A High-Eccentricity Low-Mass Companion to HD 89744

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ABSTRACT

HD 89744 is an F7 V star with mass 1.4 $M_\odot$, effective temperature 6166 K, age 2.0 Gy and metallicity [Fe/H]= 0.18. The radial velocity of the star has been monitored with the AFOE spectrograph at the Whipple Observatory since 1996, and evidence has been found for a low mass companion. The data were complemented by additional data from the Hamilton spectrograph at Lick Observatory during the companion's periastron passage in fall 1999. As a result, we have determined the star's orbital wobble to have period $P = 256$d, orbital amplitude $K = 257$ m/s, and eccentricity $e = 0.7$. From the stellar mass we infer that the companion has minimum mass $m_2 \sin i = 7.2\ M_{\rm JUP}$ in an orbit with semi-major axis $a_2 = 0.88$ AU. The eccentricity of the orbit, among the highest known for extra-solar planets, continues the trend that extra-solar planets with semi-major axes greater than about 0.15 AU tend to have much higher eccentricities than are found in our solar system. The high metallicity of the parent star reinforces the trend that parent stars of extra-solar planets tend to have high metallicity.

Subject headings: planetary systems — stars:low-mass, brown dwarfs — stars: individual (HD 89744) — techniques:radial velocities

1. INTRODUCTION

We report on the detection of a massive ($m_2 \sin i = 7.2\ M_{\rm JUP}$) planet in a highly elliptical ($e = 0.7$), 256 day orbit about the star HD 89744 (HR 4067, HIP 50786), from radial velocity variations which reveal Keplerian motions of the star. Observations were carried out from 1996 through 1999 using the Advanced Fiber Optic Echelle (AFOE) spectrograph (Brown *et al.* 1994; Nisenson *et al.* 1998), a bench-top spectrograph located at the Whipple Observatory 1.5m telescope, and also with the Hamilton spectrograph at the Lick Observatory CAT and Shane telescopes, in November and December of 1999.

The AFOE spectrograph is designed primarily for precise radial velocity studies of the seismology of bright stars, and of reflex motions of stars due to planetary companions. Long term stability of the velocity reference is provided by use of an iodine (I_2) cell (Butler *et al.* 1996). The AFOE determines radial velocity variations induced by planetary companions with a precision and long-term accuracy of approximately 10 m/s. On the order of 100 relatively bright stars ($m_v \leq 7$) have been monitored for this purpose since 1995.

Since 1995 when the planetary candidate oribiting the star 51 Pegasus was detected (Mayor & Queloz 1995), some 29 additional candidates have been detected by several groups, all from Doppler shifts measured using precise radial velocity techniques (Marcy & Butler 1998; Mayor *et al.* 1998; Noyes *et al.* 1997; Cochran *et al.* 1997).

HD 89744 (F7 V) was added to the AFOE observing list in early 1996, based on its relatively low chromospheric emission as measured with the Mt. Wilson "HK" chromospheric activity monitoring program (Baliunas *et al.* 1995). AFOE

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observations have been obtained regularly since then, and indicated the presence of a planet with a highly eccentric orbit. However data near the companion's periastron, critical to an accurate determination of the orbital parameters, were not obtained until late 1999. Between October and December 1999, while the companion was near periastron, observations were made at Lick Observatory as well as with the AFOE, to ensure good phase coverage. The data points taken with the Lick CAT and Shane telescopes agree extremely well with the AFOE data, and thus provide a confirmation of the detection along with a precise determination of the ellipticity of the planet's orbit.

2. PROPERTIES OF THE HOST STAR, HD 89744

HD 89744 is an F7V star at a Hipparcos-determined distance of 39.0 parsec. It is listed as a constant star in the Hipparcos catalog . The star has absolute magnitude $M_v = 2.78$ and color $B - V = 0.531$ (Perryman 1997). Comparing its position in the color-magnitude diagram with predictions of stellar evolution calculations, Prieto & Lambert (2000) determine it to have mass $M = (1.34 \pm 0.09) M_{\odot}$, radius $R = (2.14 \pm 0.1) R_{\odot}$, and effective temperature $T_{\rm eff} = (6166 \pm 145) K$. Independently, Ng & Bertelli (1998) determine its mass to be $M = (1.47 \pm 0.01) M_{\odot}$. For the purposes of this paper we adopt the average of the two masses listed and an uncertainty given by their spread: $M = (1.4 \pm 0.09) M_{\odot}$.

