Discovery and characterization of WASP-6b, an inflated sub-Jupiter mass planet transiting a solar-type star*

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Abstract. We report the discovery of WASP-6b, an inflated sub-Jupiter mass planet transiting every 3.3610060$^{+0.0000022}_{-0.0000035}$ days a mildly metal-poor solar-type star of magnitude V=11.9. A combined analysis of the WASP photometry, high-precision followup transit photometry and radial velocities yield a planetary mass $M_p = 0.503^{+0.019}_{-0.038}$ $M_J$ and radius $R_p = 1.224^{+0.051}_{-0.052}$ $R_J$, resulting in a density $\rho_p = 0.27 \pm 0.05 \rho_J$. The mass and radius for the host star are $M_* = 0.88^{+0.05}_{-0.08}$ $M_\odot$ and $R_* = 0.870^{+0.025}_{-0.036}$ $R_\odot$. The non-zero orbital eccentricity $e = 0.054^{+0.018}_{-0.015}$ that we measure suggests that the planet underwent a massive tidal heating $\sim 1$ Gyr ago that could have contributed to its inflated radius. High-precision radial velocities obtained during a transit allow us to measure a sky-projected angle between the stellar spin and orbital axis $\beta = 11^{+14}_{-13}$ deg. In addition to similar published measurements, this result favors a dominant migration mechanism based on tidal interactions with a protoplanetary disk.

Key words. binaries: eclipsing – stars: individual: WASP-6 – planetary systems – techniques: photometric – techniques: radial velocities – techniques: spectroscopic

1. Introduction

Transiting planets play an important role in our understanding of the nature of the extrasolar planetary objects. They are the only exoplanets for which an accurate measurement of the mass and radius is available. The deduced density is a key parameter to constraint theoretical models for the formation, evolution and structure of planets (e.g. Fortney et al. 2007; Liu et al. 2008). For the brightest transiting systems, a study of the atmospheric composition and physics is possible, even with existing instruments like HST or Spitzer (e.g. Charbonneau et al. 2008; Swain et al. 2008). The discovery rate of transiting planets has increased recently thanks mainly to the efficiency of the CoRoT space-based survey (Baglin et al. 2006) and of a handful of ground-based wide-field surveys targeting rather bright stars (V < 13): HATNet (Bakos et al. 2004), WASP (Pollaco et al. 2006), TrES (O’Donovan et al. 2006), and XO (McCullough et al. 2005).

The $\sim 50$ transiting planets known at the time of this writing show a broad range of mass and radius. Their masses go from $23 M_\oplus$ for the hot Neptune GJ436b...
(Butler et al. 2004; Gillon et al. 2007) to more than 10 $M_J$ for XO-3 (Johns-Krull et al. 2008). Many planets have a size in concord with basic models of irradiated planets (e.g. Burrows et al. 2007, Fortney et al. 2007), some of them like HD 149026 b (Sato et al. 2005) appearing to be very rich in heavy elements. Nevertheless, a few planets like HD 209458 b (Charbonneau et al. 2000, Henry et al. 2000) are ‘anomalously’ large. Several hypothesis have been proposed to explain this radius anomaly, most importantly tides (Bodenheimer et al. 2001; Jackson et al. 2008b), tides with atmospheric circulation (Guillot & Showman 2002) and enhanced opacities (Guillot et al. 2006, Burrows et al. 2007). The existence of several correlations between parameters of transiting systems has been proposed, for instance between the planet mass and the orbital period (Mazeh et al. 2005; Gaudi et al. 2005) and between the heavy-element content of the planet and the stellar metallicity (Guillot et al. 2006; Burrows et al. 2007). The astrophysics supporting these correlations has still to be fully understood.

2. Observations

2.1. WASP photometry

The host star 1SWASP J231237.75-224026.1 (= USNO-B1.0 0673-1077008 = 2MASS 23123773-2240261; hereafter WASP-6) was observed by WASP-South during the 2006 and 2007 observing seasons, covering the intervals 2006 May 07 to 2006 November 12 and 2007 July 05 to 2007 November 13 respectively. The 9630 pipeline-processed photometric measurements were detrended and searched for transits using the methods described in Collier Cameron et al. (2006). The selection process (Collier Cameron et al. 2007) elected WASP-6 as a high priority candidate presenting a periodic transit-like signature with a period of 3.361 days. A total of 18 transits are observed in the data. Figure 1 presents the WASP photometry folded with the best-fit period.

