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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 $M \sin i = 4.96\, M_{\mathrm{Jup}}$ 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 $M \sin i = 1.37\, M_{\mathrm{Jup}}$. 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-mass 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 to observe exoplanet atmospheres (Harrington et al. 2007), especially when they transit their host stars and undergo a secondary eclipse so that small differential changes in emission from the star-planet system can be measured (e.g., Charbonneau et al. 2005; Knutson et al. 2007). It is also important to have a sample of hot Jupiters that are large enough to provide meaningful constraints on the formation, migration, and evolution mechanisms of these planets (Ford & Rasio 2006).

The N2K program searches a fresh sample of the "next 2000" stars, not included in other current Doppler surveys, by extending the search radius to distances of 100–110 pc from the Sun. This project is intentionally biased toward metal-rich stars to exploit the correlation between the formation of gas giant planets and high stellar metallicity (Santos et al. 2004; Fischer & Valenti 2005). The search strategy is optimized for the detection of Jupiter-mass planets with orbital periods shorter than 14 days by obtaining RV measurements on three consecutive nights. Variability in the velocity of the host star over this short timescale flags the star as a candidate host for a short-period planet. However, gas giant planets in longer orbits are also identified and detected with additional observations. As an example, the N2K programs at the Keck and Subaru telescopes have already detected seven planets with periods between 21 days and 3.13 years (Fischer et al. 2007; Robinson et al. 2007).

Here, we report the detection of the first two planets from the Magellan N2K program. This program has been underway at the Magellan telescopes at Las Campanas Observatory in Chile since 2004, and includes ~300 FGK metal-rich stars at distances between 50 and 100 pc. The new planets orbit the stars HD 154672 and HD 205739. Both host stars showed significant RV scatter in the first year of observations and were initially flagged as hot Jupiter candidates. However, 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.

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

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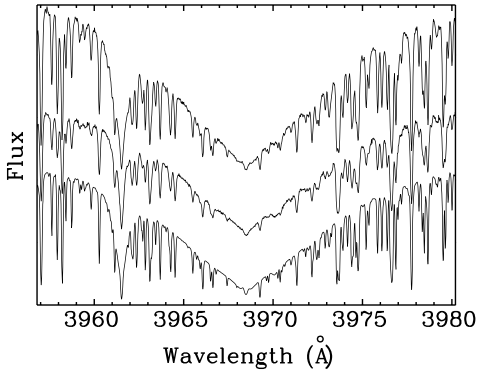

Figure 1. Ca II H lines of HD 154672 (top) and HD 205739 (middle), compared to the same spectral line region for the Sun (bottom). The lack of emission in the line cores is consistent with low chromospheric activity levels.

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 ± 1.11 mas, placing it at a distance of 65.8 ± 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 $L_{\rm bol} = 1.88\, L_\odot$, 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 $T_{\rm eff} = 5714 \pm 45$ K, $\log g = 4.25 \pm 0.08$, $v \sin i = 1.0 \pm 0.5$ km s^{-1}, and $[{\rm Fe/H}] = +0.26 \pm 0.04$ 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 ± 1.12 mas, placing it at a distance of 90.3 ± 9.1 pc. This sets the absolute magnitude of HD 205739 to $M_V = 3.78$ and its bolometric luminosity to $L_{\rm bol} = 2.3\, L_\odot$. The value of $L_{\rm bol}$ 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 $T_{\rm eff} = 6176 \pm 44$ K, $\log g = 4.21 \pm 0.08$, $v \sin i = 4.5 \pm 0.5$ km s^{-1}, and $[{\rm Fe/H}] = +0.187 \pm 0.05$. 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.

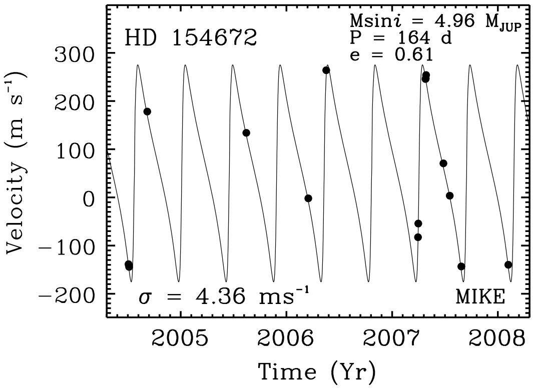

Figure 2. RV measurements for HD 154672 over 3.6 years. The minimum mass of the planet, assuming a stellar mass of $1.06\, M_\odot$, is $M \sin i = 4.96\, M_{\rm Jup}$. There is no evidence for additional planets in this system.

