TWO JUPITER-MASS PLANETS ORBITING HD 154672 AND HD 205739

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ABSTRACT

We report the detection of the first two planets from the N2K Doppler planet search program at the Magellan telescopes. The first planet has a mass of $M \sin i = 4.96 M_{\text{Jup}}$ and orbits the G3 IV star HD 154672 with an orbital period of 163.9 days. The second planet orbits the F7 V star HD 205739 with an orbital period of 279.8 days and has a mass of $M \sin i = 1.37 M_{\text{Jup}}$. Both planets are in eccentric orbits, with eccentricities $e = 0.61$ and $e = 0.27$, respectively. Both stars are metal rich and appear to be chromospherically inactive, based on inspection of their Ca II H and K lines. Finally, the best Keplerian model fit to HD 205739b shows a trend of 0.0649 m s$^{-1}$ day$^{-1}$, suggesting the presence of an additional outer body in that system.

Key words: planetary systems – stars: individual (HD 154672, HD 205739) – techniques: radial velocities.

1. INTRODUCTION

Ongoing Doppler radial velocity (RV) surveys of nearby stars have detected over 200 extrasolar planets in the past decade (Butler et al. 2006). These surveys focus on late F, G, K, and M dwarfs within 50 pc and most of the planets they have found to date are more massive than Saturn and are presumably gas giants. Recently, several Neptune- and lower-mass planets have been detected, most of them with orbital periods of a few days (Butler et al. 2004; McArthur et al. 2004; Santos et al. 2004; Bonfils et al. 2005, 2007; Rivera et al. 2005; Udry et al. 2006, 2007; Endl et al. 2008).

As the search for new extrasolar planets continues, Doppler surveys now look through a broad parameter space, including long-period Jupiter analogs, very low-mass planets in short-period orbits, multiple planetary systems, and new planets around stars with spectral types that extend beyond those traditionally searched, that is, K0V to F8V. The N2K program (Fischer et al. 2005) is a Doppler survey with distributed observing campaigns at the Keck, Magellan, and Subaru telescopes, and is primarily aimed at increasing the number of known hot Jupiters. Because of their proximity to the host stars, the atmospheres of hot Jupiters can be as hot as 2000 K, resulting in detectable emission at infrared (IR) wavelengths. This makes these short-period planets ideal targets for spaceborn follow-up observations over subsequent years revealed the presence of longer-period planets and a trend on the RV curve of HD 205739 that continues to increase after over 3.5 years.

This paper is based on data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile.

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2. CHARACTERISTICS OF THE HOST STARS

HD 154672 is classified as a G3 IV star, with apparent magnitude $V = 8.21$ and color $B - V = 0.71$ (Hipparcos Catalog; ESA 1997). The Hipparcos parallax of the star is $15.2 \pm 1.1$ mas, placing it at a distance of $65.8 \pm 4.8$ pc. The distance and the apparent magnitude of the star give an absolute visual magnitude of $M_V = 4.12$. The bolometric luminosity of the star is $L_{bol} = 1.88 L_{\odot}$, where we have included a bolometric correction of $-0.09$ derived from the empirical transformations of Van den Berg & Clem (2003), using the effective temperature, surface gravity, and metallicity of the star. Our high-resolution spectroscopic analysis, described in Valenti & Fischer (2005), yielded $T_{eff} = 5714 \pm 45$ K, $\log g = 4.25 \pm 0.08$, $v \sin i = 1.0 \pm 0.5$ km s$^{-1}$, and $[\text{Fe/H}] = +0.26 \pm 0.04$ for HD 154672. The radius of the star derived from the Stefan–Boltzmann relation and the values of the luminosity and effective temperature above is $1.39 R_{\odot}$. We have also derived a stellar mass of $1.06 M_{\odot}$, a radius of $1.27 R_{\odot}$, and an age of about 9.3 Gyr by using the Takeda et al. (2007) grid of evolutionary models, based on the Yale Stellar Evolution Code and tuned to the uniform spectroscopic analysis of Valenti & Fischer (2005). The resultant log $g$ is $4.26^{+0.06}_{-0.05}$, in agreement with the results of the spectroscopic analysis. The uncertainties in these parameters correspond to a 95% credibility interval using Bayesian posterior probability distributions. The stellar parameters of HD 154672 derived are summarized in the second column of Table 1.

