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WASP-22 b: A transiting "hot Jupiter" planet in a hierarchical triple system

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ABSTRACT

We report the discovery of a transiting planet orbiting the star TYC 6446-326-1. The star, WASP-22, is a moderately bright (V=12.0) solar-type star ($T_{\rm eff} = 6000 \pm 100$ K, [Fe/H]= -0.05 ± 0.08). The lightcurve of the star obtained with the WASP-South instrument shows periodic transit-like features with a depth of about 1% and a duration of 0.14 d. The presence of a transit-like feature in the lightcurve is confirmed using z-band photometry obtained with Faulkes Telescope South. High resolution spectroscopy obtained with the CORALIE and HARPS spectrographs confirm the presence of a planetary mass companion with an orbital period of 3.533 days in a near-circular orbit. From a combined analysis of the spectroscopic and photometric data assuming that the star is a typical main-sequence star we estimate that the planet has a mass $M_{\rm p} = 0.56 \pm 0.02 M_{\rm Jup}$ and a radius $R_{\rm p} = 1.12 \pm 0.04 R_{\rm Jup}$. In addition, there is a linear trend of $40\,{\rm m\,s^{-1}\,y^{-1}}$ in the radial velocities measured over 16 months, from which we infer the presence of a third body with a long period orbit in this system. The companion may be a low mass M-dwarf, a white dwarf or a second planet.

Subject headings: planetary systems

1. Introduction

The WASP project (Pollacco et al. 2006) is currently one of the most successful wide-area surveys designed to find exoplanets transiting bright stars (V < 12.5). Other succesful surveys include HAT-net (Bakos et al. 2004), XO (McCullough et al. 2005) and TrES (O'Donovan et al. 2006). There is continued interest in finding transiting exoplanets because they can be accurately characterized and studied in some detail, e.g., the mass and radius of the planet can be accurately measured. This gives us the opportunity to explore the relationships between the density of the planet and other properties of the planetary system, e.g., the semi-major axis, the spectral type of the star, the eccentricity of the orbit, etc. Given the wide variety of transiting planets being discovered and the large number of parameters that characterize them, statistical studies will require a large sample of sys-

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tems to identify and quantify the relationships between these parameters. These relationships can be used to test models of the formation, structure and evolution of short period exoplanets.

A particular puzzle related to the properties of hot Jupiters is the wide range in their densities. Very dense hot Jupiters such as HD 149026 are thought to contain a dense, metallic core (Sato et al. 2005). There is currently no generally agreed explanation for the existence of hot Jupiters with densities $5-10$ times lower than the density of Jupiter, e.g. WASP-17 b (Anderson et al. 2010), TrES-4 b (Mandushev et al. 2007) and WASP-12 b (Hebb et al. 2009). One possibility is that the planets are heated by tidal forces, and that these are driven by the presence of a third body in the system (Mardling 2007). Other possibilities include enhanced opacity in the atmosphere (Burrows et al. 2007), the distribution of heavy elements in the core (Baraffe et al. 2008) and kinetic heating from the irradiated atmosphere into the interior (Showman and Guillot 2002).

Here we report the discovery of a hot Jupiter system, WASP-22, identified using the WASP-South instrument and present evidence that it is a member of a hierarchical triple system.

2. Observations

The WASP survey is described in Pollacco et al. (2006) and Wilson et al. (2008) while a discussion of our candidate selection methods can be found in Collier Cameron et al. (2007), Pollacco et al. (2008), and references therein.

The WASP-South instrument consists of 8 cameras, each with a Canon 200-mm f/1.8 lens and a 2k×2k *e2V* CCD detector resulting in an image scale of approximately 14 arcsec per pixel. The star TYC 6446-326-1 (= 1SWASP J033116.32−234911.0) was observed 3133 times by one camera on the WASP-South instrument from 2006 August to 2007 January. A further 6282 obervations were obtained with the same camera from 2007 August to 2008 January. The star also appeared in the images obtained with a second camera during the second observing season, so a further 5889 observations were obtained with this camera during that interval.