Table 1
Stellar Parameters

Parameter	HD 154672	HD 205739
V	8.21	8.56
M_V	4.11	3.78
$B - V$	0.71	0.54
Spectral type	G3 IV	F7 V
Distance (pc)	65.8	90.3
$L_{\rm bol}/L_\odot$	1.88	2.3
[Fe/H]	0.26 (0.04)	0.19 (0.04)
$T_{\rm eff}$	5714 (30)	6176 (30)
$v \sin i$ (km s^{-1})	0.54 (0.5)	4.48 (0.5)
log g (cgs)	4.25 (0.08)	4.21 (0.08)
$M_{\rm star}$ ($M_\odot$)[a]	(0.97) 1.06 (1.17)	(1.16) 1.22 (1.30)
$R_{\rm star}$ ($R_\odot$)[a]	(1.18) 1.27 (1.37)	(1.23) 1.33 (1.43)
Age (Gyr)[a]	(6.92) 9.28 (11.44)	(1.72) 2.84 (3.76)

Note. [a] Values derived from evolutionary models.

Finally, the Ca II H and K lines of HD 154672 and HD 205739 (Figure 1) indicate that their chromospheric activity is low[12]. 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 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 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 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

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[12] Jenkins et al. (2008) recently measured a value of $\log R^1_{\rm HK} = -5.37$ for HD 154672.

Table 2
Radial Velocities for HD 154672

JD-2,453,000 (days)	RV ($\mathrm{m\ s^{-1}}$)	σ_{RV} ($\mathrm{m\ s^{-1}}$)
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

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 model result 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 $K_1 = 225 \pm 2\ \mathrm{m\ s^{-1}}$, and orbital eccentricity $e = 0.61 \pm 0.03$. The rms to the fit is 4.36 $\mathrm{m\ s^{-1}}$, with a reduced $\sqrt{\chi^2_\sigma} = 1.60$ relative to the RV formal uncertainties. Adopting a stellar mass of 1.06 $M_\odot$, we derive a planetary mass of 4.96 M_{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 $K_1 = 42 \pm 3\ \mathrm{m\ s^{-1}}$, and orbital eccentricity $e = 0.27 \pm 0.07$. The RVs also show a substantial linear trend of 0.0649 ± 0.0002 $\mathrm{m\ s^{-1}}$ per day that continues after over 3.5 years of observations. The rms of the data to the fit is 8.67 $\mathrm{m\ s^{-1}}$, with a reduced $\sqrt{\chi^2_\sigma} = 2.13$ relative to the RV formal uncertainties. Adopting a stellar mass of 1.22 $M_\odot$, we derive a planetary mass of 1.37 M_{Jup} and an average semimajor 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 2σ from the average ∼4 $\mathrm{m\ s^{-1}}$ 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.

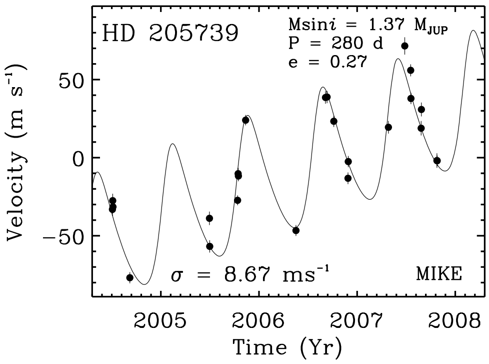

Figure 3. RV measurements for HD 205739 over 3.6 years. The minimum mass of the planet, assuming a stellar mass of 1.22 $M_\odot$, is $M \sin i = 1.37\ M_{\mathrm{Jup}}$. The best Keplerian fit shows a significant trend of 0.0649 ± 0.0002 $\mathrm{m\ s^1}$ per day, suggesting the presence of an additional outer body in the system.

