A PLANET IN A 0.6 AU ORBIT AROUND THE K0 GIANT HD 102272

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ABSTRACT
We report the discovery of one or more planet-mass companions to the K0-giant HD 102272 with the Hobby–Eberly Telescope. In the absence of any correlation of the observed periodicities with the standard indicators of stellar activity, the observed radial velocity variations are most plausibly explained in terms of a Keplerian motion of at least one planet-mass body around the star. With an estimated stellar mass of 1.9 $M_\odot$, the minimum mass of the confirmed planet is 5.9 $M_J$. The planet’s orbit is characterized by a small but nonzero eccentricity $e = 0.05$ and a semimajor axis of 0.61 AU, which makes it the most compact planet discovered so far around GK spectral type giants. This detection adds to the existing evidence that, as predicted by theory, the minimum size of planetary orbits around intermediate-mass giants is affected by both planet-formation processes and stellar evolution. The currently available evidence of another planet around HD 102272 is insufficient to obtain an unambiguous two-orbit solution.

Key words: planetary systems – stars: individual (HD 102272)

1. INTRODUCTION

Searches for planets around giant stars offer a unique way to extend studies of planetary system formation and evolution to stellar masses substantially larger than 1 $M_\odot$ (Sato et al. 2003). These evolved stars have cool atmospheres and many narrow spectral lines, which can be utilized in precision radial velocity (RV) measurements (less than 10 m s$^{-1}$). Searches for planets around giant stars (Sato et al. 2008; Hatzes et al. 2006; Hekker et al. 2008; Niedzielski et al. 2007, and references therein) begin to provide the statistics, that are needed to constrain the efficiency of planet formation as a function of stellar mass and chemical composition. In fact, the initial analyses by Lovis & Mayor (2007) and Johnson et al. (2007) suggested that the frequency of occurrence of massive planets is correlated with stellar mass. Because more massive stars probably have more massive disks, these results appear to support the core accretion scenario of planet formation (Kennedy & Kenyon 2008). Furthermore, Pasquini et al. (2008) have used the apparent lack of correlation between the frequency of planets around giants and stellar metallicity to argue that this effect may imply a pollution origin of the observed planet frequency–metallicity correlation for main-sequence (MS) stars (Fischer & Valenti 2005).

In time, the ongoing surveys will also create an experimental basis with which to study the dynamics of planetary systems orbiting evolving stars (e.g., Rasio & Ford 1996; Duncan & Lissauer 1998). Sufficiently large surveys of post-MS giants should furnish enough planet detections to meaningfully address the problem of the long-term survival of planetary systems around stars that are off the MS and on their way to the white dwarf stage. In fact, the existing data suggest a deficiency or absorption of orbits with radii below 0.6−0.7 AU, which still awaits a fully satisfactory explanation (Johnson et al. 2007b; Sato et al. 2008). In addition, the recent detection of a planet around the post-red-giant phase subdwarf V391 Peg (Silvotti et al. 2007) has already demonstrated that planets can survive both the red giant branch (RGB) and asymptotic giant branch (AGB) phases of giant evolution.

In this paper, we describe the detection of a planet around the K0-giant HD 102272 and discuss the possibility that at least one more planet-mass body exists in this system. An outline of the observing procedure and description of the basic properties of HD 102272 are given in Section 2, followed by a discussion of rotation and stellar activity indicators of the star in Section 3. The analysis of RV measurements is given in Section 4. Finally, our results are summarized and further discussed in Section 5.

2. OBSERVATIONS AND PROPERTIES OF THE STAR

Our survey, the observing procedure, and data analysis have been described in detail elsewhere (Niedzielski et al. 2007; Niedzielski & Wolszczan 2008). Briefly, observations were made between 2004 July and 2008 January, with the Hobby–Eberly Telescope (HET) (Ramsey et al. 1998) equipped with the High Resolution Spectrograph (HRS) (Tull 1998) in the queue mode (Shetrone et al. 2007). The spectrograph was used in the $R = 60,000$ resolution mode with a gas cell (I2) inserted into the optical path, and it was fed with a 2 arcsec fiber.