2.2. High-S/N transit photometry

Followup transit photometry was obtained on 2007 October 13 using the 2048×2048 pixel$^2$ camera HawkCam2 (Wilson et al. 2008, Anderson et al. 2008) on the 2.0-m Faulkes Telescope South (FTS) at Siding Spring Observatory. The camera has a scale of 0.135 arcseconds/pixel and a field of view of ∼ 4.6 × 4.6 arcminutes$^2$. We observed the target field using the SDSS i$^1$ band in the 2×2 bin mode to improve the duty cycle. We acquired 247 frames of 60 sec exposure during the run. The telescope was sufficiently defocussed to keep the stellar flux within the linear range of the CCD. The images were bias subtracted and flat-field corrected with a master bias and twilight flat field images using IRAF$^1$ DAPhOT aperture photometry (Stetson 1987) was performed around the target and comparison stars. We substracted a linear fit from the differential magnitudes as a function of airmass to correct for the different colour dependance of the extinction for the target and

We report here the discovery and characterization of WASP-6b, a new sub-Jupiter mass planet transiting a mildly metal-poor solar-type star of magnitude V=11.9.

We present in Section 2 the WASP discovery photometry plus high precision followup transit photometry and radial velocity measurements confirming the planetary nature of WASP-6b and including the observation of a spectroscopic transit. Section 3 presents the determination of the host star parameters. Our determination of the system parameters is presented in Section 4. These parameters are discussed in Section 5.

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1 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
comparison stars. The linear fit was calculated from the out-of-transit (OOT) data and applied to all the data. The corresponding fluxes were then normalized using the OOT part of the photometry. We discarded the first 17 measurements because they were obtained during twilight. Fig. 2 shows the resulting lightcurve folded on the best-fit orbital period and the residuals obtained after removing the best-fit transit model (see Section 4). Their \( \text{rms} \) is \( 1.67 \times 10^{-3} \). This can be compared to \( 9.54 \times 10^{-4} \), the mean theoretical error bar taking into account photon, read-out, scintillation and background noises.

High precision transit observations of WASP-6 were also carried out using the 1024\( \times \)1024 pixel\(^2 \) thermoelectrically cooled frame transfer CCD camera RISE mounted on the 2-m Liverpool Telescope (LT) in La Palma (Steele et al. 2008). The camera has a scale of 0.55 arcseconds/pixel and a total field of view of \( \sim 9.4 \times 9.4 \) arcminutes\(^2 \). We observed the target field using a single broad band \( V + R \) filter in the 2\( \times \)2 bin mode. We acquired 4200 frames of 3 sec exposure on the night of 2008 July 25 and 2880 frames of 5 sec exposure on the night of 2008 August 11. The telescope was, here too, defocussed. A similar reduction procedure as for the FTS photometry was used. The resulting normalized light curves of WASP-6 folded with the best-fit orbital period are shown in Fig. 2. The \( \text{rms} \) of the residuals is respectively 0.54 \% and 0.5 \% for the first and second run, while their mean theoretical error bar are 0.51 \% and 0.40 \%.

2.3. Spectroscopy

As soon as WASP-6 was identified as a high priority target, spectroscopic measurements were obtained using the CORALIE spectrograph mounted on the Euler Swiss telescope (La Silla, Chile) to confirm the planetary nature of the eclipsing body and measure its mass. WASP-6 was observed from 2007 September 16 to 2007 October 26 and from 2008 September 11 to 2008 September 25. Radial velocities (RV) were computed by weighted cross-correlation (Baranne et al. 1996; Pepe et al. 2005) with a numerical G2-spectral template. RV variations of semi-amplitude \( \sim 75 \) m s\(^{-1} \) were detected consistent with a planetary-mass companion whose period closely matches that from the WASP transit detections.

