THE ASTROPHYSICAL JOURNAL, 380:L35–L38, 1991 October 10

CONSTRAINTS ON THE COMPANION OBJECT TO HD 114762

WILLIAM D. COCHRAN, ARTIE P. HATZES, AND TERRY J. HANCOCK[1]
McDonald Observatory and Astronomy Department, University of Texas at Austin, Austin, TX 78712
Received 1991 February 14; accepted 1991 July 29

ABSTRACT

High-precision radial velocity observations of the candidate planetary system HD 114762 are presented. The new data confirm Latham et al.'s discovery of the binary nature of the system. Our new orbital solution gives an eccentricity of 0.38 compared with the Latham et al. value of 0.25, but otherwise it agrees well with the discovery orbit. The mass function for the system implies a companion object with $M_c \sin i_{\rm orb} = 0.011\ M_\odot$. A Fourier analysis of the shape of a photospheric absorption line of HD 114762 gives a best estimate of the projected stellar rotational velocity $V \sin i_{\rm rot} = 0$ km s^{-1}, with an extreme upper limit on $V \sin i_{\rm rot}$ of about 1 km s^{-1}. The derived mass for the companion object then depends on the assumptions made for the rotational velocity of the star, and on the degree of alignment of the stellar rotational axis with the companion object orbital axis. If we assume that the actual rotation rate of HD 114762 is similar to that of other F9 V stars studied by Soderblom, and that the stellar rotational axis is approximately parallel to the orbital axis, this gives a value for $\sin i_{\rm orb}$ of the companion object of ~ 0.10 ($i_{\rm orb} < 5\overset{\circ}{.}7$). This results in the companion object having the mass of a late M dwarf star in a system viewed nearly pole-on. At the other extreme, one can assume that HD 114762 is a very slow rotator, that our hard upper limit on $V \sin i_{\rm orb}$ is the actual value, and that there is a significant misalignment of the rotational and orbital axes, and derive a companion object mass as low as $0.02\ M_\odot$.

Subject headings: stars: binaries — stars: brown dwarfs — stars: planetary systems

1. INTRODUCTION

The International Astronomical Union radial velocity standard star HD 114762 was recently found by Latham et al. (1989) to exhibit low-amplitude radial velocity variations, which they attributed to the reflex orbital motion of the star due to the presence of an unseen companion object. Their orbital solution to the system gives a mass function which implies that $M_c \sin i_{\rm orb} = 0.011\ M_\odot$, where M_c is the mass of the companion object and $i_{\rm orb}$ is the inclination of the orbital plane to our line of sight. If the system is viewed edge-on, then the companion would be in the range of possible planetary masses. Intermediate values of the inclination angle would imply a substellar "brown dwarf" companion. However, if viewed nearly pole-on ($i_{\rm orb} < 8°$), the companion could be a low-mass star. Thus, this extremely interesting system could well be the first confirmed extrasolar planetary system if the value of the orbital inclination angle can be determined. A photometric investigation by Robinson et al. (1990) found no evidence for transits or eclipses in the system, effectively eliminating the nearly equator-on viewing geometry. However, they were only able to constrain the orbital inclination to a value less than 89°, and this does not place any tight constraints on the mass of the secondary object. In this paper we present new spectral observations of the HD 114762 system. High-precision radial velocity measurements confirm the binary nature of this system, and enable us to refine the orbital solution. Fourier analysis of the shape of a photospheric line profile allows us to place upper limits on the projected rotational velocity of the star. We discuss the possible implications this will have for the orbital inclination, and thus for the derived mass of the companion object in this system.