Radial velocities of HD 102272 were measured at 35 epochs spanning a period of about 1500 days. Typically, the signal-to-noise ratio (S/N) per resolution element in the spectra was 200−250 at 594 nm in 9−16 minutes of integration, depending on the atmospheric conditions. Radial velocities were measured using the standard I2 cell calibration technique (Butler et al. 1996). A template spectrum was constructed from a high-resolution Fourier Transform Spectrometer (FTS) I2 spectrum and a high signal-to-noise stellar spectrum measured without the I2 cell. Doppler shifts were derived from least-squares fits of template spectra to stellar spectra with the imprinted I2 absorption lines. The RV for each epoch was derived as a mean value of the independent measurements from the 17 usable echelle orders with a typical uncertainty of 6−8 m s$^{-1}$ at a $1\sigma$ level. This RV precision made it quite sufficient to use the Stumpff (1980) algorithm to refer the measured RVs to the solar system barycenter.

HD 102272 (BD+14 2434) is a K0-giant with $V = 8.069$, $B−V = 1.002$ and $U−B = 0.669$ (Haggkvist & Oja 1973), and
\( \pi = 2.76 \pm 1.11 \text{ mas (ESA 1997).} \) Its atmospheric parameters were estimated using the method of Takeda et al. (2005a, 2005b) as \( T_{\text{eff}} = 4908 \pm 35 \text{ K, } \log(g) = 3.07 \pm 0.12, \) and \([\text{Fe/H}] = -0.26 \pm 0.08.\) Comparing the star’s position in the Hertzsprung–Russell diagram (H-R) diagram with the evolutionary tracks of Girardi et al. (2000), we estimate the mass and radius of HD 102272 to be \( M/M_\odot = 1.9 \pm 0.3 \) and \( R/R_\odot = 10.1 \pm 4.6, \) respectively, from calibrations of Alonso et al. (2000).

3. ANALYSIS OF THE RV DATA

RV measurements of HD 102272 derived from the HRS spectra are shown in Figure 1. They reveal a correlated behavior of RV variations of the star on a timescale of about 130 days. Moreover, observations made around MJD 54140 indicate that the amplitude of the RV curve may vary in time.

We have used both the nonlinear least-squares and the genetic algorithm (GA) (Charbonneau 1995) to model the observed RV variations with the standard, six-parameter Keplerian orbits. A fixed 15 m s\(^{-1}\) error was quadratically added to the formal RV uncertainties to account for any random RV variations intrinsic to the star, such as fluctuations of the stellar surface and possible solar-type oscillations. The anticipated value of this additional jitter was conservatively adopted to lie between 20 m s\(^{-1}\), which is typical of stable K-giants (Hekker et al. 2006), and 5 m s\(^{-1}\) as measured for stable dwarfs (Wright 2005). For example, the solar-type oscillations alone, when extrapolated for HD 102272 as described by Kjeldsen & Bedding (1995), would account for a 6 m s\(^{-1}\) RV variation. The 15 m s\(^{-1}\) jitter is equivalent to \( f = 0.005 \) spot on the surface of HD 102272 that would produce 2 m s\(^{-1}\) \( B V S \) at the same time (Hatzes 2002).

The best fit of a single orbit and its residuals are shown in Figure 1. The fit, if interpreted in terms of an orbiting body, calls for a \(~ 6 \ M_\text{Jup} \) companion in a 127.6 day, slightly eccentric orbit around the star (Table 1). The 0.61 AU radius of the orbit is even smaller than the tightest planetary orbit around a red giant identified so far (Sato et al. 2008). However, not unexpectedly, the single-planet model leaves highly correlated post-fit residuals, indicating the possible presence of additional periodicities.

We have performed a search for the best-fitting two-companion Keplerian model of the observed RV variations and identified several solutions of comparable quality with very similar \( \chi^2 \) values of the fits. For example, the orbits with the respective approximate periods of 179, 350, and 520 days and eccentricities of 0.3, 0.5 and 0.7 are all almost indistinguishable in terms of their goodness of fit. At the same time, the parameters of the 127.6 day orbit remain practically unchanged for all of the best two-orbit solutions. An example of such a formal solution with the second orbit of 520 days is shown in Figure 1.

