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A Jupiter–like Planet Orbiting the Nearby M Dwarf GJ 832[1]

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ABSTRACT

Precision Doppler velocity measurements from the Anglo-Australian Telescope reveal a planet with a 9.4±0.4 year period orbiting the M1.5 dwarf GJ 832. Within measurement uncertainty the orbit is circular, and the minimum mass ($m \sin i$) of the planet is 0.64±0.06 $\mathrm{M_{JUP}}$. GJ 832 appears to be depleted in metals by at least 50% relative to the Sun, as are a significant fraction of the M dwarfs known to host exoplanets. GJ 832 adds another Jupiter-mass planet to the known census of M dwarf exoplanets, which currently includes a significant number of Neptune-mass planets. GJ 832 is an excellent candidate for astrometric orbit determination with $\alpha \sin i = 0.95$ mas. GJ 832b has the second largest angular distance from its star among radial velocity detected exoplanets (0.69 arc sec) making it a potentially interesting target for future direct detection.

Subject headings: planetary systems – stars: individual (GJ 832)

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1. Introduction

Most of the known exoplanets orbit late-F, G, or early-K dwarfs, with masses ranging from 0.7 to 1.2 $M_\odot$. There are nearly 2,000 such stars within 50 pc brighter than V=8. In contrast there are just a handful of M dwarfs brighter than V=8.

Although M dwarfs make up 70% of nearby stars, their faintness in the optical makes them difficult targets for which to obtain precision Doppler velocities. As a result they make up as little as 5% of the current planet search targets, and only 11 exoplanets have been found to date, orbiting a total of 7 M dwarfs. Just over half of these M dwarf planets are less massive than Neptune, leading to speculation that M dwarfs typically host either fewer planets than G dwarfs (Johnson et al. 2007), or lower mass planets as a result of their smaller proto-planetary disks (Laughlin et al. 2004; Ida & Lin 2005; Kennedy & Kenyon 2008).

The primary parameters in planet formation theory are the mass of the central star, the mass of the protoplanetary disk, and the metallicity of the system. While it is now well established for late-F, G, and K dwarfs that metal-rich stars are enhanced in planets relative to metal-poor stars (Gonzalez 1997, 1998; Gonzalez & Vanture 1998; Gonzalez et al. 1999; Gonzalez & Laws 2000; Santos et al. 2000, 2001, 2004; Gonzalez et al. 2001; Reid 2002; Fischer & Valenti 2005; Bond et al. 2006), it has been harder to establish the importance of stellar mass on planet formation since most of the stars under survey lie in the relatively narrow mass range encompassed by late-F, G and K dwarfs.

The searches which *are* being done for planets orbiting M dwarfs, will ultimately provide the data needed to see if the metallicity-planet relation extends down to the M dwarf regime, and whether the mass distribution of exoplanets formed around M dwarfs is similar to, or different than, that for more massive host stars. M dwarf Doppler surveys, therefore, have the power to address some of the most important questions in exoplanetary science, as they extend the mass range of potential exoplanet host stars down to 0.3 $M_\odot$.

We report here a new extrasolar planet in a long period orbit with eccentricity consistent with zero, discovered by the Anglo-Australian Planet Search (AAPS). The AAPS program is described in Section 2. The characteristics of the host star and our Doppler measurements are presented in Section 3. A discussion follows.

2. The Anglo-Australian Planet Search

The AAPS began in 1998 January, and is currently surveying 250 stars. Thirty exoplanets with $m \sin i$ ranging from 0.17 to 10 $M_{\rm JUP}$ have first been discovered by the AAPS

(Tinney et al. 2001, 2002a, 2003, 2005, 2006; Butler et al. 2001, 2002; Jones et al. 2002, 2003a,b, 2006; Carter et al. 2003; McCarthy et al. 2004; O'Toole et al. 2007). Our precision Doppler measurements are made with the UCLES echelle spectrometer (Diego et al. 1990) on the 3.9m Anglo-Australian Telescope (AAT). An iodine absorption cell provides wavelength calibration from 5000 to 6200 Å. The spectrometer point-spread function and wavelength calibration are derived from the iodine absoption lines embedded on every spectrum by the cell (Valenti et al. 1995; Butler et al. 1996). Our observing and analysis system has demonstrated long term precision of $3\,\mathrm{m\,s^{-1}}$ for late-F, G, and early-K dwarfs brighter than V=7.5 (Tinney et al. 2005; Butler et al. 2001).