The WASP-South lightcurves of WASP-22

Table 1: Radial velocity measurements.

BJD–2 400 000	RV (km s^{-1})	$\sigma_{\rm RV}$ (km s^{-1})	BS (km s^{-1})
CORALIE			
54704.8563	−7.236	0.013	0.005
54706.8761	−7.368	0.026	0.030
54708.8417	−7.189	0.011	−0.020
54709.7625	−7.320	0.019	−0.038
54710.7697	−7.291	0.024	0.046
54715.8843	−7.201	0.018	0.058
54716.8457	−7.262	0.041	−0.127
54717.7794	−7.386	0.041	0.034
54720.7520	−7.312	0.017	0.002
54721.8184	−7.289	0.019	0.028
54722.8233	−7.201	0.012	−0.033
54724.7367	−7.314	0.017	−0.011
54726.8108	−7.225	0.012	0.010
54729.8623	−7.206	0.013	−0.005
54731.8658	−7.345	0.012	−0.015
54740.7564	−7.199	0.020	−0.058
54834.5647	−7.304	0.018	0.014
54836.5707	−7.225	0.017	−0.019
54853.6313	−7.171	0.014	0.046
54854.6322	−7.275	0.013	0.018
54855.6091	−7.310	0.012	0.001
54860.5404	−7.183	0.013	0.051
54862.5589	−7.327	0.015	−0.046
54865.5628	−7.313	0.014	0.024
54879.5256	−7.280	0.017	−0.039
54880.5402	−7.273	0.021	0.033
54882.5242	−7.193	0.021	0.043
54885.5207	−7.159	0.016	−0.014
54886.5443	−7.299	0.017	−0.015
55095.8758	−7.308	0.013	0.013
55100.8593	−7.154	0.015	−0.002
55126.7935	−7.266	0.015	0.005
55128.7415	−7.169	0.016	0.006
55185.6618	−7.147	0.011	−0.007
55186.6153	−7.234	0.011	−0.025
55189.6571	−7.164	0.010	0.004
55190.6690	−7.284	0.011	−0.008
HARPS			
54743.7527	−7.1832	0.0029	0.0090
54746.7683	−7.2391	0.0026	0.0040
54749.7650	−7.2941	0.0024	0.0039
54750.6791	−7.1940	0.0029	0.0109
54754.7257	−7.1752	0.0025	0.0118
54755.7558	−7.2726	0.0032	0.0329

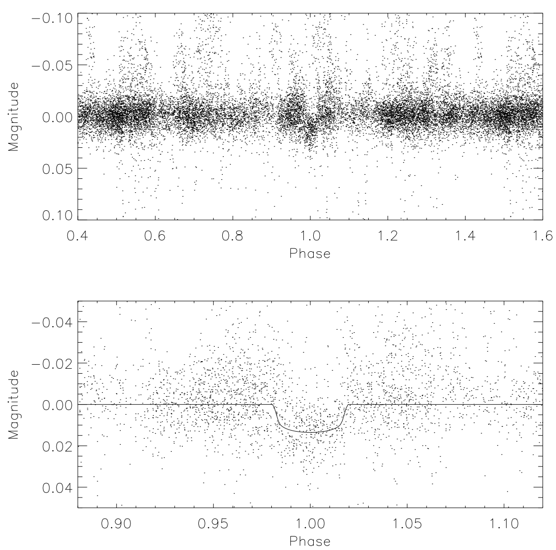

Fig. 1.— WASP-South photometry of WASP-22 folded on the orbital period $P = 3.532759\,\mathrm{d}$. Upper panel: all data. Lower panel: data within 0.12 phase units of mid-transit together with the model fit described in Section 3.1 (solid line).

