor axis of 0.63 AU. The rms dispersion of the data around the orbital solution is 10.2 m s\(^{-1}\), and the reduced \( \chi^2 = 9.67 \). This goodness-of-fit parameter is significantly higher than would be expected, as it is based purely on the internal errors quoted in Table 1. Wright (2005) gives a median “jitter” of 4.4 m s\(^{-1}\) for main-sequence stars similar to HD 155358. Wright also mentions that subgiants typically have jitters of about 5 m s\(^{-1}\), as do blue stars (with \( B - V < 0.6 \)). HD 155358 appears to fall into both categories (cf. § 4) with our derived age of 10 Gyr and \( V \). While some of the additional scatter might be explained as intrinsic stellar velocity variability expected in this star, there is probably some additional source for much of the scatter. Thus, we have searched carefully for additional planets in the system.

3.2. The Second Planet

A Lomb-Scargle periodogram of the residuals around the single-planet orbital fit shows very significant power over a broad range of periods from 200 to 800 days, with the strongest peak around 530 days. The false-alarm probability (FAP) of this power at 530 days is less than \( 10^{-6} \). Smaller peaks around 330 days show FAP slightly less than \( 10^{-3} \). Thus, we investigated the possibility of a second long-period planet HD 155358c. We used GaussFit to compute simultaneous least-squares solutions of double-Keplerian orbits to the observed velocities. We investigated periods around both 330 and 530 days. While we were able to find formal Keplerian solutions for both periods, the solutions with \( 330 \) days gave significantly better fits than did shorter period second planets.

When we couple this with the results of our genetic algorithm orbital fits (§ 3.3) and dynamical calculations (§ 3.4), we have concluded that the 530 day period is correct for HD 155358c. This solution is given in Table 2 and is shown in Figure 1. The uncertainties reported in Table 2 were generated by GaussFit fitting.
from a maximum likelihood estimation that is an approximation to a Bayesian maximum a posteriori estimator with a flat prior (Jefferys 1990). The observed HET velocity residuals to the HD 155358c fit, phased to the period of HD 155358b, are shown in the top panel of Figure 2, and vice versa in the bottom panel.

In fitting a Keplerian orbit to observed data, the eccentricity is often the least well determined of the orbital elements, and is the one element that is most often able to absorb any additional signals or periodicities that may be in the data. For example, in comparing the HD 155358b single-planet orbit fit with the elements of HD 155358b in the two-planet fits, the most significant changes in the orbital elements of HD 155358b are that the eccentricities dropped somewhat and the changes in the orbital elements of HD 155358b are that the eccentricities dropped somewhat and the $e_b$ value increased. The uncertainty in the eccentricity of HD 155358c is rather large. This is probably due to some regions of sparse phase coverage, particularly in the phase intervals 0.30–0.45 and 0.8–1.0. The rms scatter of the observations around this two-planet fit is 6.0 m s$^{-1}$. This rms is quite consistent with a stellar internal jitter of 4.5–5.0 m s$^{-1}$ and our typical internal observed velocity uncertainty of 2–4 m s$^{-1}$. If we add a stellar jitter of 5 m s$^{-1}$ in quadrature with the internal errors given in Table 1, we then get a reduced $\chi^2$ for our two-planet fit of 1.15.

| Parameter | Value |
|-----------|-------|
| $P_{b}$   | 195.0 ± 1.1 days |
| $T_{0b}$  | 2,453,950.0 ± 10.4 BJD |
| $K_{b}$   | 34.6 ± 3.0 m s$^{-1}$ |
| $e_{b}$   | 0.112 ± 0.037 |
| $\omega_{b}$ | 162° ± 20° |
| $P_{c}$   | 530.3 ± 27.2 days |
| $T_{0c}$  | 2,444,420.3 ± 79.3 BJD |
| $K_{c}$   | 14.1 ± 1.6 m s$^{-1}$ |
| $e_{c}$   | 0.176 ± 0.174 |
| $\omega_{c}$ | 29° ± 38° |
| $M_{c} \sin i$ | 0.075 ± 0.12 $M_J$ |
| $a_{b}$   | 0.628 ± 0.020 AU |
| $a_{c} \sin i$ | 1.224 ± 0.081 AU |
| $r_{\text{rms}}$ | 6.0 m s$^{-1}$ |