2. OBSERVATIONS

We have been conducting the McDonald Observatory Planetary Search (MOPS) program, an ultra–high-precision survey of stellar radial velocity variations, since 1987 September. Details of the MOPS observational techniques and data reduction methods are given by Cochran & Hatzes (1990). Following the announcement of the binary nature of HD 114762 by Latham et al. (1989), we added this star to our survey list in an effort to improve the orbital solution. We obtained 28 high-precision relative radial velocity measurements on this system between 1988 November and 1990 July. The measured relative velocities are listed in Table 1. These data were acquired using the coudé spectrograph of the McDonald Observatory 2.7 m telescope. The spectral resolution was 0.035 Å, and a Texas Instruments 800 × 800 three-phase CCD yielded a wavelength coverage of 11.6 Å which was centered at 6300 Å. The typical signal-to-noise ratio of these spectra was 60–80. Although we obtained only about 10% of the number of observations that went into the discovery orbit of Latham et al., these new data are of sufficiently high precision to allow us to make our own orbital solution for HD 114762, which is shown in Table 2. We confirm the binary nature of this system. Our orbital solution agrees quite well with the values given by Latham et al. The major difference in the orbital solutions is that we have determined an orbital eccentricity significantly larger than that found previously. There is no obvious explanation for this difference in e. We are quite confident of our software, and we are able to reproduce the Latham et al. solution from their data. Figure 1 shows the relative radial velocity curve calculated from our orbital solution. Our data are shown as the large filled circles, and the Latham et al. data are the small dots. The rms dispersion of our observations from the orbital solution is 0.034 km s^{-1}. HD 114762 is the faintest star in the MOPS program, and thus

---

[1] Postal address: Steward Observatory, University of Arizona, Tucson, AZ 85721.

1991ApJ...380L..35C

TABLE 1

MEASURED RELATIVE RADIAL VELOCITIES OF HD 114762

Date[a]	V (km s^{-1})	Date[a]	V (km s^{-1})	Date[a]	V (km s^{-1})
7496.0033......	4.633	7610.8302......	3.941	7956.9388......	3.404
7496.9951......	4.627	7611.8268......	3.857	7958.8635......	3.497
7516.9648......	4.301	7633.7799......	4.271	7998.8158......	4.695
7516.9970......	4.304	7634.8315......	4.257	8016.7310......	4.386
7517.9807......	4.298	7674.7094......	4.512	8017.7328......	4.405
7551.9137......	4.277	7675.6884......	4.456	8018.7394......	4.379
7552.9235......	4.409	7696.6751......	3.790	8084.6783......	4.665
7581.8664......	4.613	7697.6957......	3.773	8086.7131......	4.516
7582.8510......	4.663	7880.9619......	3.884		
7585.8553......	4.618	7882.0008......	3.960		

[a] All dates are Julian Date −2,440,000.

TABLE 2

HD 114762 ORBIT SOLUTION

Parameter	Value
Period P (days)	83.91 ± 0.13
Orbital half-amplitude K (km s^{-1})	0.617 ± 0.017
Eccentricity e	0.380 ± 0.015
Longitude of periastron ω (deg)	199.8 ± 4.4
Epoch T (Julian Date −2,440,000)	7371.65 ± 1.21
Mass function (10^{-6} $M_\odot$)	1.6 ± 0.1

these are the least precise data of the survey. Since we are measuring only relative radial velocities, we are not able to compute an accurate system velocity, γ.

3. DISCUSSION

Our new orbital solution, while in good agreement with of Latham et al. (1989), places interesting constraints on the nature of this system. The companion object is in an orbit with a semimajor axis similar to that of Mercury, but with twice the eccentricity. Current solar nebula models cannot exclude the formation of either a planet or a star in such an orbit. This semimajor axis is well within the radius at which one would expect H_2O condensation in the protostellar nebula which formed the HD 114762 system. Therefore, formation of a giant-planet core at this radius would probably require a nebula considerably more massive than the nebula which formed our solar system. Planet formation in this large-eccentricity orbit will effectively sweep up most of the nebular material in the inner disk, and will prevent formation of other planets in nearby orbits.

The mass of the companion of HD 114762 is critically dependent on the inclination of the orbital plane to our line of sight. If this plane lies along the line of sight (equator-on), then a minimum mass of 0.011 $M_\odot$ results for the companion, and this truly represents a unique, interesting, and important system. On the other hand, if the orbital plane is nearly perpendicular to the line of sight (pole-on), then the mass of the companion can have any arbitrarily large value, and this object represents a more normal binary star system.