44 additional spectroscopic measurements were obtained with the HARPS spectrograph (Mayor et al. 2003) based on the 3.6-m ESO telescope (La Silla, Chile) in the context of the programs 082.C-0040(E) and 082.C-0608(E). These programs aim to improve the characterization of WASP transiting planets. As CORALIE, HARPS is a cross-dispersed, fiber-fed, echelle spectrograph dedicated to high-precision Doppler measurements. HARPS data were reduced with a pipeline very similar to the CORALIE one. In addition to several measurements covering the whole orbital phase, high-cadence measurements of a spectroscopic transit were obtained with HARPS on 2008 October 08 in order to determine the sky-projected angle between the planetary orbital axis and the stellar rotation axis and included two points taken the night before, a point as far as possible from the transit on the transit night and a point the night after. This strategy aims to determine the systematic RV with greater accuracy than if the RM effect was taken on its own, assuming that stellar activity is the same over the three nights.

Our RV measurements are listed in Table 1 (CORALIE) and Table 2 (HARPS) and are shown phase-folded and over-plotted with the best-fitting orbital+RM model in Fig. 3.
3. WASP-6 Stellar Parameters

The individual CORALIE and HARPS spectra are relatively low signal-to-noise, but when co-added into 0.01Å steps they give a S/N of in excess of 100:1 which is suitable for a photospheric analysis of WASP-6. 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, Gratton & Kurucz 1997). The Hα line were used to determine the effective temperature (Teff), 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 3.

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

We have determined the elemental abundances of several elements (listed in Table 3) from their measured equivalent widths. The quoted error estimates include that given by the uncertainties in Teff, log g and ξt, as well as the scatter due to measurement and atomic data uncertainties. In our spectra the Li I 6708Å line is not detected (EW < 2mÅ), allowing us to derive an upper-limit on the Lithium abundance of log n(Li/H) + 12 < 0.5. The lack of lithium implies an age in excess of ~3 Gyr (Sestito & Randich 2005).

Projected stellar rotation velocity (Vrot sin I) was determined by fitting the profiles of several unblended Fe I lines in the HARPS spectra. We used a value for macro-turbulence (vmac, see Gray 2008) of 2 km s⁻¹ and an in-
Table 1. CORALIE radial velocity measurements for WASP-6 (BS = bisector spans).

| BJD-2,400,000 | RV      | $\sigma_{RV}$ | BS    |
|---------------|---------|---------------|-------|
| (days)        | (km s$^{-1}$) | (km s$^{-1}$) | (km s$^{-1}$) |
| 54359.687716  | 11.48815 | 0.01636 | 0.01618 |
| 54362.573582  | 11.43618 | 0.01602 | -0.05289 |
| 54364.628975  | 11.44037 | 0.02006 | -0.02655 |
| 54365.707645  | 11.42032 | 0.01334 | -0.03610 |
| 54372.735312  | 11.42022 | 0.02888 | -0.06013 |
| 54377.716124  | 11.48411 | 0.01452 | -0.04330 |
| 54377.739618  | 11.48861 | 0.01393 | -0.04916 |
| 54378.693586  | 11.36836 | 0.01271 | -0.03449 |
| 54378.719349  | 11.38469 | 0.01306 | 0.01096 |
| 54379.690065  | 11.45960 | 0.01414 | -0.03955 |
| 54379.713452  | 11.46897 | 0.01333 | -0.04065 |
| 54380.563292  | 11.53222 | 0.01202 | -0.01290 |
| 54380.586751  | 11.51439 | 0.01142 | -0.02735 |
| 54382.617808  | 11.39778 | 0.01422 | -0.06658 |
| 54383.601838  | 11.50697 | 0.01225 | -0.03998 |
| 54383.625413  | 11.49114 | 0.01253 | -0.04571 |
| 54385.740623  | 11.36965 | 0.02555 | -0.10750 |
| 54386.686647  | 11.46303 | 0.01407 | -0.01829 |
| 54386.664860  | 11.49377 | 0.01384 | -0.02509 |
| 54387.686883  | 11.48742 | 0.02578 | -0.06456 |
| 54387.609088  | 11.49402 | 0.03290 | 0.04418 |
| 54390.521372  | 11.52130 | 0.01273 | -0.08028 |
| 54390.544901  | 11.51282 | 0.01314 | -0.03094 |
| 54398.647981  | 11.36002 | 0.01361 | -0.02246 |
| 54398.671428  | 11.38428 | 0.01373 | -0.02346 |
| 54399.616495  | 11.41113 | 0.01204 | -0.05097 |
| 54399.652117  | 11.42110 | 0.01225 | -0.05205 |
| 54720.614742  | 11.50358 | 0.03352 | -0.05665 |
| 54722.651535  | 11.45913 | 0.01843 | -0.04094 |
| 54724.579899  | 11.40131 | 0.01616 | -0.00673 |
| 54725.545387  | 11.43430 | 0.01835 | -0.06935 |
| 54726.613463  | 11.52363 | 0.01670 | -0.01711 |
| 54730.622609  | 11.47459 | 0.01459 | -0.00302 |
| 54732.703073  | 11.47021 | 0.01808 | -0.03689 |
| 54734.747409  | 11.41662 | 0.01649 | 0.00588 |