Table 3
Radial Velocities for HD 205739

JD-2,453,000 (days)	RV ($\mathrm{m\ s^{-1}}$)	σ_{RV} ($\mathrm{m\ s^{-1}}$)
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

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 χ_σ 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 χ_σ of the FAP histogram is about 30, the first percentile χ_σ is 16.1, and the minimum χ_σ after 1000 trial tests is 12.5. None of the FAP trial fits produces χ_σ lower than the value reported above for the best Keplerian fit for HD 154672.

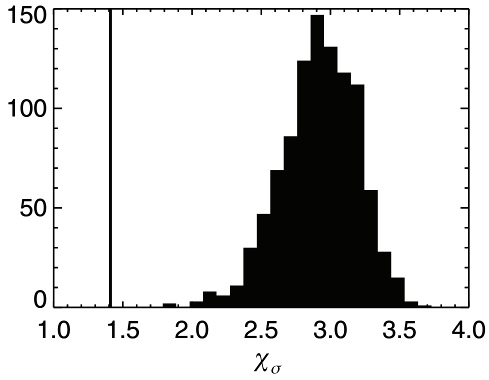

Figure 4. Empirical evaluation of the FAP of the single-planet Keplerian fit plus a linear trend model for HD 205739 reported in Section 3. The χ_σ of that fit is ∼1.4 and is indicated by the vertical line in the plot. The vertical axis shows the number of trials that produce a given χ_σ. Less than 1 of the 1000 trial fits produce χ_σ values lower than the original time series of the observations, indicating that the FAP of the reported fit is less than 0.1%.

4. DISCUSSION

We present two new Jovian-mass planets orbiting metal-rich stars.

HD 154672b is a fairly massive planet with a mass of $M \sin i = 4.96\ M_{\rm Jup}$ 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.

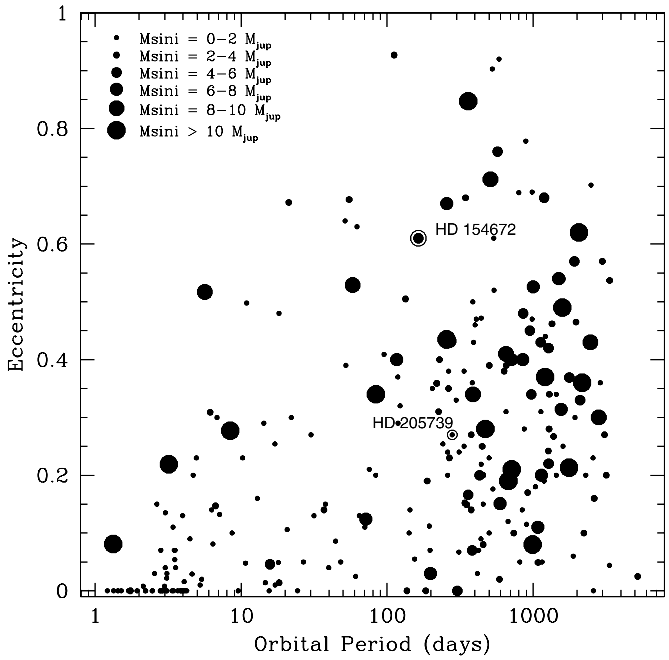

Figure 5. Orbital eccentricity vs. period diagram for known extrasolar planets. The size of the symbols scales with the mass of the planets. The two open circles around the data symbols indicate the location of HD 154672 and HD 205739 in this diagram, respectively.

Table 4
Orbital Parameters

Parameter	HD 154672	HD 205739
P (days)	163.94 (0.01)	279.8 (0.1)
T_p (JD + 2,450,000)	3045.3 (0.1)	3390.7 (0.7)
ω (deg)	265 (2)	301 (8)
Eccentricity	0.61 (0.03)	0.27 (0.07)
K_1 (m s^{-1})	225 (2)	42 (3)
dv/dt (m s^{-1} per day)	0.0000	0.0649 (0.0002)
$a_{\rm rel}$ (AU)	(0.580) 0.597 (0.617)	(0.881) 0.896 (0.915)
$M \sin i$ (M_J)	(4.61) 4.96 (5.36)	(1.28) 1.37 (1.44)
$N_{\rm obs}$	16	24
rms (m s^{-1})	4.36	8.67
Jitter (m s^{-1})	4.0	4.5
Reduced $\sqrt{\chi^2_\sigma}$	1.60	2.13

HD 205739b has a mass of $M \sin i = 1.37\ M_{\rm Jup}$, 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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