3. GJ 832

At 4.93 pc, GJ 832 (LHS 3865, HD 204961, HIP 106440) is amongst the nearest stars in the sky (Perryman et al. 1997). It is an M1.5 dwarf with an optical absolute magnitude and colors of $\mathrm{M_V} = 10.19$, $V = 8.66$, and $B - V = 1.52$, and an infrared absolute magnitude and colors of $\mathrm{M_K} = 6.03$, $K = 4.50$, and $V - K = 4.16$. Both Hipparcos and ground-based photometry (Koen et al. 2002) find GJ 832 to be photometrically stable at the several milli-magnitude level. Gautier et al. (2007) have combined Nstars[1] visible photometry with Spitzer far-infrared photometry, to estimate an "infrared flux method" effective temperature of 3657 K for GJ 832. The Spitzer observations reveal no evidence of mid- or far-infrared excess. The radius of GJ 832 is estimated to be $0.48\,\mathrm{R_\odot}$ (Pasinetti-Fracassini et al. 2001).

Although accurate metallicities for M dwarfs are problematic, GJ 832 is likely to be rather metal poor. Matching synthetic spectra to high-resolution spectra of the FeH band near 9900Å, Schiavon et al. (1997) estimate a metallicity for GJ 832 of $[\mathrm{Fe/H}] = -0.7$, and a surface gravity of $\log g = 4.7$. The photometric metallicity calibration of Bonfils et al. (2005a) gives an estimated metallicity of $[\mathrm{Fe/H}] = -0.31 \pm 0.2$.

Due to its late spectral type, GJ 832 has not (to date) been subject to detailed spectroscopic analysis, and so to estimate its mass we must rely on either theoretical isochrones, or empirical mass-luminosity calibration. The latter indicate a mass for GJ 832 of $0.45{\pm}0.05\,\mathrm{M_\odot}$ (with the mass uncertainty being largely due to the scatter about the mass-luminosity calibration relationship of Delfosse et al. (1998)). The Padova theoretical isochrones (Marigo et al. 2008) predict $\mathrm{M_K}$ ranging from 5.97 (at 10^9 yr) to 6.03 (at 10^{10} yr) for a $0.45\,\mathrm{M_\odot}$ dwarf with $[\mathrm{Fe/H}] = -0.3$ which is consistent with the observed luminosity of GJ 832. At $[\mathrm{Fe/H}] = -0.7$ they predict $\mathrm{M_K}$ in the range 5.92 (at 10^9 yr) to 5.86 (at 10^{10} yr). Given the difficulty in

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[1] http://nstars.nau.edu

determining metallicities for M dwarfs, we therefore derive a mass estimate for the primary of $0.45 \pm 0.05\,\mathrm{M}_\odot$.