Instrumental FWHM of 0.060 ± 0.005 Å, determined from the telluric lines around 6300Å. A best fitting value of $V_{rot} \sin I = 1.4 \pm 1.0$ km s$^{-1}$ was obtained. If, however, macroturbulence is lower, then higher rotation values are found, with $V_{rot} \sin I = 3.0 \pm 0.5$ km s$^{-1}$ obtained for $v_{mac} = 0$ km s$^{-1}$. If, on the other hand, $v_{mac}$ is slightly higher than 2 km s$^{-1}$, then it is possible that $V_{rot} \sin I$ is close to, or even, zero.

In addition to the spectral analysis, we have also used broad-band photometry from TYCHO-2, USNO-B1.0 R-mag., CMC14 r’, DENIS and 2MASS to estimate the total observed bolometric flux. The Infrared Flux Method (Blackwell & Shallis 1977) was then used with 2MASS magnitudes to determine $T_{eff}$ and stellar angular diameter ($\theta$). This gives $T_{eff} = 5470 \pm 130$ K, which is in close agreement with that obtained from the spectroscopic analysis and implies a spectral type of G8V (Gray 2008).

4. Derivation of the system parameters

We derived stellar and planetary parameters for the system by fitting simultaneously the WASP, FTS and LT/RISE photometry with the CORALIE and HARPS RVs. These data were used as input into the Markov Chain Monte Carlo (MCMC; Ford 2006) code described in Gillon et al. (2008). MCMC is a Bayesian inference method based on stochastic simulations and provides the a posteriori probability distribution of adjusted parameters for a given model. Here the model is based on a
each MCMC simulation is composed of a large number of consecutive steps for which the jump parameters are randomly modified or not depending of the result of a test on the merit function ($MF$). The $MF$ used here is the sum of the $\chi^2$ for all the data with respect to the models added to a Bayesian prior on $V_{rot} \sin I$ and $M_*$ representing our constraints on these parameters from spectroscopy:

$$MF = \chi^2 + \frac{(V_{rot} \sin I - (V_{rot} \sin I)_0)^2}{\sigma^2_{V_{rot} \sin I}} + \frac{(M_* - (M_*)_0)^2}{\sigma^2_{M_*}}$$ (1)

where $(V_{rot} \sin I)_0 = 1.4$ km s$^{-1}$, $\sigma_{V_{rot} \sin I} = 1$ km s$^{-1}$, $M_* = 0.87$ and $\sigma_{M_*} = 0.08$. These last two values were obtained by interpolation of the Gandolfi stellar evolution models (Girardi et al. 2000) in order to find the mass and age that best match the spectroscopic parameters. We notice that our data do not constrain strongly $M_*$ and that it is a free parameter under the control of a Bayesian prior in our simulations only to propagate its uncertainty to the other physical parameters.