The second star, HD 205739, is F7 V with $V = 8.56$ and $B - V = 0.546$ (Hipparcos Catalog; ESA 1997). The Hipparcos parallax of the star is $11.07 \pm 1.12$ mas, placing it at a distance of $90.3 \pm 9.1$ pc. This sets the absolute magnitude of HD 205739 to $M_V = 3.78$ and its bolometric luminosity to $L_{bol} = 2.3 L_{\odot}$. The value of $L_{bol}$ includes a bolometric correction of $-0.03$ derived from the same empirical transformations of Van den Berg & Clem (2003) mentioned above. Our spectroscopic analysis yields $T_{eff} = 6176 \pm 44$ K, $\log g = 4.21 \pm 0.08$, $v \sin i = 4.5 \pm 0.5$ km s$^{-1}$, and $[\text{Fe/H}] = +0.187 \pm 0.05$. Using the effective temperature and stellar luminosity with the Stefan–Boltzmann relation, we calculate the radius of the star to be $1.33 R_{\odot}$. The stellar mass, radius, and age derived from the Takeda et al. (2007) grid of evolutionary models are in this case $1.22 M_{\odot}$, $1.33 R_{\odot}$, and 2.9 Gyr, and log $g$ is $4.29^{+0.06}_{-0.05}$. The parameters of HD 205739 are summarized in the last column of Table 1.

Finally, the Ca II H and K lines of HD 154672 and HD 205739 (Figure 1) indicate that their chromospheric activity is low. We can therefore reject activity as the cause of the observed RV variations of the stars. Based on these observations, we adopt a conservative upper limit of about $4 \text{ m s}^{-1}$ to the expected jitter (or astrophysical noise) of the stars (Wright et al. 2004).

3. DOPPLER OBSERVATIONS AND KEPLERIAN FITS

Doppler observations were carried out between mid 2004 and February 2008 at the Magellan Clay telescope using the Magellan Inamori Kyocera Echelle (MIKE) spectrograph (Bernstein et al. 2003), with the addition of an iodine cell behind the spectrograph’s entrance slit to model the instrumental profile and to set an accurate reference wavelength scale (Butler et al. 1996). The typical signal-to-noise ratio ($S/N$) of our spectra is about 130, producing photon-limited uncertainties of $2–4 \text{ m s}^{-1}$. Two additional sources of noise are present in the data. The first one is the stellar jitter estimated in Section 2. The second source of noise is systematic instrumental errors, which for MIKE has a root mean square (rms) deviation of $5 \text{ m s}^{-1}$, as derived from a subset of observed stars that appear to have stable RVs over the time span of the observations. A sample of stable stars measured with MIKE are presented in Figures 1 and 2 of Minniti et al. (2008).

We obtained a total of 16 RV measurements for HD 154672 and 24 measurements for HD 205739. These measurements are

* Jenkins et al. (2008) recently measured a value of $\log R'_{HK} = -5.37$ for HD 154672.
summarized in Tables 2 and 3, including the observation dates and the RV formal uncertainties introduced by photon-limited noise. The data are represented in Figures 2 and 3, respectively.

For each data set, we modeled the RVs to fit single-planet Keplerian orbits by using a Levenberg–Marquardt fitting algorithm. In the case of HD 205739, it was necessary to include an additional variable linear trend to best reproduce the observed RV variations. The parameter uncertainties of each best model fit were estimated by running 1000 Monte Carlo trials on each data set, where the result model of each trial was subtracted from the individual data points and the residual velocities were scrambled and added back to the velocities predicted by the models, before running a new trial fit. The adopted final uncertainties of each parameter are derived from the standard deviation of all the model trials.