The metallicity of HD 89744 has been determined to be [Fe/H]= 0.18 by Edvardsson *et al.* (1993). Its age is determined by Ng & Bertelli (1998) to be 2.04 ± 0.10 Gy.

From rotational modulation of the Ca II flux, Baliunas, Sokoloff, & Soon (1996) determined that the rotation period of the star is $P_{\rm rot} = 9$ days. This, combined with the above-mentioned radius of the star, implies an equatorial velocity $v = 12$ km/sec. Rotational broadening of the spectrum implies $v \sin i = 8$ km/s (Bernacca & Perinotto 1970; Uesugi & Fukuda 1970). This further implies that the star's rotational equator is inclined by about 40° to the plane of the sky.

Speckle observations (McAlister *et al.* 1989) have not revealed any indication of a stellar companion to HD 89744.

Table 1 summarizes the relevant parameters of the star HD 89744.

Table 1: Parameters for HD 89744.

Parameter	Value		
Mass [$M_{\odot}$]	1.4	±	0.09
Radius [$R_{\odot}$]	2.14	±	0.1
$T_{\rm eff}$[K]	6166	±	145
M_v	2.78		
Age [Gy]	2.04		
[Fe/H]	0.18		
$P_{\rm rot}$ [days]	9		
$v \sin i$ [km/s]	8		

3. OBSERVATIONS

3.1. Instrumentation and Data Reduction

The AFOE is a bench-mounted, fiber-fed, high-resolution cross-dispersed echelle spectrograph designed for high radial velocity precision and stability both on short time scales (better than 1 m/s over hours, for asteroseismology) and long term (approximately 10 m/s, for radial velocity exo-planet searches, through use of an iodine absorption cell). The AFOE is located at the 1.5m telescope of the Whipple Observatory on Mt. Hopkins, Arizona. A more complete description of the AFOE is available in Brown *et al.* (1994) and Nisenson *et al.* (1998). The AFOE exo-planet survey program monitors the radial velocity of about 100 stars brighter than $m_v = 7.5$, with an accuracy of 10 – 15 m/s for integrations with a signal-to-noise ratio of 100 to 150. Most observations consist of three consecutive exposures, primarily to limit cosmic ray contamination by keeping the exposure times short.

Our data reduction methodology is conceptually similar to that described by Butler *et al.* (1996), but differs in details. Echelle images are dark subtracted and one dimensional spectra extracted and corrected for scattered light, then flat-fielded using the spectrum of a tungsten lamp. For each of the six spectral orders that contain strong iodine lines a model is adjusted to match the observed star-plus-iodine spectrum in the least-squares sense. This model is computed using a Doppler-shifted high SNR spectrum of the star alone, plus a very high resolution high SNR spectrum of the iodine cell. The model incorporates the sought-for Doppler-shift of the star as well as mechanical drifts within the spectrograph, the instrumental wavelength solution, the instrumental resolution profile, and a residual scattered light correction. The resulting radial velocities, after correction for the motion of the telescope relative to the solar system barycenter, are averaged for all six orders and the three consecutive observations. The scatter around the mean provides an estimate of the uncertainty. The root-mean-square (RMS) velocity of several radial velocity standard stars is commensurate with this estimate of uncertainty. The Doppler analysis for the Lick observations is described in detail in Butler *et al.* (1996).

3.2. Observations and Orbital Fit

AFOE observations of HD 89744 were obtained on 74 separate nights between December 1996 and December 1999. Additional observations on 14 nights during November and December 1999 were also taken at the Lick Observatory CAT and Shane telescopes, to ensure complete phase coverage near the November 1999 periastron passage. The data with their uncertainties are plotted in Figure 1.

The RMS of the zero-averaged velocities for the AFOE data alone is 129.1 m/s, while the averaged uncertainty on these observations is 15.2 m/s; the corresponding reduced χ is 10; where the reduced χ is given by

$$\chi = \left[\frac{1}{N_o - N_m} \sum_{i=1}^{N_o} \left(\frac{O_i - M_i}{\sigma_i}\right)^2 \right]^{\frac{1}{2}} \qquad (1)$$

where O_i are the observations, σ_i the observational uncertainties, M_i the corresponding values of the model, N_o the number of observations and N_m the number of adjustable parameters in the model. After fitting a Keplerian orbit in the least-squares sense, the RMS of the residuals is 26.2 m/s, corresponding to a reduced χ of 1.7. If we include the Lick observations, by adding one additional free parameter to account for the arbitrary offset between the two data sets, the RMS of the residuals is 20.5 m/s, or a reduced χ of 1.6. (One velocity point was rejected based on a 3-pass 3-σ rejection algorithm.) The resulting orbital parameters are given in Table 2. These are almost identical to the parameters obtained when using only the AFOE observations, except that the combined data set leads to smaller uncertainties, primarily on the amplitude but also on the eccentricity. The orbital fit phase plot and the residuals to the fit are shown in Figures 2 and 3. The periodic variation of the radial velocity, and the highly eccentric character of the orbit, are evident. For a stellar mass of 1.4 $M_\odot$, the orbital elements imply a minimum mass for the companion of $m_2 \sin i = 7.2\ M_{\rm JUP}$, and a semi-major axis of 0.88 AU.