A first MCMC run was performed and led to a refined value for the stellar density. We converted it to $R_*/M_*^{1/3}$ in solar units, and compared this property and the stellar temperature to the Girardi models interpolated at -0.2 metallicity. The quantity, $R_*/M_*^{1/3}$, depends only on the observed transit properties (duration, depth, impact parameter, and orbital period) and is independent of the measured temperature. We generated the same property from the mass and log $g$ values in the models, and then interpolated the models in the $R/M_*^{1/3}$-$T_{\text{eff}}$ plane to determine a mass and age for WASP-6. We interpolated linearly along two consecutive mass tracks to generate an equal number of age points between the zero-age main sequence and the evolutionary state where the star reaches the end of core hydrogen burning. We then interpolated between the mass tracks along equivalent evolutionary points to find the mass and age from the models that best match the stellar density derived from the MCMC and the effective temperature. In this way, we obtained a value for the stellar mass of, $M_* = 0.83^{+0.07}_{-0.09} M_\odot$ and a derived age for the system of $11 \pm 7$ Gyr.

The best-fitting model found in the first MCMC run was used to estimate the level of correlated noise in each photometric time-series and a jitter noise in the RV time series. For each photometric time-series, the red noise was estimated as described in Gillon et al. (2006), by comparing the $rms$ of the unbinned and binned residuals. We used a bin size corresponding to a duration of 25 minutes, similar to the timescale of the ingress/egress of the transit. For the SW data, the red noise was estimated to be negligible when compared to the theoretical error bar of the measurements and it was thus neglected. The deduced red noise values (Table 4) were added quadratically to the theoretical uncertainties of each corresponding time-series. No jitter is detected in the CORALIE data. For the HARPS data, a significant jitter is obtained, but it seems to be originating mostly from the residuals of the RM effect and is probably more due to lower-than-usual $S/N$ on the spectra and a worsening of airmass (reaching 1.8

| Parameter | Value |
|-----------|-------|
| R.A. (J2000) | $23^h12^m37.74^s$ |
| Dec (J2000) | $-22^\circ40'26'.2$ |
| $T_{\text{eff}}$ | 5450 ± 100 K |
| log $g$ | 4.6 ± 0.2 |
| $\xi$ | 1.0 ± 0.2 km s$^{-1}$ |
| $V_{rot} \sin I$ | 1.4 ± 1.0 km s$^{-1}$ |
| [Na/H] | $-0.17 ± 0.06$ |
| [Mg/H] | $-0.13 ± 0.07$ |
| [Al/H] | $-0.15 ± 0.10$ |
| [Si/H] | $-0.12 ± 0.08$ |
| [Ca/H] | $-0.09 ± 0.10$ |
| [Sc/H] | $-0.22 ± 0.15$ |
| [Ti/H] | $-0.05 ± 0.09$ |
| [V/H] | $-0.02 ± 0.08$ |
| [Cr/H] | $-0.17 ± 0.09$ |
| [Mn/H] | $-0.20 ± 0.13$ |
| [Fe/H] | $-0.20 ± 0.09$ |
| [Co/H] | $-0.16 ± 0.14$ |
| [Ni/H] | $-0.21 ± 0.08$ |
| log $N(Li)$ | $< 0.5$ |
| $T_{\text{eff}}$ (IRFM) | 5470 ± 130 K |
| $\theta$(IRFM) | 0.037 ± 0.002 mas |