Because of sparse sampling of the observed RV curve and the resulting ambiguities in its modeling, it is useful to perform an additional test of nonrandomness of the residuals obtained from the best fit of a single-planet model to the data. To accomplish this, we have chosen the test of scrambled velocities (Butler et al. 2004) using the GA algorithm. In this test, the residuals were randomly scrambled at the epochs of observations and then searched for the best-fit parameters of the second orbit. A likelihood, \( p_H, \) that the residuals represent a white noise can be quantified as the ratio of the number of best fits, for which \( \chi^2 \) is less than or equal to that derived from the fit to unscrambled data, to the total number of trials. The result of the test with 100,000 trials is shown in Figure 2. Clearly, the fit to the real signal stands apart from those for the randomly scrambled data with \( p_H \sim 10^{-5}, \) which strongly suggests the presence of a second, nonrandom signal in the RV data.

In principle, the existing ambiguities in the modeling of the RV variations in HD 102272 can be constrained by imposing

![Figure 1](image_url)

**Figure 1.** (a) RV measurements of HD 102272 (filled circles) and the best-fit models of a single orbit (gray line) and a two-planet system close to the 4:1 MMR (solid line). (b), (c) The respective best-fit residuals for the above models.

### Table 1

| Parameter | HD 102272 b | HD102272 c |
|-----------|-------------|------------|
| \( P \) (days) | 127.58 ± 0.30 | 520 ± 26 |
| \( T_0 \) (MJD) | 52146 ± 64 | 54135 ± 260 |
| \( K \) (m s\(^{-1}\)) | 155.5 ± 5.6 | 59 ± 11 |
| \( e \) | 0.05 ± 0.04 | 0.68 ± 0.06 |
| \( \omega \) (deg) | 118 ± 58 | 320 ± 10 |
| \( m_2 \sin \iota \) (\( M_J \)) | 5.9 ± 0.2 | 2.6 ± 0.4 |
| \( a \) (AU) | 0.61 ± 0.001 | 1.57 ± 0.05 |
| \( \mathcal{M}(T_0) \) (deg) | 12 ± 60 | 324 ± 40 |
| \( V_0 \) (m s\(^{-1}\)) | 94.2 ± 3.6 | 87 |
| \( (\chi^2)^{1/2} \) | 15.4 |

**Notes.** \( \mathcal{M} \) is the mean anomaly computed for the epoch of the first observation, \( T_0 = \text{MJD} 53042.976890. \)
the obvious requirement that the true two-planet solution is dynamically stable. A convenient way to apply this constraint is to use the GAMP algorithm (Goździewski et al. 2006), in which an N-body model of the observed RV curve has the $\chi^2$ criterion modified by a penalty term for unstable orbits, and the MEGNO test (Cincotta & Simò 2000) is applied to check the stability of a given two-planet solution.

We have performed a GAMP search for the dynamically acceptable orbits of the second companion, with the MEGNO integration time set to $\sim 600$ orbital periods of the outer companion. The results, in which the $\chi^2$ values relative to the best solution found by the search are mapped onto the semimajor axis–eccentricity plane, are shown in Figure 3.

The plot reveals three regions of stability, one of which is located between the mean motion resonances (MMR) of 5:2 and 3:1, another one is extended along the 4:1 MMR, and yet another one occupies a high-eccentricity region between the 4:1 and 5:1 MMRs. Further discussion of these results will be given in Section 5.

4. STELLAR PHOTOMETRY, ROTATION, AND LINE BISECTOR ANALYSIS

We have followed the standard procedure to verify that the observed RV variations are due to orbital motion. It included an examination of the existing photometry of the star for possible variations and an analysis of the bisectors and curvatures of the selected spectral line profiles. We have also searched for stellar activity signatures in the Hα line.

The most precise existing photometry of HD 102272 consists of 70 photometric observations of the star in the Hipparcos (ESA 1997) H$_p$ filter between JD 2447877.95490 and 2448961.44322. The observed scatter in H$_p$ amounted to only 0.015 mag, and no variability above this threshold was detectable. The star was also observed by the Northern Sky Variability Survey (NSVS) (Woźniak et al. 2004). We have analyzed the 31 photometric observations made between JD = 2451318.18842 and JD = 2451630.300686, which were of a sufﬁcient quality, and found no photometric variations of the star. Finally, our Lomb–Scargle periodogram analysis of these data did not reveal any spectral peaks above a threshold level set at six times the mean power computed for periods shorter than 1 month. Of course, it should be kept in mind that the Hipparcos and NSVS data were not simultaneous with our RV measurements.