Table 2: Orbital parameters resulting from a Keplerian fit to the combined data set. The last two rows of the table use the adopted value $m_1 = 1.4$ $M_\odot$

Parameter	Value		
P [day]	256.0	±	0.7
K [m/s]	257	±	14
e	0.70	±	0.02
ω	195	±	3
T_o [JD-2,450,000]	994	±	2
$f(m_1, m_2, i)$ [$M_\odot$]	$1.64\,10^{-7}$		
$a_1 \sin i$ [AU]	0.0043		
RMS(residuals) [m/s]	20.5		
reduced χ	1.6		
$N_{\rm Tot}$, $N_{\rm Rej}$	88,		1
a_2 [AU]	0.88		
$m_2 \sin i$ [$M_{\rm JUP}$]	7.2		

4. DISCUSSION

The radial velocity data shown in Figure 2 are unambiguous in revealing a periodic radial velocity variation of HD 89744, which can be fit well by a Keplerian orbit. Since observations obtained with two different radial velocity instruments at two different telescopes yield exactly the same radial velocity variations within their respective instrumental errors, the evidence is compelling that the measured velocities are real variations on the star. There is no known way a stellar signal in a late F-type main sequence star could mimic a Keplerian orbital signature with such a long period and large amplitude, and with such a large eccentricity. Hence we are driven to the interpretation that the star is orbited by a low-mass companion, HD 89744 b, ($m_2 \sin i = 7.2 M_\odot$), in an orbit with semi-major axis 0.88 AU and eccentricity 0.70.

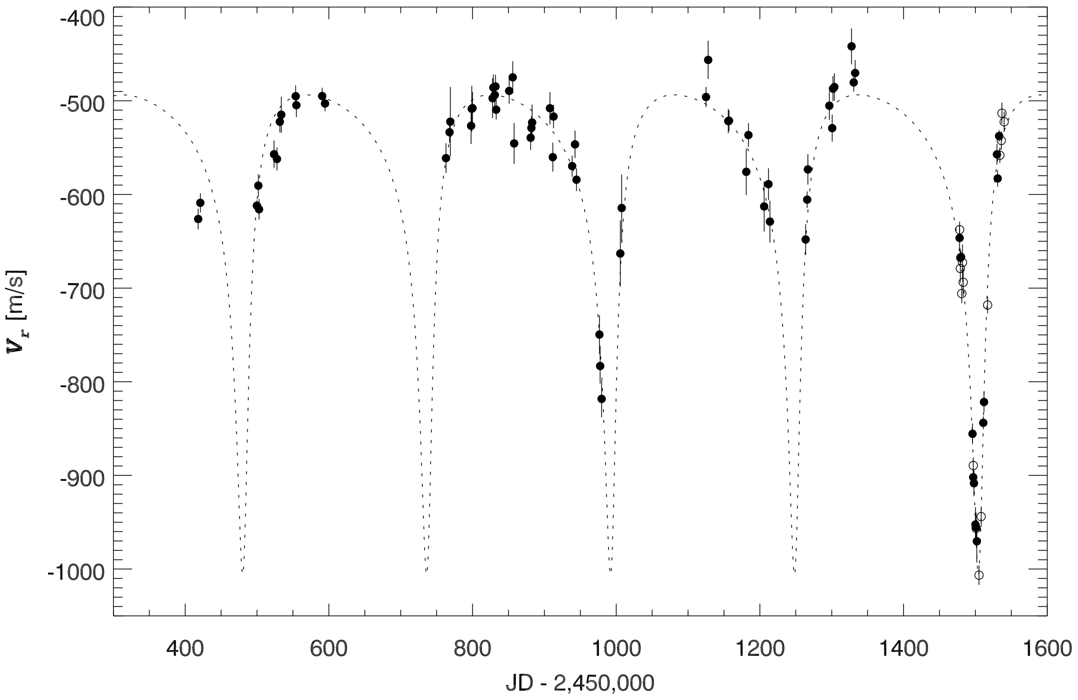

Fig. 1.— Radial velocity observations of HD 89744 with their respective uncertainties. Filled circles denote AFOE observations, and open circles Lick observations after applying an offset determined by the combined orbital fit. The Keplerian orbital fit is indicated by the dotted line.