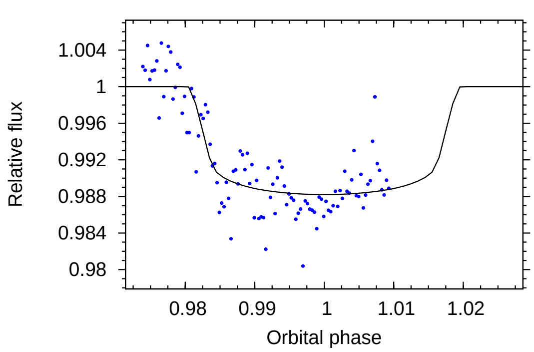

Fig. 2.— Faulkes Telescope South z-band photometry of WASP-22 (points) with the model fit described in Section 3.1 (solid line).

show transit-like features with a depth of approximately 0.012 magnitudes recurring with a 3.53-d period (Fig. 1). These were detected in the WASP photometry from the 2006 season using the detrending and transit detection methods described in Collier Cameron et al. (2007), but judged to be "unconvincing" at that stage. The same 3.53-d periodicity was detected in the 2007 data from both cameras, which was taken as strong evidence that the periodic transit signal was real. The spectral type of the star was estimated to be approximately G1 based on the catalogue photometry available for this star at the time. The duration and depth of the transit is consistent with the hypothesis that it is due to the transit of a planet-like companion to a main-sequence G1 star and the WASP lightcurves show no indication of any ellipsoidal variation due to the distortion of the star by a massive companion.

We also considered whether WASP-22 was likely to be a dwarf star given its J−H colour and J-band reduced proper motion, $\mathrm{H_J}$. The position of WASP-22 relative to the polynomial boundary between dwarfs and giants given in Collier Cameron et al. (2007) suggests that WASP-22 is a dwarf. We have also used the results of the RAVE survey DR2 (Zwitter et al. 2008) to calibrate the probability that a star is a dwarf given the observed values of J−H and $\mathrm{H_J}$. The RAVE survey observed stars at a similar range of magnitudes and galactic positions to the WASP survey and so it is well suited to this purpose. Stars listed in the survey with $\log g \geq 3.5$ were identified as dwarf stars, those with lower $\log g$ estimates were identified as giants. We then created a look-up table of the relative numbers of dwarfs and giants as a function of position in the $H_{\rm J}$ v. J−H plane. This criterion also suggested that WASP-22 is likely to be a dwarf star because the ratio of dwarfs to giants in this region of the $H_{\rm J}$ v. J−H plane is dwarf:giant = 10:0.

The star was included as a "grade-A" candidate in our programme of follow-up spectroscopic observations using the CORALIE spectrograph on the Euler 1.2-m telescope and the HARPS spectrograph on the 3.6-m ESO telescope, both located at La Silla, Chile. We obtained 37 radial-velocity measurements during the interval 2008 August 27 to 2009 December 25 with CORALIE and 6 measurements with HARPS during the interval 2008

Oct 4 – 16. The CORALIE spectra have a signal-to-noise ratio of 10 – 20, while the typical signal-to-noise ratio of the HARPS spectra is 50. The measurements are given in Table 1, where we also provide the bisector span, BS, which measures the asymmetry of the cross-correlation function. The standard error of the the bisector span measurements is $2\sigma_{\rm RV}$.

We also obtained photometry of TYC 6446-326-1 and other nearby stars on 2009 August 8 using the LCOGT 2.0-m Faulkes Telescope South (FTS) at Siding Spring Observatory. The Merope camera we used has an image scale of 0.279 arcseconds/pixel when used in the 2x2 binning mode we employed. We used a Pan-STARRS[1] z-band filter to obtain 107 images covering one ingress of the transit. These images were processed in the standard way with IRAF[2] using a stacked bias image, dark frame, and sky flat. Minimal fringing was present in the z-band images due to the deep depletion CCD in the camera, so no fringe correction was applied. The DAOPHOT photometry package (Stetson 1987) was used to perform object detection and aperture photometry with an aperture size of 10 binned pixels in radius. The 5' × 5' field of view of the instrument contained 6 comparison stars that were used in deriving the differential magnitudes with a photometric precision of 3.1 mmag. The coverage of the out-of-transit phases is quite limited, but the data are sufficient to confirm that transit-like features seen in the WASP-South data are due to the star TYC 6446-326-1 and to provide better measurements of the depth of the transit and the duration of ingress than is possible from the WASP-South data (Fig. 2). We note that the star 1SWASP J033121.40-234857.8 77 arcsec from WASP-22 is also a variable star. This star showed a dip in brightness of about 0.01 magnitudes lasting about 100 minutes during our observation of WASP-22.