GJ 832 is chromospherically quiescent. Based on high resolution spectroscopy of the CaII H&K lines, Tinney et al. (2002b) report $logR'_{\mathrm{HK}} = -5.10$. This would suggest a jitter of $3.9\,\mathrm{m\,s^{-1}}$ using the $B-V$, $\mathrm{M_V}$ & $\mathrm{T_{eff}}$ in the most recent stellar "jitter" calibration of J.Wright (priv.comm). Bonfils et al. (2005b) estimate the stellar jitter of GJ 832 to be less than $2\,\mathrm{m\,s^{-1}}$. GJ 832 is among the fainter stars on the AAT program. The signal-to-noise of these observations range from 46 to 150 per spectral pixel, with a median of 98, which is lower than typical for AAPS targets. Four late dwarfs from the long term AAT program are shown in Figure 1. These stars are shown in order of descending B−V. GJ 887 is an especially close match to GJ 832 in B-V colour and V magnitude. Based on this we estimate the combined velocity uncertainty due to photon statistics, jitter, unknown planets, and systematic errors is $5\,\mathrm{m\,s^{-1}}$ for late-K and M dwarfs in the AAPS. This is comparable to that estimated for late-K and M dwarfs in the Keck program, as shown in Figures 2-4 of Butler et al. (2008).

A total of 32 precision Doppler measurements of GJ 832 spanning 9.6 years are listed in Table 1 and shown in Figure 2 (upper panel). The root-mean-square (RMS) scatter of the residuals about the mean velocity of this data set is $11.6\,\mathrm{m\,s^{-1}}$.Using the 2-Dimensional Keplerian Lomb-Scargle (2DKLS) peridogram of O'Toole et al. (2007) to identify an initial period and eccentricity, the subsequent best-fit Keplerian to all 32 epochs of data reduces this to an RMS of $5.5\,\mathrm{m\,s^{-1}}$, and gives a reduced χ^2_ν of 1.54 (see Table 2 – a stellar jitter of $3.9\,\mathrm{m\,s^{-1}}$ was used, together with the internal velocity measurement uncertainty for each epoch in Table 1, to determine reduced χ^2_ν). These fit parameters strongly suggest the presence of an exoplanet with minimum mass $m \sin i$ of $0.64\,\mathrm{M}_\odot$, period 9.4 ± 0.4 yr, eccentricity 0.12 ± 0.11 (which we consider to be consistent with zero eccentricity, particularly when the bias against measuring zero eccentricities demonstrated by O'Toole et al. (2008) is taken into account) and semi-major axis 3.4 ± 0.4 AU.

We have determined the False Alarm Probability (FAP, i.e. the probability that we have falsely identified an exoplanet that is not present) for this orbit determination using the Monte Carlo "scrambled velocities" approach described by Marcy et al. (2005). This method tests the hypothesis that no planet is present and the Keplerian fit could have been obtained from mere noise, by generating randomly scrambled data sets in which the order of velocities are changed but the times remain the same. These are then subjected to the same analysis as our actual data set (i.e. identfying the strongest peak in the 2DKLS followed by a full Keplerian fit). In this case 2002 random trials were carried out and only one of these yielded a χ^2_ν less than the value of 1.54 obtained with the original data. The histogram of χ^2_ν

is shown in Figure 3. These results imply a FAP of 0.05% for the GJ 832 planet detection.

4. Discussion

GJ 832 at a distance of 4.93pc is one of the nearest known exoplanetary systems. The combination of the small distance and relatively long period gives a large angular distance from the star of 0.69 arc seconds for an edge-on circular orbit. This is exceeded only by ϵ Eri among radial velocity detected exoplanets, and only six other systems exceed 0.2 arc sec. GJ 832b is therefore a potentially interesting target for direct detection, although the high constrast with the star (likely to be $< 10^{-8}$; Burrows et al. 2004) still makes this an extremely challenging observation.

GJ 832 is an excellent candidate for astrometric orbit determination. The astrometric orbit semimajor axis is $\alpha \sin i = 0.95$ mas, which is comparable to that of ϵ Eri for which an astrometric orbit was determined by Benedict et al. (2006) and larger than that of GJ 876 which also has an astrometric orbit determination (Benedict et al. 2002). The astrometric orbit would enable the inclination to be determined, removing the current $\sin i$ uncertainty on the mass.