The residuals to the orbital fit are larger than would be expected from internal errors in the data; this is true both for the AFOE data and the Hamilton echelle data. However, Saar *et al.* (1998) conclude that for a typical F stars with this rotation period, the velocity jitter induced by stellar magnetic activity and inhomogeneous convection is approximately 10 m/s. Adding this jitter in quadrature to the uncertainties lower the reduced χ to 1.2. The residuals display a long term trend (≈ 15 m/s/year) that is marginally significant. While it might be caused by a residual instrumental drift in the AFOE data, we can not rule out that it might be due to a distant companion; further observations over a longer baseline are required.

The orbital eccentricity of the companion to HD 89744 is among the highest planetary eccentricities known. Only two other planets, 16 Cyg B b ($e = 0.68$, $a_2 = 1.70$ AU; Cochran *et al.* 1997) and HD 222582 b ($e = 0.71$, $a_2 = 1.35$ AU; Vogt *et al.* 1999) have comparable eccentricities. HD 89744 b, with $a_2 = 0.88$ AU, has the smallest semi-major axis of the three. At periastron it dips to within 0.26 AU, still well outside a periastron distance which could lead to tidal circularization within the stellar lifetime.

The discovery of the first highly eccentric planet, 16 Cyg B b, led to the suggestion (Mazeh *et al.* 1997; Holman *et al.* 1997) that its eccentricity may have been "pumped up" by the influence of a nearby companion star, 16 Cyg A. However, neither HD 89744 nor HD 222582 is orbited by a stellar companion. Thus a different explanation is required for their high eccentricities, an explanation that might also apply to 16 Cyg B b.

The high orbital eccentricity of the HD 89744 system continues the trend that planetary-mass companions whose semi-major axes are greater than about 0.15 AU tend to have a broad range of eccentricities, with no apparent trends of eccentricity with mass or semi-major axis. This circumstance must be explained by any successful

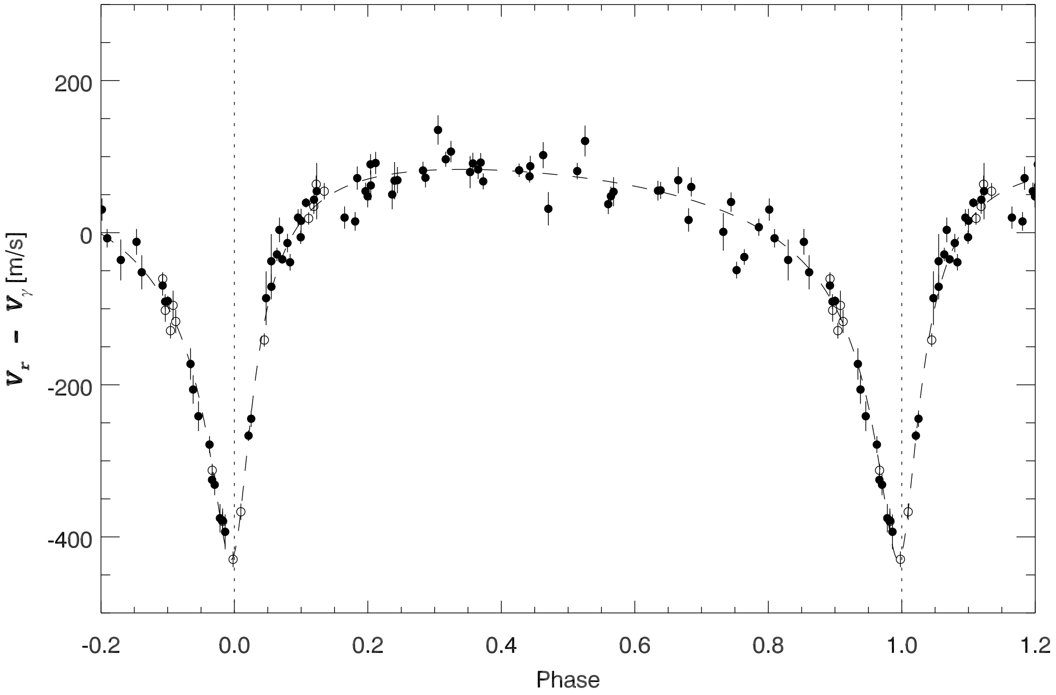

Fig. 2.— Phase plot of the Keplerian orbital fit. Filled circles denote AFOE observations, open circles Lick observations.

planetary formation and migration scenario. As noted by others (*e.g.*, Vogt *et al.* 1999; Marcy *et al.* 1999), this causes difficulties with a number of proposed mechanisms for planetary formation and migration.