3.3. Genetic Algorithm Investigation

In order to understand fully the nature of the orbit of the second planet in this system, we used a standard genetic algorithm to explore further the $\chi^2$-landscape of a two-planet solution and to find possible additional $\chi^2$ minima. The initial orbital parameters were distributed randomly over a certain range of start values, and during each iteration these parameters were randomly mutated. The solutions “evolve” by using $\chi^2$ as the environmental selection mechanism. Solutions that improve $\chi^2$, or at least do not degrade it by a certain threshold, are allowed to survive and to multiply. Solutions that are above this threshold (e.g., $\chi^2 > \chi^2_{\text{best}} + 0.1$%), and are not able to move back into this $\chi^2$ range, are terminated after a few generations (typically six generations). Repeating this process many times (each time with new randomly selected starting values) allowed us to probe a much larger parameter space than is usually possible with standard orbital fit programs.

For HD 155358 we performed >10,000 trial runs, allowing the period of HD 155358c to vary between 250 and 2100 days (the time span of observations). We constrained the period of HD 155358b to the range of 185–200 days and its eccentricity to $e_b < 0.5$.

Three $\chi^2$ minima were found by the genetic algorithm: the first with periods for HD 155358c around 326 days, the second around $P_c$ 530 days, and a third one with $P_c$ around 1540 days. The parameters of the solutions found for the first two minima coincide with the solutions found by GaussFit. However, the third minimum at 1540 days was intriguing, as it represents another possible period for HD 155358c. A detailed examination of the solutions in this minimum revealed that their eccentricities were all in the range of 0.835–0.86. With such a high eccentricity the orbits of the two planets would cross, and the system would quickly disrupt itself. It appears that this 1540 day solution represents a good formal fit for a physically impossible orbital configuration. In order to further rule out the 1540 days as the true period of the outer
planet, we performed 1000 additional trials in the period range of 1500–1600 days for HD 155358c and using an upper limit on $e_c$ of 0.6. This time no solutions were found with comparable low $\chi^2$ values. We thus conclude that the 530 day period is the most likely period for the second planet.

### 3.4. Dynamical Stability Calculations

While the orbits given in Table 2 represent the least-squares Keplerian orbit solution to the observations, they may not necessarily represent physically realistic orbits for two planets in this system. The inclusion of the second planet HD 155358c drops the eccentricity of the first planet HD 155358b slightly, but the new outer planet solution has a somewhat nonzero eccentricity itself. While the orbits for this solution do not cross each other, they do have sufficiently close approaches that the planets may well be interacting dynamically.

To investigate the orbital stability of the two-planet Keplerian orbital solution for the HD 155358 system, we conducted dynamical simulations using the N-body integrator SWIFT. A full description of SWIFT’s capabilities is given by Levison & Duncan (1994). We adopted the stellar mass $M_\ast = 0.87 M_\odot$, as discussed in §4, and the parameters of the two planets were those given in Table 2. The planets were assumed to be coplanar, and the planet masses were taken to be the minimum values (i.e., $\sin i = 1$). However, similar results are obtained for $\sin i \approx 0.4$.

The three-body system (star and two planets) was integrated for a total of $10^8$ yr. Initial orbits for the planets were taken from Table 2. The system remained stable for the duration of the simulation. As shown in Figure 3, the two planets exchanged eccentricities on a relatively short timescale, with a period of approximately 2700 yr. The eccentricity of planet b varied between 0.02 and 0.18, while the eccentricity of planet c varied between 0.08 and 0.22. The argument of periastron $\omega$ for both planets circulated with a period of about 2300 yr. The two planets spend most of their time with $|\omega_b - \omega_c|$ between 120° and 240°.

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Fig. 3.—Results of dynamical simulations of the HD 155358 system. The evolution of semimajor axis ($a$), eccentricity, and the argument of periastron ($\omega$) are shown for a typical $10^4$ yr interval. The simulation was run for a total of $10^8$ yr. The two planets exchange eccentricities on a timescale of about 2700 yr, and $\omega$ circulates with a period of about 2300 yr. The semimajor axes of both planets are stable throughout the simulation. These computations were for a star of mass 0.87 $M_\odot$ and planet masses fixed at the minimum mass ($\sin i = 1$). However, similar results are obtained for $\sin i \approx 0.4$.
Noting the significant interaction between the two planets in the minimum-mass case, we tested the effect of inclination of the entire system by adjusting the planetary masses and repeating the simulations. More massive planets (sin $i < 1$) should interact more strongly with each other, and thus may be less stable. Systems with sin $i \geq 0.33$ ($i \geq 20^\circ$) remained stable for the duration of the tests ($10^7$ yr). These results indicate that the dynamical stability evidenced in Figure 3 does not require the special circumstance of a nearly edge-on inclination and thus minimum-mass planets. Even though the two planets are definitely interacting dynamically, the timescale of this interaction is long compared with the span of our observations. Thus, our two-planet least-squares Keplerian solution given in § 3.2 is a valid approximation.