Seven M dwarfs (including GJ 832) are currently known to host as many as 11 exoplanets, and these are listed in Table 3 (see table notes for references). As noted earlier, determining the metallicities of M dwarfs is notoriously difficult – published metallicity estimates are available for several of the known exoplanet host M dwarfs, and these are listed in the Table. In addition, we have also derived for all seven M-dwarfs a photometric metallicity estimate, using the technique of Bonfils et al. (2005a), which has the advantage of being uniform over all these M dwarfs. On average the Schiavon et al. (1997) metallicities appear to be systematically 0.3-0.4 dex lower than those derived from the Bonfils et al. calibration. The Bean et al. (2006) metallicities are similarly on the metal-poor side of the Bonfils et al. results, though not by as much (≈ 0.2 dex). In general, the metallicity trends are similar across all three calibrations, and it is clear there is a metallicity spread across the observed M dwarf exoplanet hosts.

Based on these metallicity estimates, it would appear that four of the current M dwarf exoplanet host stars are somewhat metal-poor, two have about solar metallicity, and one is slightly metal rich. Given the well known correlation between stellar metallicity and observed exoplanet frequency for F, G, and K dwarf host stars, this metallicity distribution for M dwarf host stars is quite unexpected. Whhile the numbers of systems are small there is no obvious difference in metallicity between the stars hosting Jupiter-mass planets and those hosting Neptune-mass planets.

The correlation between high stellar metallicity and planets for late-F, G, and early-K dwarfs points toward the core accretion model for planet formation. But there does not appear to be strong evidence to date that M dwarf planet formation is strongly correlated with high metallicity. This is puzzling, particularly in view of the fact that M dwarfs probably have lower mass protoplanetary disks, and therefore would need even higher metallicity than a F, G or K dwarf to provide enough solid material (silicates and ices) to build a planetary core. Obviously it must be kept in mind that measuring metallicities for M dwarfs is problematic, and that even the Bonfils et al. (2005a) calibration (though empirically based and moderately robust) is only good to ±0.2 dex. Nonetheless it is interesting to consider possible means by which M dwarf exoplanets could be formed in such a manner as to *not* display the strong metallicity correlation seen in FGK dwarfs. One initially attractive explaneation is that since M dwarfs are essentially immortal on a Hubble time scale, the vast majority of nearby M dwarfs could be old metal poor stars. Unfortunately such an explanation would appear unlikely. The study of M dwarf kinematics has an extensive and venerable history (e.g. Wielen 1977; Weis & Upgren 1995; Reid et al. 1995) which has contributed to the creation of extensive and sophisticated models of the stellar populations present in the Solar Neighbourhood (e.g. the Besancon models of Robin et al. 2003). More recently, the availability of huge numbers of M dwarf spectra from the SDSS survey have enabled sophisticated tests of the kinematics of the Besancon models by Bochanski et al. (2007), and have substantially born out the Besancon model predictions for M dwarfs. Those models indicate that dominant solar neighbourhood M dwarfs will be thin disc members with ages almost uniformly spread between 0.1 and 10 Gyr. Thick disc M dwarfs (which would indeed be expected to have systematically lower metallicities) will be present at much lower densities (around a factor of one twentieth or less; Robin et al. 2003), and the probability that they would make up four of the seven M dwarf exoplanet hosts would seem to be negligibly small.

An alternative explanation could be that M dwarf planets might form primarily via the disk instability mechanism (see e.g. Boss 2008, and references therein), rather than via core accretion, which would make their formation probability more or less independent of metallicity.

Six of the eleven exoplanets known to orbit M dwarfs have minimum masses less than $0.1\,\mathrm{M_{JUP}}$. In contrast, only nine planets with $m \sin i < 0.1\,\mathrm{M_{JUP}}$ have been found among the 216 Doppler velocity planets with B-V < 1.2 in the "Catalog of Nearby Exoplanets" (Butler et al. 2006b). With a minimum mass of $0.64 \pm 0.06\,\mathrm{M_{JUP}}$, GJ 832b is the fifth jovian mass planet found orbiting an M dwarf. The most massive M dwarf planet yet found is $1.93\,\mathrm{M_{JUP}}$. Since massive planets are by far the easiest ones to find, planets of more than

$2\,\mathrm{M}_{\mathrm{JUP}}$ orbiting within 3 AU of M dwarfs must be rare, occuring less than around once per 300 M dwarfs.