The values of $v\sin i$, $P_{\rm rot}$, and R for HD 89744 given in Table 1 imply an inclination of the stellar rotational equator of $i = 42°$ (*i.e.*, $\sin i = 0.66$). Moreover, if we assume that the orbit is coplanar with the star's equatorial plane, we infer that $m_2 = 10.8\ M_{\rm JUP}$. The astrometric orbital amplitude would be 0.17 mas, too small for Hipparcos detection but within the range of next-generation astrometric missions.

The mass of 10 $M_{\rm JUP}$ suggested by the stellar rotational data is near the upper limit of masses associated with extra-solar giant planets (*e.g.*, Marcy *et al.* 2000). If such large masses hold up to further investigations, then theoretical understanding of the origin and evolution of extrasolar giant planets must be able to accommodate a mass range spanning at least values between 0.5 $M_{\rm JUP}$ and 10 $M_{\rm JUP}$.

The metallicity of HD 89744, [Fe/H]= 0.18, is substantially higher than the mean for nearby sun-like stars (Favata *et al.* 1997; Gonzalez 1998). HD 89744 was placed on the AFOE observing list without reference to its metallicity; therefore the association of its high metallicity with the presence of a planet is not a selection effect. This association continues the trend, already noted (*e.g.*, Gonzalez & Law 1999, and references therein) and references therein that the metallicity of stars with planets tends to be higher than that of stars without planets.

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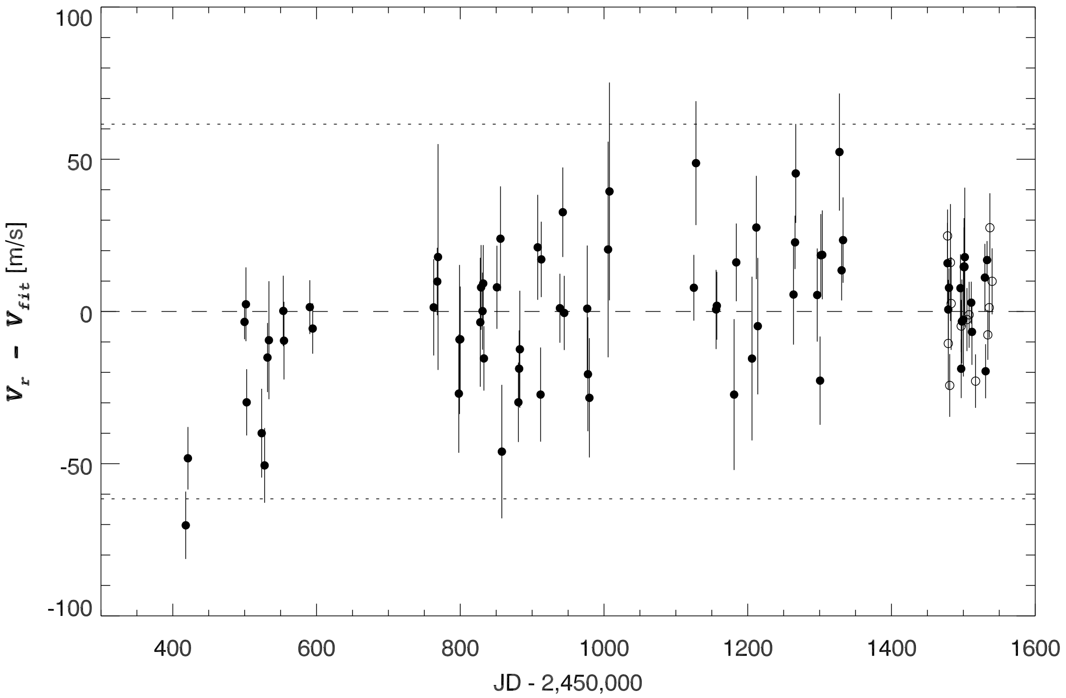

Fig. 3.— Residuals to the Keplerian orbital fit. Filled circles denote AFOE observations, open circles Lick observations. The dotted lines illustrate the 3-sigma rejection bounds.

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