The projected rotational velocity of HD 102272, $v \sin i = 3 \pm 1$ km s$^{-1}$, was estimated using the cross-correlation method (Benz & Mayor 1984). From this value and the adopted stellar radius, we have obtained an estimate of the rotation period of $P_{rot} \sim 170$ days, which is longer than the observed 127.6 day period of RV variation and appears to be typical for K0 giants (de Medeiros et al. 1996). In principle, given the error estimates of Alonso et al. (2000), the rotation period of HD 102272 may range from 90 to 250 days.

Most analyses of the variations of spectral lines using line bisectors are based on a cross-correlation function (CCF) representation of an “average” spectral line of the observed star. As the $I_2$ lines affect stellar spectra in the iodine cell method of RV determination, they have to be properly removed before the CCF computation. An efﬁcient method to accomplish this has been proposed by Martínez Fiorenzano (2005).

In our implementation of the method, we ﬁrst cross-correlated the stellar spectrum with that of the flat-ﬁeld $I_2$, in order to measure the wavelength offset between the iodine lines present in both spectra. The ﬂat ﬁeld ﬂux was adjusted to the new wavelength scale, adding the previously-determined offset by using a Hermite spline interpolation (Hill 1982).

The CCFs were computed by correlating the stellar spectrum with a numerical “zero-one,” in which the nonzero points were aligned with the positions of stellar absorption lines at zero velocity. The numerical mask was constructed out of 980 lines of a very high S/N spectrum of HD 17092, the ﬁrst star with a planet in our survey (Niedzielski et al. 2007), cleared from spectral features lying within $\pm 30$ km s$^{-1}$ of the known telluric lines (Hanuschkin 2003). Out of the 35 resulting bisector measurements, three were affected by a low S/N in the original spectra and hence removed from further analysis. The typical uncertainties of the $BVS$, calculated with the expression given by Martínez Fiorenzano (2005), were around $\sim 20$ m s$^{-1}$. The mean value of $BVS$ was calculated to be $25 \pm 21$ m s$^{-1}$.

As both the Ca II K emission line (393.4 nm) and the infrared Ca II triplet lines at 849.8–854.2 nm are outside the range of our spectra, we used the Hα line (656.28 nm) as a chromospheric activity indicator. To minimize a contamination from the telluric lines, we measured the equivalent width (EW) of the central part of the line proﬁle deﬁned by $I/I_e \leq 0.7$. Our analysis has shown that the EW exhibited a 0.69% rms scatter around its mean value of 944.4 $\pm$ 6.5 mÅ, which was not correlated with the observed RV variability ($r = 0.06$).
Figure 4. Lomb-Scargle periodograms of (a) radial velocities, (b) bisector velocity span, (c) Hipparcos Hp photometry, and (d) NSVS photometry. The position of the periodicity identified in the RV data is indicated with a vertical arrow. Two false alarm probability levels, 10% and 1%, are marked with dotted lines.

The analysis of the existing photometry and bisector variability span for HD 102272 is summarized in Figure 4, which shows the Lomb-Scargle periodograms computed for all the time series of interest. We conclude that the only measured parameter, which exhibits a significant periodic variability, is RV. Similarly, as evident in the plot of BVS against the RVs in Figure 5, no correlation between the bisector velocity span and the radial velocities exists in HD 102272.

Using the scatter seen in the Hipparcos photometry of the star, and its rotational velocity determined above, we can estimate the amplitude of RV variations and of the bisector velocity span due to possible presence of a spot on the stellar surface (Hatzes 2002). The observed RV amplitude of HD 102272 is almost an order of magnitude larger than the 35 m s$^{-1}$ RV amplitude predicted by Hatzes (2002) for a spot with a filling factor of $f = 0.015$, on a star rotating at $v \sin i = 3$ km s$^{-1}$. The expected bisector variations of 5 m s$^{-1}$ are comparable with the precision of our RV measurements and cannot have a detectable effect on our results. Similar results have been derived with the NSVS photometry using the spot-induced RV variation modeling described by Saar & Donahue (1997).