The special case of $i_{\rm orb} = 90°$ (equator-on orientation of orbital plane) was probably eliminated by the lack of eclipses or transits in the photometric investigation of Robinson et al. (1990). There are also means of estimating the value of sin $i_{\rm orb}$. The mean radial component of the rotation rate (V sin $i_{\rm rot}$) of main-sequence stars exhibits a steep but smooth decline from F0 to G0, and stars with spectral types as late as our Sun exhibit rotational velocities of the order of a few kilometers per second. Soderblom's (1982) survey of rotational velocities of solar-type stars revealed that stars with spectral type F8 V

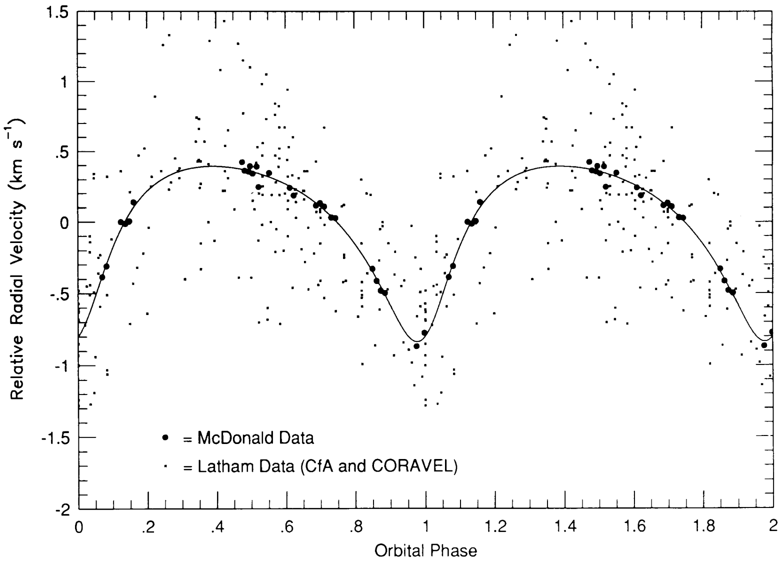

FIG. 1.—Radial velocity curve for HD 114762. The McDonald data presented in this paper are shown as large filled circles. The original discovery data of Latham et al. (1989) are shown as small dots. The solid curve is from the orbital solution derived from the McDonald data.

have mean $V \sin i_{\rm rot} = 6.7 \pm 4.3$ km s^{-1}, and G0 V stars have a mean value of 4.4 ± 3.5 km s^{-1}. Thus we should expect HD 114762 to exhibit a measurable intrinsic equatorial rotational velocity. If we can measure the projected rotational velocity $V \sin i_{\rm rot}$ and determine or estimate the intrinsic rotational velocity V, then we can obtain a value of $\sin i_{\rm rot}$ by division. The high spectral resolution of our data ($R \approx 180{,}000$) enables us to determine accurately the projected rotational velocity of this star.

Fourier transform techniques provide an accurate method for measuring the rotational velocity of stars (Gray 1988). The two dominant broadening mechanisms in stellar line profiles are rotation and macroturbulence, and each produces its own characteristic shape in Fourier space. Spectral lines having appreciable amounts of rotational broadening ($V \sin i_{\rm rot} >$ 1 km s^{-1}) are characterized by the appearance of a sidelobe in the Fourier transform, whereas the transform of a profile with only macroturbulence is devoid of such features. Fourier techniques have been extensively employed to measure the rotational and macroturbulent velocities in stars (Gray 1975; Soderblom 1982) as well as search for differential rotation in stars (Gray 1977; Bruning 1981).

Ten spectra were co-added to produce a mean spectral line profile for the Fe I 6302.5 Å line in HD 114762. The telluric O_2 features were removed from each spectrum through division by the spectrum of a hot star which is devoid of stellar lines in this wavelength region. The 6302.5 Å line was chosen because it was not severely blended with any nearby telluric O_2 lines. Although Fourier techniques were used to deconvolve the instrumental profile from the data, similar results were obtained by analyzing the original line profiles without deconvolution.