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Table 1. Velocities for GJ 832

JD (-2451000)	RV ($\mathrm{m\,s^{-1}}$)	Uncertainty ($\mathrm{m\,s^{-1}}$)
34.0873	6.8	2.2
119.0159	14.0	6.0
411.1222	10.8	3.3
683.2628	17.4	2.8
743.1456	18.4	2.7
767.0812	24.4	2.3
1062.2443	19.2	2.2
1092.1677	8.4	2.5
1128.1273	1.6	4.0
1455.2341	1.7	1.6
1477.1455	10.0	2.6
1859.0874	-3.5	2.1
1943.0361	-3.3	2.7
1946.9712	1.8	1.9
2214.2066	-10.0	2.5
2217.2117	-14.2	2.3
2243.0503	12.8	2.5
2245.1511	-15.4	2.5
2281.0469	-17.7	1.9
2485.3011	-12.9	2.0
2523.3005	-5.3	1.6
2576.1420	-9.7	1.7
2628.0699	1.0	5.2
2629.0549	-15.2	2.1
2943.1074	-4.8	1.3
3009.0378	-11.3	1.6
3036.9559	-6.5	1.5
3254.2003	2.7	1.7
3371.0670	1.6	1.7
3375.0442	2.0	1.7

Table 1—Continued

JD (-2451000)	RV ($\mathrm{m\,s^{-1}}$)	Uncertainty ($\mathrm{m\,s^{-1}}$)
3552.2912	6.8	4.1
3553.3041	17.2	2.8

Table 2. Orbital Solutions for GJ 832

Parameter	Value
Orbital period P (days)	3416±131
Velocity semiamplitude K ($\mathrm{m\,s^{-1}}$)	14.9±1.3
Eccentricity e	0.12±0.11
Periastron date (Julian Date−2451000)	211±353
ω (degrees)	304±38
$m \sin i$ ($\mathrm{M_{JUP}}$)	0.64±0.06
semimajor axis $a \sin i$ (AU)	3.4±0.4
$\mathrm{N_{obs}}$	32
RMS ($\mathrm{m\,s^{-1}}$)	5.5
χ^2_ν	1.54

Table 3. Known M dwarf Exoplanet Hosts

Host	Type	M_K	$V-K$	Phot [Fe/H][a]	[Fe/H][b]	[Fe/H][c]	$m \sin i (M_{JUP})$	Refs[d]
GJ 832	M1.5	6.03	4.16	-0.31	-0.7		0.64	1
GJ 876	M4	6.64	5.16	0.02	-0.4	-0.12	0.019,0.619,1.935	2,8,9
GJ 849	M3.5	5.87	4.83	0.16			0.82	4
GJ 317	M3.5	7.26	4.97	-0.23			1.2	7
GJ 436	M2.5	6.02	4.61	-0.02		-0.32	0.067	3
GJ 581	M2.5	6.85	4.72	-0.26	-0.1	-0.33	0.049,0.016,0.026	5,10
GJ 674	M3	6.57	4.50	-0.30			0.035	6

[a] Photometric [Fe/H] determined using catalogued V, 2MASS K_s and parallax data, with the Bonfils et al. (2005a) relation.