We examined the power spectra of the WASP data from each camera and season separately to look for any intrinsic photometric variability due to magnetic activity in WASP-22. There is no periodic signal consistently detected in all three data sets so any such variability must have an amplitude less than a few milli-magnitudes.

All photometric presented in this paper are available from the NStED database.[3]

3. WASP-22 Stellar Parameters

The individual HARPS spectra of WASP-22 were co-added to produce a single spectrum with a typical S/N of around 100:1 that we have analysed to determine the atmospheric parameters of the star. The standard pipeline reduction products were used in the analysis.

The analysis was performed using the UCLSYN spectral synthesis package (Smith 1992; Smalley et al. 2001) and ATLAS9 models without convective overshooting (Castelli et al. 1997). The H_α line was used to determine the effective temperature ($T_{\rm eff}$), while the Na I D and Mg I b lines were used as surface gravity ($\log g$) diagnostics. The parameters obtained from the analysis are listed in Table 2.

The equivalent widths of several clean and unblended lines were measured. Atomic line data was mainly taken from the Kurucz and Bell (1995) compilation, but with updated van der Waals broadening coefficients for lines in Barklem et al. (2000) and $\log gf$ values from Gonzalez and Laws (2000), Gonzalez et al. (2001) or Santos et al. (2004). A value for microturbulence ($\xi_{\rm t}$) was determined from Fe I using the method of Magain (1984). The ionization balance between Fe I and Fe II and the null-dependence of abundance on excitation potential were used as an additional $T_{\rm eff}$ and $\log g$ diagnostics (Smalley 2005).

We have determined the elemental abundances of several elements (also listed in Table 2) from their measured equivalent widths. The quoted error estimates include that given by the uncertainties in $T_{\rm eff}$, $\log g$ and $\xi_{\rm t}$, as well as the scatter due to measurement and atomic data uncertainties. There is no evidence from these data for any abundance anomalies in WASP-22.

The spectrum of WASP-22 shows a clear Li I 6708Å line with EW = 32 ± 1 mÅ, indicating an abundance of log n(Li/H) + 12 = 2.23 ± 0.08 dex. We have compared this lithium abundance to the relations between effective temperature and age by Sestito and Randich (2005). For stars with

[1] http://pan-starrs.ifa.hawaii.edu/public

[2] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

[3] http://nsted.ipac.caltech.edu

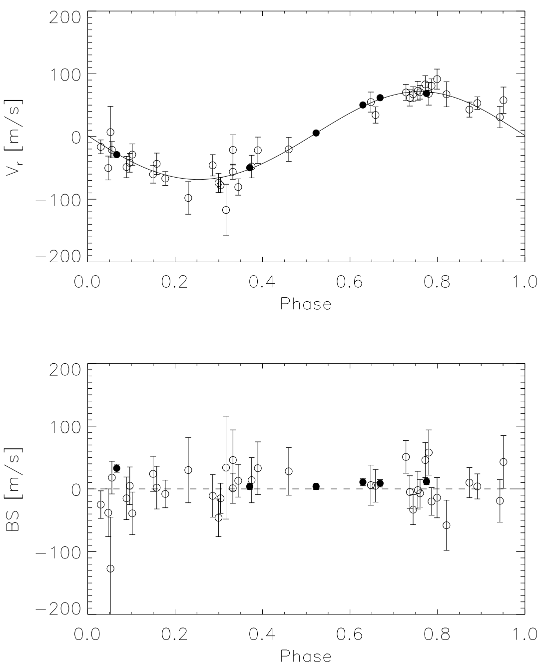

Fig. 3.— Radial velocity and bisector span measurements for WASP-22. Upper panel: Radial velocity relative to the centre-of-mass velocity including the long-term drift $\frac{d\gamma}{dt}$ (points with error bars) compared to our model for the spectroscopic orbit (solid line). Lower panel: bisector span measurements. Data obtained with the HARPS spectrograph are plotted with filled circles, CORALIE data with open circles.