Throughout the dynamical simulations, we have assumed that the two planets are in coplanar orbits. It is, however, conceivable that the planetary orbits are inclined with respect to each other. We have conducted further tests with mutually inclined planetary orbits to determine the maximum mutual inclination for which the system remained stable. For the purposes of these experiments, the initial inclination of the inner planet was set to 0$^\circ$, and that of the outer planet was assigned a grid of starting values ranging from 5$^\circ$ up to 50$^\circ$. The planetary masses were again assumed to be the minimum values, and the systems were integrated for $10^7$ yr. Systems with mutual inclinations less than 45$^\circ$ remained stable for the duration of the simulations. For higher values of the inclination between the two planets, the eccentricities of both planets experienced chaotic variations, resulting in the ejection of the outer planet within $10^6$ yr (45$^\circ$) and $2 \times 10^5$ yr (50$^\circ$).

### 4. STELLAR PROPERTIES

We measured the photospheric iron abundance, [Fe/H], of HD 155358 by analyzing the “template” spectrum used in the radial velocity analysis. We assumed that [Fe/H] was an effective proxy for the general photospheric metallicity, [M/H]. Our analysis method is the same as described by Bean et al. (2006) for solar-type stars. We briefly describe the technique here, and refer the reader to that paper for a complete description.

We fit synthetic spectra to the profiles of 30 Fe i lines in the observed spectrum. We generated the synthetic spectra with an updated version of the plane-parallel, local thermodynamic equilibrium, stellar analysis computer code MOOG (Sneden 1973). We assumed astrophysical log $g f$ values for the Fe i lines, which were determined by fitting a solar spectrum and assuming the solar iron abundance log $\epsilon$(Fe)$_\odot$ = 7.45. Our analysis was therefore differential to the Sun.

We also adopted model atmospheres computed with the general-purpose stellar atmosphere code PHOENIX (ver. 13; Hauschildt et al. 1999) for our analysis. The model atmosphere effective temperature, $T_{\text{eff}}$, was constrained using the $(B-V)$, [Fe/H]--$T_{\text{eff}}$ relationship of Ramirez & Meléndez (2005). The surface gravity, log $g$, was constrained by interpolating the Bertelli et al. (1994) evolutionary isochrones for a given $M_*$, $T_{\text{eff}}$, and [Fe/H]. We took the needed $V$ magnitude, $(B-V)$ color, and parallax from the Hipparcos catalog (Perryman et al. 1997).

We determined [Fe/H], microturbulence $\xi$, and macroturbulence $\eta$ for HD 155358 by fitting the line profiles in the observed spectrum simultaneously. As the constraints on the stellar $T_{\text{eff}}$ and log $g$ described above are both dependent on [Fe/H], these parameters were also varied simultaneously. We fit the observed spectrum by using an adaptation of the “Marquardt” $\chi^2$ minimization algorithm (Marquardt 1963; Press et al. 1986). The uncertainty in the determined [Fe/H] was calculated from the scatter in the abundances determined for each line individually, and deviations due to the uncertainties in the adopted $T_{\text{eff}}$ and log $g$.

In addition to the standard spectroscopic parameters, we have also estimated the mass and age of HD 155358 by interpolating the Bertelli et al. (1994) evolutionary isochrones as we did to constrain the log $g$. The parameters that we determined for HD 155358 are given in Table 3. Table 4 lists the literature values of the stellar parameters for comparison. Most notably, we found [Fe/H] = $-0.68 \pm 0.07$. This is in very good agreement with the literature values, which have a range $-0.72 \leq [\text{Fe/H}] \leq -0.60$, and median value $[\text{Fe/H}] = -0.67$. The derived value of log $g$, coupled with the mass, age, and effective temperature of HD 155358 indicate that the star has evolved off the main sequence.