[b] Metallicity estimates from Schiavon et al. (1997)

[c] Metallicity estimates from Bean et al. (2006)

[d] M dwarf exoplanet properties from; 1 - this paper; 2 - Delfosse et al. (1998); 3 - Butler et al. (2004); 4 - Butler et al. (2006a); 5 - Bonfils et al. (2005b); 6 - Bonfils et al. (2007); 7 - Johnson et al. (2007); 8 - Marcy et al. (2001) ; 9 - Rivera et al. (2005); 10 - Udry et al. (2007)

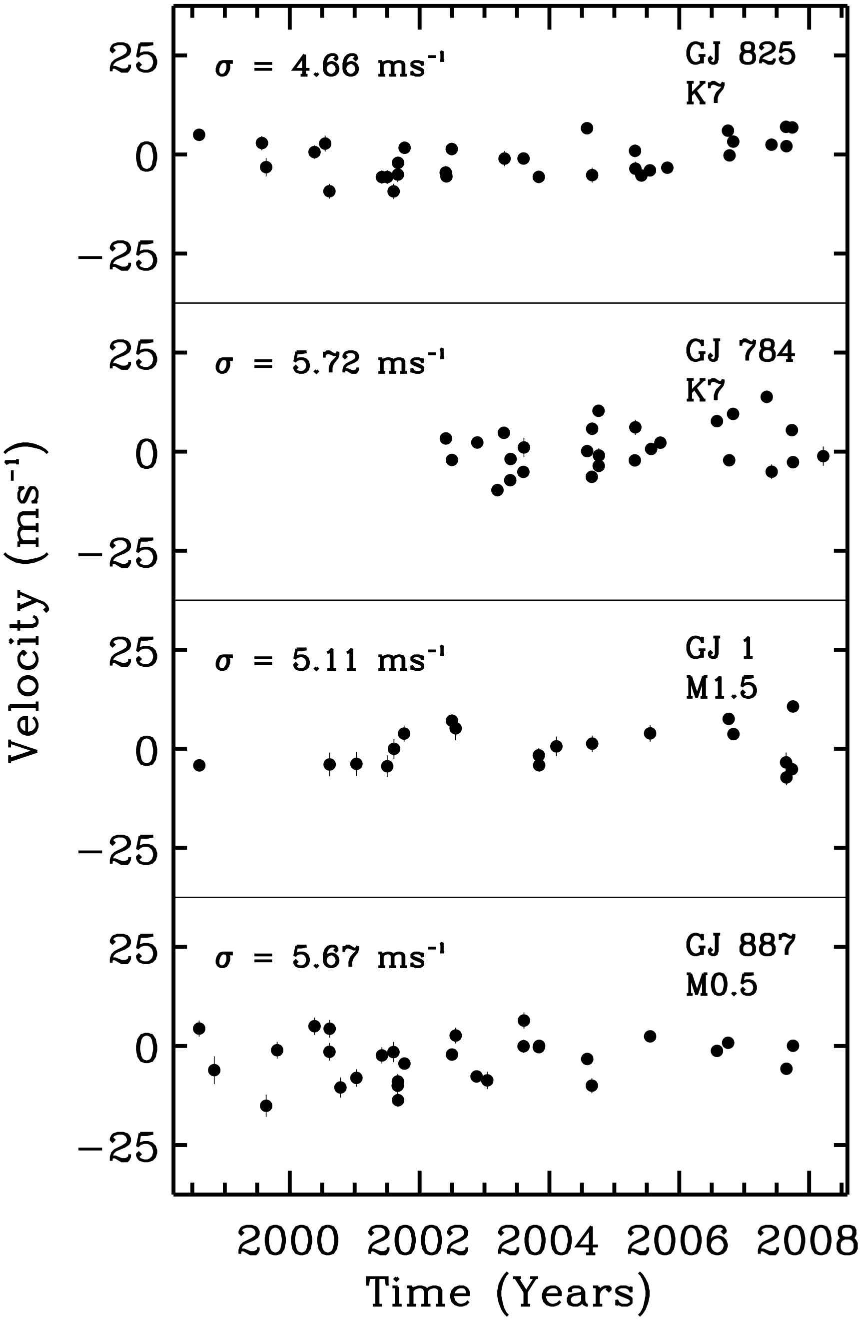

Fig. 1.— Four stable late K and M dwarfs from the AAT.