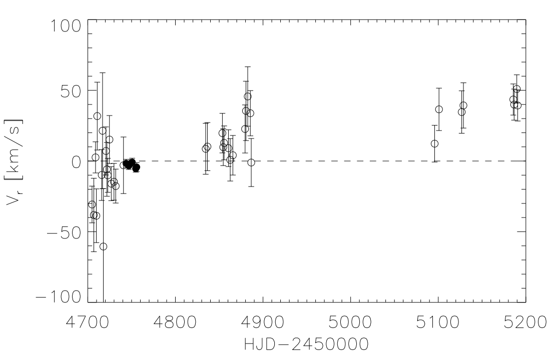

Fig. 4.— Residuals from a Keplerian orbit fit to our radial velocity data without a linear trend in the model. Symbols are as for Fig. 3.

$T_{\rm eff} \approx 6000\,$K we find that this lithium abundance implies a lower limit to the age of about 1 Gyr.

The projected stellar rotation velocity ($v \sin i$) was determined by fitting the profiles of several unblended Fe I lines. A value for macroturbulence ($v_{\rm mac}$) of 4.5 km s^{-1} was assumed, based on the tabulation by Gray (2008), and an instrumental FWHM of 0.065Å, determined from the telluric lines around 6300Å. A best fitting value of $v \sin i$ = 3.5 ± 0.6 km s^{-1} was obtained. Inspection of the Ca II H and K lines shows no indication of any emission due to chromospheric activity, as expected for such a slowly rotating star. If we assume that the rotation axis of the star is approximately aligned with the orbital axis of the planet's orbit we can estimate that the rotation period of the star is $P_{\rm rot} = 16 \pm 3\,$d. The rotation-colour-age relation of Collier Cameron et al. (2009) then yields an age estimate of approximately $3 \pm 1\,$Gyr for this star. We have also compared the values of $T_{\rm eff}$ and the stellar density $\rho_\star$ to the models of Girardi et al. (2000) and find that the age of the star is likely to be less than 6 Gyr based on these models.

We did not see any indication of additional spectral lines in the spectrum nor any trend in equivalent widths that might suggest contamination of the spectrum by another star. We estimate that the third body in this system discussed below contributes less than 5% of the light in the optical spectrum.

In summary, WASP-22 appears to be a slowly rotating, chromospherically inactive, main-sequence star that is slightly hotter than the Sun.

3.1. Planetary parameters

The amplitude of the radial velocity variation with the same period as the transit lightcurve (Fig. 3) and the lack of any correlation between this variation and the bisector span establish the presence of a planetary mass companion to this star (Queloz et al. 2001).

The CORALIE and HARPS radial velocity measurements were combined with the WASP-South and FTS photometry in a simultaneous Markov-chain Monte-Carlo (MCMC) analysis to find the parameters of the WASP-22 system. The shape of the transit is not well defined in the WASP-South or FTS photometry, so we have imposed an assumed main-sequence mass-radius relation as an additional constraint in our analysis of the data. The stellar mass is determined from the parameters $T_{\rm eff}$, $\log g$ and [Fe/H] using the procedure described by Enoch et al. (2010), based on the compilation of eclipsing binary data by Torres et al. (2010). The code uses $T_{\rm eff}$ and [Fe/H] as MCMC jump variables, constrained by Bayesian priors based on the spectroscopically-determined values given in Table 2. Limb-darkening coefficients are taken from Claret (2000).