The parameter values of the best Keplerian model fit for each target are summarized in Table 4. The best model for HD 154672 has an orbital period of 163.94 ± 0.01 days, RV semi-amplitude $K_1 = 225 \pm 2$ m s$^{-1}$, and orbital eccentricity $e = 0.61 \pm 0.03$. The rms to the fit is 4.36 m s$^{-1}$, with a reduced $\chi^2 = 1.60$ relative to the RV formal uncertainties. Adopting a stellar mass of 1.06 $M_\odot$, we derive a planetary mass of 4.96 $M_{\text{Jup}}$ and an average relative separation of 0.597 AU for the system. The RV data are plotted in Figure 2, together with the best Keplerian model fit.

In the case of HD 205739, the best model has an orbital period of 279.8 ± 0.1 days, RV semi-amplitude $K_1 = 42 \pm 3$ m s$^{-1}$, and orbital eccentricity $e = 0.27 \pm 0.07$. The RVs also show a substantial linear trend of 0.0649 ± 0.0002 m s$^{-1}$ per day that continues after over 3.5 years of observations. The rms of the data to the fit is 8.67 m s$^{-1}$, with a reduced $\chi^2 = 2.13$ relative to the RV formal uncertainties. Adopting a stellar mass of 1.22 $M_\odot$, we derive a planetary mass of 1.37 $M_{\text{Jup}}$ and an average semi-major axis for the system of 0.896 AU. The data with the best Keplerian model fit are represented in Figure 3. As seen in the figure, the residuals to the fit of a single planet plus a long-term trend still appear large, showing points that deviate about 2$\sigma$ from the average $-4$ m s$^{-1}$ precision of the individual data points; however, an analysis of the periodogram of these residuals reveals no significant peaks, so we cannot discard nor confirm the presence of additional shorter-period planets in this system with the current dataset.

The amplitude of the observed RV variations for each star is 10–100 times larger than the uncertainties of the individual RV measurements, which makes the possibility that the detected signals are caused by noise fluctuations very unlikely. We quantitatively assert this statement by performing a false alarm probability (FAP) analysis of the data using the method described by Marcy et al. (2005; see Section 5.2), with the inclusion of possible linear trends (Wright et al. 2007). Figure 4 shows the result of 1000 FAP trial tests for HD 205739. The FAP, that is, the fraction of trials of scrambled velocities that yield lower $\chi_\sigma$ than the best reported fit, is less than 0.1%. A similar analysis of the HD 154672 data gives a negligible FAP (<1.0%). In this last case, the median $\chi_\sigma$ of the FAP histogram is about 30, the first percentile $\chi_\sigma$ is 16.1, and the minimum $\chi_\sigma$ after 1000 trial tests is 12.5. None of the FAP trial fits produces $\chi_\sigma$ lower than the value reported above for the best Keplerian fit for HD 154672.

### Table 2
Radial Velocities for HD 154672

| JD-2,453,000 (days) | RV (m s$^{-1}$) | $\sigma_{\text{RV}}$ (m s$^{-1}$) |
|---------------------|-----------------|-------------------------------|
| 189.7132            | −167.7          | 2.9                           |
| 190.7083            | −169.7          | 2.8                           |
| 191.7204            | −173.4          | 3.3                           |
| 254.5062            | 149.1           | 2.6                           |
| 596.6893            | 104.9           | 3.1                           |
| 810.9097            | −31.1           | 2.5                           |
| 872.8136            | 234.8           | 2.5                           |
| 1189.8750           | −111.7          | 2.5                           |
| 1190.8402           | −83.3           | 2.8                           |
| 1215.8605           | 216.6           | 2.5                           |
| 1216.7893           | 217.8           | 2.6                           |
| 1217.8725           | 224.9           | 2.8                           |
| 1277.7025           | 41.6            | 2.7                           |
| 1299.6210           | −25.6           | 2.6                           |
| 1339.5574           | −172.5          | 4.1                           |
| 1501.8960           | −168.9          | 2.8                           |