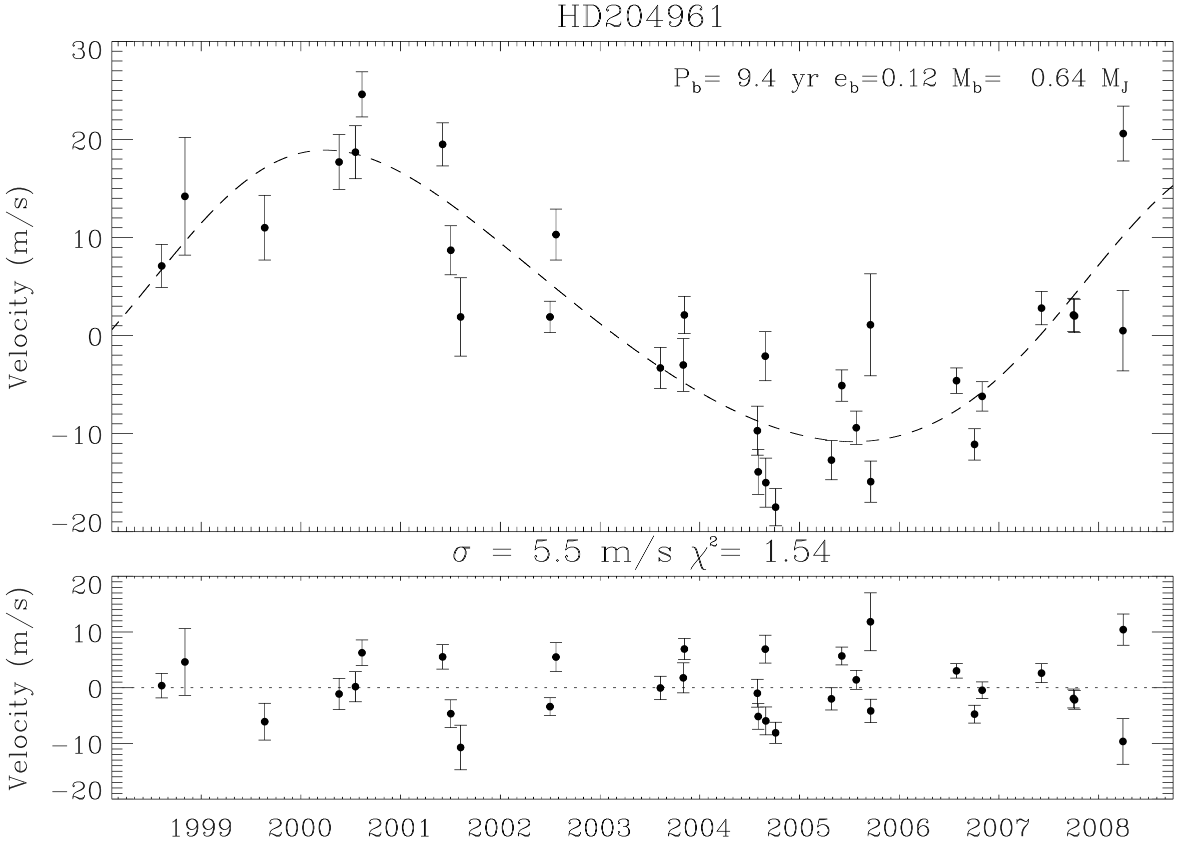

Fig. 2.— Doppler velocities for GJ 832 spanning 9.6 yr. The upper panel shows the measured velocities with a best-fit Keplerian over-plotted as a dashed line. The residuals to this fit are plotted in the lower panel. The Keplerian orbital parameters obtained listed in see Table 2, and strongly suggest the presence of a $m \sin i$=0.64 M_{JUP} exoplanet.