Table 3. Stellar parameters for WASP-6.
5. Discussion

The large radius of WASP-6b (∼1.2R_J) and the metal deficiency of its host star strengthen the existence of a correlation between the heavy-element content of giant planets and the stellar metallicity (Guillot et al. 2006; Burrows et al. 2007). With half of the mass of Jupiter and a radius significantly larger, WASP-6b appears nevertheless too large for basic models of irradiated planets (Burrows et al. 2007a; Fortney et al. 2007), even if an absence of core is assumed. For instance, tables presented in Fortney et al. (2007) predict a maximum radius of ∼1.1R_J for a 0.5 Jupiter-mass planet orbiting at 0.045 AU of a 4.5 Gyr solar-type star. WASP-6 is smaller, cooler and probably older than the Sun, so 1.2R_J is clearly too large for these models. In this context, it is worth noticing the non-null eccentricity that we infer for its orbit (e = 0.054±0.018). The fact that the planetary orbit is still not circularized despite the large age of the system indicates that the tidal evolution of WASP-6b probably played an important role in its energy budget. As outlined by Jackson et al. (2008b), tidal heating could have been large enough for many close-in planets to explain at least partially the large radius of some of them. To assess the past and future tidal evolution of WASP-6b, we integrated the equations for da/dt and de/dt presented in Jackson et al. (2008a) and computed at each step the tidal heating rate H using the formula presented in Jackson et al. (2008b). We assumed values of Q_p = 10^{6.5} and Q_p' = 10^{5.5} for respectively the planetary and stellar tidal dissipation parameters. These values were found by Jackson et al. (2008a) to conciliate the eccentricity distribution of close-in planets before their tidal evolution to the one of the planets detected furar from their star. We also took into account the evolution of the stellar rotation period due to the tide raised by the planet using (Goldreich & Soter 1966):

\[ \frac{d\Omega_s}{dt} = -\text{sign}(\Omega_s - n) \frac{G}{4} \frac{R_s^3}{\alpha_s M_p Q'_s} \frac{M_p^2}{a^6}, \]

where G is the gravitational constant, n is the mean orbital motion, Ω_s is the stellar spin angular rate and \( \alpha_s = L_s / (M_s R_s^2) \) with \( L_s \) being the moment of inertia though the spin axis of the star. For \( \alpha_s \), we assumed a value of 0.07 (Pätzold et al. 2004). To assess the reliability limits of the model, we also computed the evolution of the total angular momentum of the system (assuming a negligible contribution of the planet rotation):

\[ L_{tot} = \frac{M_s M_p}{M_s + M_p} a^2 \sqrt{1 - e^2} + \alpha_s M_s R_s^2 \Omega_s, \]

Neglecting the possible decrease due stellar wind (Dobbs-Dixon et al. 2004), \( L_{tot} \) should be a conserved quantity during the whole tidal evolution of the system.

Fig. 6 shows the obtained evolution for a, e, H, \( L_{tot} \) and the orbital and stellar rotation period from 2 Gyr ago to 5 Gyr in the future. Interestingly, the model predicts (1) that the eccentricity and semi-major axis of WASP-6b were significantly larger in the past, (2) that the orbit will be fully circularized one Gy from now, and (3) that the planet will continue to slightly approach the star until finally reaching its Roche limit. This last results agrees well with the fact that the ratio \( L_{tot}/L_c \), where \( L_c \) is critical angular momentum (see Levrard et al. 2009), has a value of ∼0.6, implying that the system is tidally unstable and will ultimately merge. Levrard et al. (2009) showed that all the other transiting systems, except HAT-P-2, are in the same case.

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2 We use here the same convention than Jackson et al. (2008a): the coefficients \( Q_p \) and \( Q'_p \) used here are equal to the actual tidal dissipation parameters \( Q_p \) and \( Q'_p \) multiplied by the ratio 3/2k where k is the Love number.
Table 5. WASP-6 system parameters and 1-σ error limits derived in this work.