The high spectral resolution of our spectral data allowed us the luxury of analyzing the shape of the line profile in both wavelength and Fourier space; both methods produced the same result. Also, the analysis was performed on a single observation in which the telluric line was well separated from the Fe I line. Thus, no division by a hot star was required. Again, the same result was obtained. Finally, as a test, the Fourier technique was applied to the same Fe I photospheric line in the solar spectrum obtained from an observation of the Moon. A $V \sin i_{\rm rot}$ of 1.9 km s^{-1} and a macroturbulent velocity of 3.4 km s^{-1} were derived. This compares favorably with the value of $V \sin i_{\rm rot} = 1.9$ km s^{-1} and $M = 2.9$ km s^{-1} for the Sun found by Soderblom (1982). Our slightly higher value of M may be due to the fact that the Fe I 6302 Å line is a magnetically sensitive line, and part of the line width may be due to Zeeman broadening which we would model as a higher macroturbulent velocity.

Figure 2 shows the deconvolved data transform as filled circles. In modeling the transform, model atmospheres from Kurucz (1979) as well as his WIDTH5 routines were used to generate the specific intensity profiles as a function of limb angle across the stellar disk. A microturbulent velocity of 1 km s^{-1} was used (Gray 1988). These local line profiles were then integrated over a grid of 6400 elements representing the stellar disk. This integration included the rotational velocity of the star, macroturbulence, and limb darkening. The standard radial-tangential prescription was used to incorporate macroturbulence. The solid line represents the best fit to the Fourier transform using a projected rotational velocity ($V \sin i_{\rm rot}$) of 0 km s^{-1} and a macroturbulence velocity (M) of 4.7 km s^{-1}. The model Fourier transform with only macroturbulent broadening fits the observed transform rather well, except at higher frequencies where the data transform is systematically higher than the model transform. Gray (1988) also found no measurable rotation in the K1 IV star γ Cephei, and at the higher frequencies the observed transform for that star was also systematically above the model transform. In both cases the slight departures between the model and the data are most likely due to errors in determining the true instrumental profile or errors due to photon noise, choice of continuum level, etc.

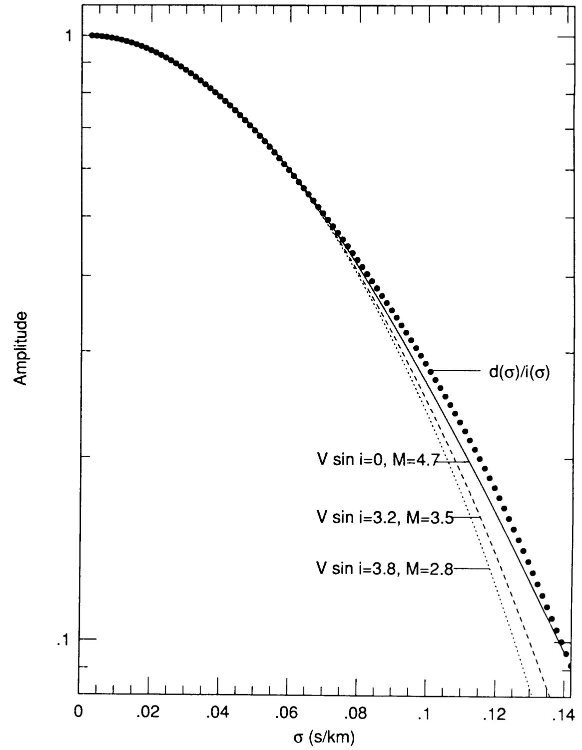

FIG. 2.— Fourier transform of the Fe I 6302.5 Å line of HD 114762 (*filled circles*). The lines represent fits to the data Fourier transform using synthetic lines with various combinations of $V \sin i$ and macroturbulent velocity M. The solid line is the model with $V \sin i = 0$ and $M = 4.7$ km s^{-1}; the dashed line is for $V \sin i = 3.2$ and $M = 3.5$ km s^{-1}; and the dotted line is for $V \sin i = 3.8$ and $M = 2.8$ km s^{-1}.