In principle, it is possible that HD 102272, having no spots over the periods covered by both the Hipparcos data ($\sim$ 1083 days) and those from the NSVS ($\sim$ 312 days), had developed a spot later on, at the time of our RV measurements. Using the results of Hatzes (2002) and Saar & Donahue (1997), we estimate that to generate RV variations as large as $K = 155$ m s$^{-1}$, at a period similar to that of HD 102272 rotation, would require a large spot with the filling factor of $f = 0.17$–0.22.

Figure 5. RV measurements of HD 102272 plotted against the bisector velocity span. Within errors, the BVS remains constant during the period covered by observations at the mean value of 25 m s$^{-1}$ and rms scatter of $\sigma = 21$ m s$^{-1}$. There is no correlation between RV and BVS ($r = 0.03$).

Such a spot would translate into a 50–60 m s$^{-1}$ bisector velocity span that is most certainly excluded by our measurements. We also find it unlikely that such a large spot, apparently not present in the NSVS data mere $\sim$ 1400 days prior to our observations, would show no evolution in our measurements collected over 1500 days or 11 cycles of the observed periodicity. Therefore, we conclude that a rotating spot on the surface of HD 102272 is unlikely to be a cause of the observed periodic RV variations.

5. DISCUSSION

Our observations of the K0-giant, HD 102272, reveal that the measured RVs of this star undergo strictly periodic variations at a period of 127.6 ± 0.3 days. When interpreted in terms of a Keplerian motion, this periodicity indicates the presence of a substellar companion with a minimum mass of $5.9 M_J$, in a low eccentricity, $e = 0.05 \pm 0.04$ orbit, 0.61 AU away from the star (Table 1). In addition, our data indicate the possible presence of another, more distant planetary-mass companion. Unfortunately, in this case, the sparse sampling of a putative second orbit does not allow an unambiguous distinction between orbital motion and intrinsic stellar effects. In any case, the inner planet has the shortest orbital period and the most compact orbit among planets around GK spectral type giants discovered so far (Sato et al. 2008, and references therein).

As the long-period RV variations in red giants may also be related to a combination of effects including stellar rotation, activity, and nonradial pulsations (e.g., Hatzes et al. 2006), we have analyzed the photometric data and the behavior of line bisectors of the star, following the established practices (Queloz et al. 2001). The details of our procedure have been described by Niedzielski et al. (2008). Its application to HD 102272 has not shown any significant correlation between the RV variations and the photometry or line variability of the star. Consequently, the most plausible explanation of our data is the presence of at least one substellar mass companion around the star.

The orbital parameters of the confirmed planet are, within errors, independent of the choice of the orbit of a putative outer companion. The small orbital radius of the planet reinforces the existing evidence that orbits of GK-giant planets appear to be wider than $\sim 0.6$ AU, as suggested by Johnson et al. (2007b) and
These authors have considered the two obvious scenarios to create such a zone of avoidance around the GK giants, namely the tidal capture of a nearby planet by the expanding star and a paucity of compact orbits around giants caused by peculiarities of the disk evolution around intermediate-mass stars (Burkert & Ida 2007). In particular, simulations carried out by Sato et al. (2008) indicate that, for giants that are over the peak of the RGB, a tidal capture of planets at orbital radii $< 0.5$ AU is possible. Clearly, much more observational evidence is needed to place these tentative conclusions on a firmer statistical footing.

Some of the past reports on planet discoveries around GK giants do indicate a possible existence of more planet-sized companions to the stars in question (Sato et al. 2008), but none of them include analyses designed to constrain their possible orbital parameters. As discussed above, and illustrated in Figure 3, our analysis has revealed three regions of plausible two-planet solutions. The better two of them, located between the MMRs of 5:2 and 3:1 and close to the 4:1 MMR (Table 1), offer a significant improvement of the quality of the fit, in comparison with the one-planet model. In addition, these solutions remain dynamically stable over at least 1 Gyr, as shown by our numerical integration of the corresponding orbits. However, a more in-depth analysis of these orbits (K. Goździewski et al. 2008, in preparation) suggests that, because of the compactness of the stability regions for the two solutions, a probability for such systems to become trapped in the respective MMRs in the course of their dynamical evolution must be very low. Evidently, a confirmation or dismissal of a possible dynamical origin of the observed RV variations will have to wait until more data become available in the near future.

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