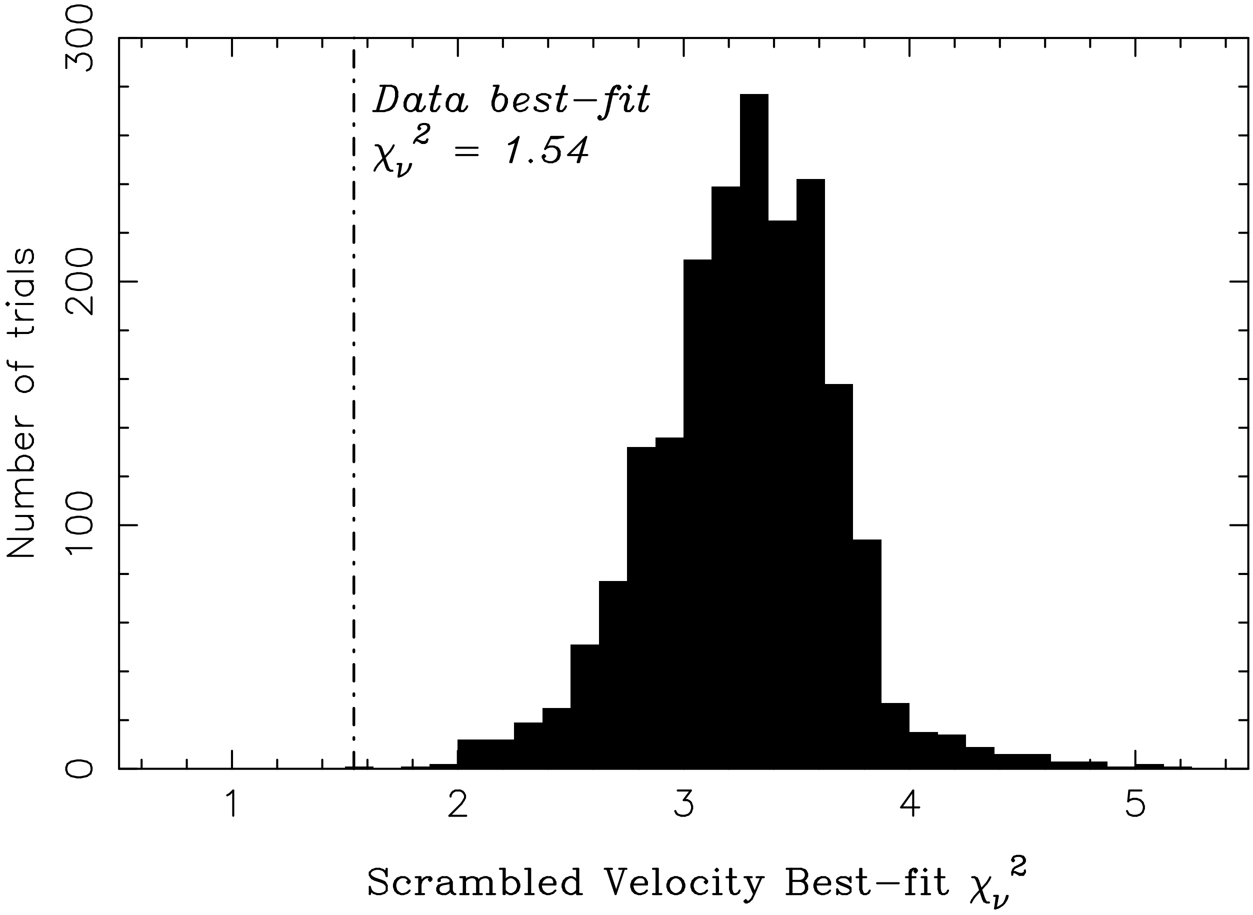

Fig. 3.— Assessment of the FAP of the Keplerian model for GJ 832. The histogram shows the values of χ^2_ν from 2002 trials with randomly scrambled velocities. Only one of these trials had χ^2_ν lower than the value of 1.54 from the original fit, implying a FAP of 0.05%