### Table 3
Radial Velocities for HD 205739

| JD-2,453,000 (days) | RV (m s$^{-1}$) | $\sigma_{\text{RV}}$ (m s$^{-1}$) |
|---------------------|-----------------|-------------------------------|
| 189.8080            | −33.3           | 4.0                           |
| 190.8643            | −27.7           | 4.4                           |
| 191.8243            | −31.7           | 4.0                           |
| 254.6094            | −77.0           | 3.6                           |
| 550.8993            | −39.0           | 4.3                           |
| 551.8692            | −57.0           | 3.9                           |
| 655.6332            | −27.5           | 3.2                           |
| 657.5999            | −10.4           | 3.6                           |
| 658.6117            | −11.9           | 3.4                           |
| 685.5468            | 23.8            | 3.3                           |
| 872.8832            | −46.8           | 3.5                           |
| 982.7455            | 38.4            | 4.0                           |
| 988.7200            | 38.7            | 3.9                           |
| 1013.6776           | 23.1            | 3.6                           |
| 1066.5152           | −13.4           | 3.7                           |
| 1067.5231           | −2.7            | 3.6                           |
| 1216.9394           | 19.3            | 4.0                           |
| 1277.8176           | 71.4            | 5.6                           |
| 1299.8091           | 55.8            | 3.9                           |
| 1300.7959           | 37.7            | 3.6                           |
| 1338.7675           | 18.7            | 4.6                           |
| 1339.7078           | 30.7            | 4.4                           |
| 1397.5266           | −2.0            | 4.7                           |
| 1398.5065           | −2.2            | 3.3                           |
4. DISCUSSION

We present two new Jovian-mass planets orbiting metal-rich stars. HD 154672b is a fairly massive planet with a mass of $M \sin i = 4.96 \, M_{\text{Jup}}$ and a very pronounced orbital eccentricity of $e = 0.61$, which causes the planet to move from 0.23 to 0.96 AU between periastron and apastron. The planet will, therefore, experience surface temperature changes of about 300 K along its orbit, reaching a maximum temperature at a periastron of about 600 K, assuming that the albedo of the planet is low. If water is present in the atmosphere of HD 154672b, it could transition between gaseous and liquid phases along the planet’s orbit.

When placed in the eccentricity versus orbital period parameter space diagram of known exoplanets illustrated in Figure 5, HD 154672b shows an orbital eccentricity larger than 90% of the discovered planets, and is only the seventh planet found with an orbital period shorter than 300 days and an eccentricity larger than 0.6. Of the other six planets, four have been found to be either in multiple-planet systems (HD 74156; Naef et al. 2004; Bean et al. 2008), to have a brown dwarf companion (HD 3651; Mugrauer et al. 2006), to be part of a wide stellar binary system (HD 80606; Naef et al. 2001), or to present a large RV trend induced by a distant body associated with that system (HD 37605; Wittenmyer et al. 2007). The high eccentricities in these cases can be explained by either Kozai oscillations (Kozai 1962) or chaotic evolution of planetary orbits in multiple systems. Another planet in this subgroup, HD 17156, has been recently reported to have a large orbital axis misalignment with respect to the stellar rotation axis, which can best be explained by gravitational interactions with other planets (Narita et al. 2007). There is, however, no evidence for additional objects associated with the last planet in this subgroup, orbiting HD 89744. The RV curve of HD 154672 in Figure 2 shows no trend nor significant residuals to the fit that indicate the presence of other massive objects in that system.

HD 205739b has a mass of $M \sin i = 1.37 \, M_{\text{Jup}}$, with an average relative separation of 0.896 AU and an eccentricity of $e = 0.27$. In the eccentricity versus orbital period diagram in Figure 5, the parameters of this planet do not seem atypical. For planets with orbital periods longer than 20 days, the mean eccentricity is 0.29; therefore, HD 205739b has an orbital eccentricity that is typical of detected planets that have not experienced tidal circularization. The separation of HD 205739b from its host star changes from 0.65 AU to 1.14 AU between periastron and apastron. The maximum surface temperature of this planet is expected to be of the order of 400 K, and the amplitude of its surface temperature change will only be of about 100 K along the entire orbit. One peculiarity of the RV curve of HD 205739 is the presence of a pronounced trend of 0.0649 m s$^{-1}$ per day, indicating the presence of an additional outer body in the system with an orbital period longer than the 3.5 year time span covered by our observations, and a RV semi-amplitude greater than 35 m s$^{-1}$. Finally, the residuals of our best fit are a factor of 2 larger than expected, which hints the possible presence of other bodies in this system. However, more observations are needed to confirm this hypothesis.

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