It is clear that the projected rotational velocity $V \sin i_{\rm rot}$ of HD 114762 is indeed very small. At such low values there is a tradeoff between broadening due to rotation and that due to macroturbulence which makes it difficult to distinguish between the two broadening mechanisms. A profile can also be fitted by decreasing the macroturbulent velocity and increasing the projected rotational velocity. The actual projected rotational velocity for HD 114762 may thus be somewhat higher than 0 km s^{-1}. Figure 2 also shows the results of two additional models using $V \sin i_{\rm rot} = 3.2$ km s^{-1}, $M = 3.5$ km s^{-1} (*dashed line*) and $V \sin i_{\rm rot} = 3.8$ km s^{-1}, $M = 2.8$ km s^{-1} (*dotted line*). Increasing the projected rotational velocity to any nonzero value and making a compensating decrease in the macroturbulence always results in poorer fits to the data transform in that residuals between the observed and model transform at the higher frequencies are much larger. The poorer fit of the model transform to the observed transform thus precludes the rotational velocity being much larger than our best value of 0 km s^{-1}.

The measured macroturbulent velocity for HD 114762 can also be used as an argument in favor of a very low $V \sin i_{\rm rot}$. Gray (1984) has found that there is a tight correlation between the macroturbulent velocity and the spectral type for a star.

Using the results of that work, we find that the mean value for the macroturbulent velocity for an F8 V star is about 4.8 km s^{-1}, and for a G0 V star it is about 4.5 km s^{-1}. Our measured macroturbulent velocity is thus consistent with HD 114762 being a late F star. Even assuming a rather modest $V \sin i_{\rm rot}$ of 1 km s^{-1} would force the macroturbulence to have a value more consistent with a G3 V star than with an F9 V star. Also, HD 114762 is an evolved star, and Gray has shown that the macroturbulent velocity increases as one moves away from the main sequence. This would argue against HD 114762 having a lower macroturbulent velocity. We therefore placed a hard upper limit of 1 km s^{-1} on the $V \sin i_{\rm rot}$ of HD 114762. Adopting Soderblom's (1982) mean $V \sin i_{\rm rot}$ for F9 stars (5 km s^{-1}) as the best estimate for the actual rotation velocity V for HD 114762 results in $\sin i_{\rm rot} \leq 0.20$. The actual value of $\sin i_{\rm rot}$ may well be lower, since Soderblom's value is for stars having a distribution of inclinations. If we include a factor of $\pi/4$ for the mean inclination of stars in Soderblom's sample, then a $\sin i_{\rm rot} \leq 0.14$ results. Finally, our Fourier modeling suggests that the actual $V \sin i_{\rm rot}$ is almost certainly much less than 1 km s^{-1}, implying a smaller value for the actual value of $\sin i_{\rm rot}$.

On the other hand, HD 114762 is a high-velocity metal-poor star, indicating that its age is probably somewhat larger than that of the stars in Soderblom's sample. Thus HD 114762 may well have had a much longer time to lose rotational angular momentum, and its intrinsic rotational velocity may be smaller than other F9 V stars. The low metal abundance of HD 114762 may also be used to argue for a somewhat later spectral type than the F9 V commonly assigned to this star.

An alternative method for determination of $\sin i_{\rm rot}$ is to obtain a rotational period for the star through high-precision photometric monitoring. In spite of attempts by several groups to do this for HD 114762, there are as yet no reported periodic photometric variations for this star. This result is consistent with a nearly pole-on orientation of HD 114762. A second way to determine stellar rotational periods is to measure the Ca II emission index S and to apply the Rossby number relationship between S, rotational period, and mass (Noyes et al. 1984). However, the Ca II emission for HD 114762 is rather weak, and the Rossby number relationship is not well determined for the F stars (S. Baliunas, private communication). While this technique may well be successful in the future, the published data and calibration may not be useful in the case of HD 114762 at present.

Our best estimate of $\sin i_{\rm rot} < 0.20$ ($i_{\rm rot} < 11\overset{\circ}{.}5$) from the stellar line profile analysis refers to the inclination of the stellar rotation axis. The orbital solution limit on the companion object mass $M_c \sin i_{\rm orb} = 0.011\ M_\odot$ refers to the inclination of the companion object orbital plane. While we would expect the rotational and orbital axes to be roughly aligned, there is no reason to believe that they should be exactly parallel. In our solar system, the solar equator is inclined to the ecliptic by $7\overset{\circ}{.}25$. A tilt of this order of magnitude in the HD 114762 system could result in $i_{\rm orb}$ either larger or smaller than $i_{\rm rot}$, depending on the relative orientations of the axes.