| Parameter                        | Value       | Units     |
|----------------------------------|-------------|-----------|
| Transit epoch $T_0$              | 2454596.43267$^{+0.00015}_{-0.00010}$ | HJD       |
| Orbital period $P$               | 3.3610060$^{+0.000022}_{-0.000035}$ | days      |
| Planet/star area ratio $(R_p/R_*)^2$ | 0.02999$^{+0.00019}_{-0.00025}$ |          |
| Transit duration $t_T$           | 0.10860$^{+0.00073}_{-0.00067}$ | days      |
| Impact parameter $b$             | 0.26$^{+0.07}_{-0.11}$ | $R_*$     |
| RV semi-amplitude $K$            | 74.3$^{+1.7}_{-1.4}$ | m s$^{-1}$ |
| $\epsilon \cos \omega$          | $-0.007^{+0.011}_{-0.008}$ |          |
| $\epsilon \sin \omega$          | 0.05$^{+0.018}_{-0.017}$ |          |
| $V_{rot} \sin I \cos \beta$    | 1.57$^{+0.28}_{-0.10}$ |          |
| $V_{rot} \sin I \sin \beta$    | 0.32$^{+0.49}_{-0.50}$ |          |
| Orbital semi-major axis $a$      | 0.042$^{+0.008}_{-0.013}$ | AU        |
| Orbital inclination $i$          | 88.4$^{+0.65}_{-0.47}$ | degrees   |
| Orbital eccentricity $e$         | 0.05$^{+0.018}_{-0.015}$ |          |
| Argument of periastron $\omega$ | 1.76$^{+0.12}_{-0.23}$ | rad       |
| Spin-orbit angle $\beta$        | 0.26$^{+0.25}_{-0.42}$ | rad       |
| Stellar mass $M_*$               | 0.886$^{+0.050}_{-0.080}$ | $M_\odot$ |
| Stellar radius $R_*$             | 0.870$^{+0.025}_{-0.036}$ | $R_\odot$ |
| Stellar surface gravity $g_*$    | 4.50 ± 0.06 | [cgs]     |
| Stellar density $\rho_*$         | 1.34$^{+0.11}_{-0.10}$ | $\rho_\odot$ |
| Projected rotational velocity $V_{rot} \sin I$ | 1.60$^{+0.27}_{-0.17}$ | km s$^{-1}$ |
| Planet radius $R_p$              | 1.224$^{+0.051}_{-0.052}$ | $R_J$     |
| Planet mass $M_p$                | 0.503$^{+0.019}_{-0.038}$ | $M_J$     |
| Planetary surface gravity $g_p$  | 7.857 ± 0.028 | [cgs]     |
| Planet density $\rho_p$          | 0.27 ± 0.05 | $\rho_J$ |
| Planet temperature $(A = 0, f = 1/4) T_{eff}$ | 1194$^{+58}_{-57}$ | K         |

Under this tidal evolution model, WASP-6b was brought to a distance $> 0.05$ AU of its host star in the very early life of the system, then its orbital evolution has been totally dominated by tides until now. This evolution does not consider the possible influence of one or more other planets able to pump the eccentricity of WASP-6b (Mardling 2007), but our RV data do not reveal the presence of another planet so it seems reasonable at this stage to assume that the orbital evolution of WASP-6b was not dominated by planet-planet interactions. The model assumes also a constant radius for the planet during the whole tidal evolution, which is not very likely (Liu et al. 2008). Furthermore, Fig. 6 shows that it does not conserve $L_{tot}$ for $e > 0.3$ and during the final runaway merging of the planet with the star. Considering as valid only the part of the tidal evolution for which $L_{tot}$ is conserved at...
the 1-% level, we can nevertheless conclude from Fig. 6 that WASP-6b experienced 0.6 - 1.2 Gyr ago a large tidal heating rate of $5 - 10 \times 10^{19}$ W. Such a large heating rate in the past should have modified drastically the thermal history of the planet and could have contributed significantly to the measured inflated radius.

With a stellar irradiation $\sim 4.7 \times 10^8$ erg s$^{-1}$ cm$^{-2}$, WASP-6b belongs to the theoretical pL planetary class proposed by Fortney et al. (2008; see also Burrows et al. 2008). Under this theory, Ti and V-bearing compounds should mostly be condensed in the planetary atmosphere and secondary eclipse measurements at different wavelengths should not reveal any stratospheric thermal inversion. Such secondary eclipses observations would not only constrain atmospheric models of giant close-in planets, they would also constrain the eccentricity of the orbit and thus the tidal thermal history of the planet.

The value that we determine for the sky-projected angle between the stellar spin and the planetary orbital axis is compatible with zero ($\beta = 11^{\circ} _{14}$). This good alignment was observed only for the planet XO-3 (Hébrard et al. 2008). Together, these results favor migration via tidal interactions with a protoplanetary disk (Lin et al. 1996) as the dominant mechanism of planetary migration, because it should preserve spin-orbit alignment (Ward & Hahn 1994) contrary to migration via planet-planet scattering (Rasio & Ford 1996) or Kozai cycles (Fabrycky & Tremaine 2007).

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