### 5. DISCUSSION

The planetary system around HD 155358 is quite remarkable in that it contains two Jovian-mass planets in relatively short-period orbits around one of the most metal-poor planet host stars yet found. Thus, this system is crucial to our understanding of the physics of planetary system formation and early dynamical evolution.

The final configuration of any planetary system results from a competition of several different physical processes, each occurring on its own independent timescale. The planets themselves must form from the remnant disk of material left over from star formation. This must happen before the circumstellar disk is dissipated. After planet formation, the system must evolve into the final state in which we detect it. The dependence of each of these processes on the metallicity of the material from which the entire system forms then determines the range of allowed planetary systems as a function of metallicity.

Matsuo et al. (2007) investigated the circumstances under which stars of various metallicity and mass could form planets.
within the framework of both the core accretion model and the disk instability model. They derive a low-metallicity threshold for planet formation within the core accretion model of [Fe/H] = −0.85 for a disk of 5 times the mass of the minimum mass solar nebula (MMSN) and [Fe/H] = −1.17 for a disk of 10 times the MMSN. They also showed that the disk instability model has essentially no dependence on stellar metallicity, but would require a disk mass of at least 10 times the MMSN to form these planets. Thus, the two giant planets we have discovered in the HD 155358 system could have formed from either formation mechanism. In either model they require a disk that was substantially more massive than the MMSN.

Ida & Lin (2004, 2005) investigated the dependence of the formation of planetary systems on stellar metallicity within the core accretion model. The motivation for their model was to explain the observed correlation between high stellar metallicity and planetary systems easily detected by radial velocity techniques. The basic idea is that in systems of high metallicity, the dust surface density in the protoplanetary disk will be enhanced. This will lead to planetary cores being formed on a much shorter timescale. Ida & Lin (2005) derived a planetary core mass at time $t$ (prior to depletion of the feeding zone) that is proportional to $10^{-38}$, where $Z$ is the stellar metallicity (10$^{-3}$, $Z_\odot$). For a giant planet to grow, a core must achieve a mass above a critical value of about $10^{-20} \, M_\oplus$ before the gas disk is dissipated. If the core does reach a supercritical mass while there is still significant gas content in the disk, it will rapidly accrete gas and grow to become a gas giant planet. If the core remains subcritical through gas disk dissipation, then the planetary core will remain a Neptune or a super-Earth. Since the disk dissipation has a much weaker (if any) dependence on stellar metallicity, gas giant planet formation around low-$Z$ stars is significantly more difficult than around stars of solar or higher metallicity. Unless the circumstellar disk is rather massive to begin with, there simply is not time to grow critical mass cores before the gas disk dissipates. Thus, one might expect a critical lower metallicity threshold for the formation of gas giant planets. The value of this threshold would depend on the physics governing the overall mass of the disk, which are poorly understood.

The third relevant timescale for determining the final configuration of a planetary system is that of the planetary system dynamical evolution, which transforms the system from the one that formed the planets into the system that we detect today. There are two basic physical processes governing postformation dynamical evolution. These are tidal migration prior to disk dissipation, and planet-planet or planet-planetesimal scattering following disk dissipation. Only tidal migration can have any significant dependence on stellar metallicity. The disk evolution is driven by the disk viscosity. In type II migration, in which the planet has opened a gap in the disk as a result of depleting the local gas in the disk from runaway gas accretion, the planet is locked into the viscous evolution of the disk. Ida & Lin (2005) give a disk migration timescale that depends linearly on the disk viscosity, $\alpha$. The dependence of $\alpha$ on metallicity is not known, and most models assume a constant $\alpha$ of order $10^{-4}$ for all disks. Thus, it appears that once a system of several planets is able to form in a disk, the subsequent dynamical evolution of that system is probably reasonably independent of $Z$. Detailed modeling of the dependence of disk evolution and type II migration on $Z$ is needed. If the dynamical evolution of the planetary system is due to tidal migration in the disk, this migration must still occur before the disk is dissipated. If the final configuration of the HD 155358 system is due to postformation planet-planet scattering, or dynamical interactions of the planets with remnant planetesimals, then we would not necessarily expect any significant dependence of the process on the stellar metallicity. For low-metallicity systems, the theoretical challenge is to form the planets of the required mass before the disk dissipates.

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Facilities: HET

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