A careful analysis of the radial velocity data clearly shows a trend in the residuals as a function of time (Fig. 4). We therefore adapted our MCMC analysis to include an extra parameter, $\frac{d\gamma}{dt}$, which describes a linear trend in the centre-of-mass velocity of the star.

The parameters derived from our MCMC analysis are listed in Table 3. We found that we did not need to account for any additional noise in the radial velocity data to due to stellar activity ("jitter"). The contribution to the total chi-squared from our 43 radial velocity measurements is 32.4. The surface gravity derived from our MCMC solution is consistent with the $\log g$ value from the analysis of the spectrum, but the large uncertainty on the latter value means that this is a rather weak constraint.

We considered the contribution of red noise to the standard errors quoted in Table 3. While the individual transits in the WASP data are affected by red noise, the analysis of the combined lightcurve covering many individual transits will not be strongly affected by red noise because there will be no correlation between the systematic noise from different nights. The FTS lightcurve is affected by red noise so we have investigated the effect of this using the "prayer bead" method. A separate MCMC analysis was performed in which synthetic FTS lightcurves were created from the model fit to the lightcurve and the residuals from this model after cyclic permutation at each step in the MCMC chain. We find that this does not significantly increase the error estimates for any of the parameters with the exception of the transit epoch and period. The standard errors for these two parameters in Table 3 are taken from the "prayer bead" MCMC analysis.

We have included the parameters $e\sin(\omega)$ and $e\cos(\omega)$ as free parameters in the solution because the orbit of the planet is not known to be circular, although the values of derived and their standard errors are quite consistent with this hypothesis. Imposing a circular orbit in the solution has a negligible effect on the value of the other parameters derived, but would reduce the estimated errors on these parameters, perhaps unrealisitically so.

4. Discussion

Apart from the presence of a third body, WASP-22 is a typical hot Jupiter planetary system. WASP-22 b joins a growing number of planets discovered with masses $\approx 0.5 M_{\rm Jup}$, radii $\approx 1 R_{\rm Jup}$ orbiting solar-like stars with periods of about 3 days, e.g., WASP-13 b, WASP-11 b/HAT-P-10 b, CoRoT-5 b, WASP-6 b, HAT-P-1 b, OGLE-TR-111 b, WASP-25 b, HAT-P-3 b, Kepler-8 b, etc.[4]

The third body we have detected from the linear trend in the radial velocities contributes less than 5% of the flux in the optical spectrum, so it is at least 3 magnitudes fainter than WASP-22 at V. This rules out the possibilty that the companion is K-type dwarf star, but leaves the possibility that the companion is an M-dwarf or a white dwarf. There is good agreement between the effective temperature we derive from the analysis of the optical spectrum and the effective temperature derived using the infrared flux method (Blackwell et al. 1979). We estimate that we would have been able detect a cool companion to WASP-22 if the 2MASS K_s-band magnitude ($K_s = 10.318 \pm 0.020$, Skrutskie et al. 2006) were increased by more than 0.1 magnitudes. This also rules out a K-dwarf companion but not an M-dwarf companion or a white dwarf companion. For example, a K-dwarf companion to WASP-22 would produce K-band infrared excess of 0.1 magnitudes or more, in which case the effective temperature derived using the infrared flux method would be inconsistent with the value derived from the analysis of the optical spectrum.

There are few direct constraints on the properties of the third body from the radial velocity data available to date. The observation that the trend is linear over 16 months suggests that the

[4] *http://exoplanet.eu*

orbital period is at least a few years. If the orbit of the third body is approximately circular and coplanar with the inner orbit with a period of several years and an amplitude comparable to the velocity range observed so far, then it is possible that the third body is a second planet, i.e., a configuration similar to the double-planet system HAT-P-13 (Bakos et al. 2009). Further radial velocity monitoring will be required to determine whether any or all of these assumptions is reasonable. This is certainly worth doing because the detection of a second planet in the WASP-22 system may make it possible to infer the interior structure of WASP-22 b using the method of Batygin et al. (2009). This method relies on an accurate measurement of the eccentricity for the orbit of the inner planet. The data available to date are only of sufficient quality to state that the eccentricity of the orbit is small ($e \lesssim 0.06$) so more data of the quality we obtain from HARPS will be required to measure a precise value for the eccentricity of WASP-22 b's orbit.