4. SUMMARY AND CONCLUSIONS

We have confirmed the low-amplitude radial velocity variability and the binary nature of the star HD 114762. Our orbital solution agrees well with the discovery orbit of Latham et al. (1989). The mass function of the system gives $M_c \sin i_{\rm orb} = 0.011\ M_\odot$, which means that the companion object could be the first confirmed extrasolar planetary system if the orbital inclination $i_{\rm orb}$ is near 90°. Our higher precision radial velocity measurements are able to constrain the orbital eccentricity of the system to a value of 0.38. While this larger eccentricity does not by itself preclude the presence of a planetary mass companion, it probably will significantly inhibit the formation of more than one planetary mass object close to the primary. We are able to place a possible limit on the inclination of the stellar rotation axis of $\sin i_{\rm rot} \leq 0.20$ as derived from the Fourier analysis of the shape of a photospheric line profile.

Given these new results, we would obviously like to place interesting limits on the mass of the companion object. If $\sin i_{\rm orb} < 0.138$, then the secondary is a low-mass star. Larger values of $\sin i_{\rm orb}$ imply a substellar (brown dwarf or planetary) companion. It is possible to make quite plausible arguments for either case. On the one hand, an argument can be made that HD 114762 is simply an intrinsically slowly rotating star. This star is considerably older than the Sun and has had a longer time in which it could spin down. Thus, it is possible for the equatorial rotational velocity to be as low as 2–3 km s^{-1}. This low $V_{\rm rot}$, coupled with a large (or fortuitously oriented) misalignment between the rotational and orbital axes, could conceivably result in a companion object mass as low as 0.02 $M_\odot$ if one also adopts our upper limit on $V \sin i_{\rm rot}$ as the actual value. On the other hand, we note that our best-fit value of $V \sin i_{\rm rot}$ is 0.0 km s^{-1}. The value of 1.0 km s^{-1} is a generous upper limit. Using a value of $V \sin i_{\rm rot}$ somewhat less than 1.0 km s^{-1} and an equatorial rotation of 5 km s^{-1} would give $\sin i_{\rm rot} \sim 0.1$. Then the companion object could easily be a low-mass star as long as the rotational axis is not seriously misaligned with the orbital axis.

The determination of the mass of the companion object thus depends on two quantities which remain unknown: the stellar equatorial velocity and the relative orientation of the orbital axis and the rotational axis. It is dangerous to attempt to infer properties of a particular system from statistics of similar stars. There is some hope of being able to measure a rotational period (and thus V) for HD 114762 in the near future. This would resolve the largest uncertainty in determining the secondary mass. Until then, we cannot rigorously conclude that the companion is either stellar or substellar in mass.

We wish to thank David Latham and Sallie Baliunas for several helpful comments and suggestions. This material is based in part upon work supported by the Texas Advanced Research Program under grant 3547 and by NASA grant NAGW-1477.

REFERENCES

Bruning, D. H. 1981, ApJ, 248, 274

Cochran, W. D., & Hatzes, A. P. 1990, in Optical Spectroscopic Instrumentation and Techniques for the 1990s: Applications in Astronomy, Chemistry, and Physics, ed. B. J. McNamara & J. M. Lerner (Proc. SPIE, Vol. 1318), 148

Gray, D. F. 1975, ApJ, 202, 148

———. 1977, ApJ, 211, 198

———. 1984, ApJ, 281, 719

———. 1988, Lectures on Spectral-Line Analysis: F, G, and K Stars (Arva, Ontario: The Publisher)

Kurucz, R. L. 1979, ApJS, 40, 1

Latham, D. W., Mazeh, T., Stefanik, R. P., Mayor, M., & Burki, G. 1989, Nature, 339, 38

Noyes, R. W., Hartmann, L. W., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763

Robinson, E. L., Cochran, A. L., Cochran, W. D., Shafter, A. L., & Zhang, E.-H. 1990, AJ, 99, 672

Soderblom, D. R. ApJ, 263, 239