The distance to WASP-22 is approximately 300pc so it may be possible to detect the companion directly if it is a M-dwarf using high-constrast, high-resolution imaging.

5. Conclusion

The star WASP-22 (TYC 6446-326-1) has a hot Jupiter companion. A long-term linear trend in the mean value of the radial velocity shows that WASP-22 has a distant companion, i.e., it is a hierarchical triple system. The properties of the third body are poorly constrained by the data available to-date, but it may be an M-dwarf, a white dwarf or a second planet.

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Table 3: System parameters for WASP-22. The planet equilibrium temperature is calculated assuming a value for the Bond albedo A= 0. **N.B.** an assumed main-sequence mass-radius relation is imposed as an additional constraint in this solution so the mass and radius of the star are not independent parameters – see Enoch et al. (2010)) for details.

Parameter	Symbol	Value	Unit
Transit epoch (BJD)	T_C	2454780.2496 ± 0.0042	d
Orbital period	P	3.53269 ± 0.00004	d
Transit duration	T_{14}	0.137 ± 0.003	d
Planet/star area ratio	R_P^2/R_*^2	0.0104 ± 0.0004	
Impact parameter	b	0.13 ± 0.08	
Stellar reflex velocity	K_1	70.0 ± 1.7	$m\,s^{-1}$
Centre-of-mass velocity at time T_C	$\gamma_{CORALIE}(T_C)$	-7262 ± 2	$m\,s^{-1}$
Velocity offset, HARPS − CORALIE	$\gamma_{HARPS} - \gamma_{CORALIE}$	21 ± 2	$m\,s^{-1}$
Drift in centre-of-mass velocity	$\frac{d\gamma}{dt}$	40 ± 5	$m\,s^{-1}\,yr^{-1}$
Orbital separation	a	0.0468 ± 0.0004	AU
Orbital inclination	i	89.2 ± 0.5	$^\circ$
Orbital eccentricity	e	0.023 ± 0.012	
Arg. of periastron	ω	27^{+51}_{-78}	$^\circ$
	$e\cos(\omega)$	0.012 ± 0.011	
	$e\sin(\omega)$	0.006 ± 0.021	
Stellar mass	M_*	1.1 ± 0.3	$M_\odot$
Stellar radius	R_*	1.13 ± 0.03	$R_\odot$
Stellar surface gravity	$\log g_*$	4.37 ± 0.02	(cgs)
Stellar density	ρ_*	0.76 ± 0.06	$\rho_\odot$
Planet mass	M_P	0.56 ± 0.02	M_J
Planet radius	R_P	1.12 ± 0.04	R_J
Planet surface gravity	$\log g_P$	3.00 ± 0.03	(cgs)
Planet density	ρ_P	0.40 ± 0.04	ρ_J
Planet equil. temp.	T_P	1430 ± 30	K

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Table 2: Stellar parameters of WASP-22 from our spectroscopic analysis.

Parameter	Value
$T_{\rm eff}$ (K)	6000 ± 100
$\log g$	4.5 ± 0.2
$\xi_{\rm t}$ (km s^{-1})	1.2 ± 0.1
$v \sin i$ (km s^{-1})	3.5 ± 0.6
[Fe/H]	−0.05 ± 0.08
[Mg/H]	+0.06 ± 0.04
[Si/H]	+0.17 ± 0.11
[Ca/H]	+0.10 ± 0.11
[Sc/H]	+0.12 ± 0.12
[Ti/H]	+0.10 ± 0.07
[V/H]	+0.07 ± 0.09
[Cr/H]	0.00 ± 0.08
[Mn/H]	+0.02 ± 0.06
[Co/H]	+0.09 ± 0.13
[Ni/H]	+0.09 ± 0.06
log N(Li)	2.23 ± 0.08