Orbital eccentricity of WASP-12 and WASP-14 from new radial velocity monitoring with SOPHIE*

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ABSTRACT
As part of the long-term radial velocity monitoring of known transiting planets, we have acquired new radial velocity data for the two transiting systems WASP-12 and WASP-14, each harbouring a gas giant on a close orbit (orbital period of 1.09 and 2.24 d, respectively). In both cases, the initial orbital solution suggested a significant orbital eccentricity, 0.049 ± 0.015 for WASP-12b and 0.091 ± 0.003 for WASP-14b. Since then, measurements of the occultation of WASP-12 in the infrared have indicated that one projection of the eccentricity (e cos ω) was close to zero, casting doubt on the eccentricity from the initial radial velocity orbit. Our measurements show that the radial velocity data are compatible with a circular orbit. A MCMC analysis taking into account the presence of correlated systematic noise in both the radial velocity and photometric data gives e = 0.017±0.015. In contrast, we confirm the orbital eccentricity of WASP-14b, and refine its value to e = 0.0877 ± 0.0030, a 10σ detection. WASP-14b is thus the closest presently known planet with a confirmed eccentric orbit.

Key words: planet–star interactions – planetary systems.

1 INTRODUCTION
Transiting planets are an important source of information on the formation, structure and evolution of exoplanets. We are monitoring known transiting planetary systems in radial velocity with the SOPHIE spectrograph in the Northern hemisphere and HARPS spectrograph in the Southern hemisphere to refine our knowledge of the dynamics of these systems – such as measuring the orbital eccentricity (e.g. Hébrard et al. 2008; Loeillet et al. 2008, ESO Programme 0812.C-0312).

In this paper, we analyse our new SOPHIE radial velocity data for two transiting planetary systems, WASP-12 and WASP-14. Both are characterized by close-in but apparently eccentric orbits, and therefore represent potentially important systems to constrain the migration, tidal and thermal evolution of gas giant planets. We combine our radial velocity data with previously published data and a realistic treatment of correlated noise to calculate updated constraints on the orbital eccentricities.

The planetary companion of the 11.7 mag star WASP-12 is a particularly interesting example (Hebb et al. 2009, hereafter H09). It orbits extremely close to its host star, even by the standards of the so-called ‘hot Jupiters’, with a period of 1.09 d, corresponding to an orbital distance only three times the radius of its host star. Moreover, WASP-12b has an inflated radius, R ∼ 1.8 R_J, one of the most extreme examples of anomalous radii for hot Jupiters. As a result, the planet fills about half of its Roche lobe (Li et al. 2010).

With such a short orbital distance and large size, a gas giant planet is expected to undergo complete orbital synchronization and circularization on a short time-scale (∼100 000 yr, using Mazeh 2008, and assuming Q/k ~ 10^5), much shorter than the age of the system (2 Gyr, H09).

Indeed, most planets orbiting closer than 0.05 au are observed to have circular orbits. However, H09 determined a value of
$e = 0.049 \pm 0.015$ for the orbital eccentricity of WASP-12b, a $2.8 \sigma$ significant departure from circularity (based upon the Lucy & Sweeney 1971, test). This would make the planet by far the subject of the strongest tidal dissipation in any known planetary system – by a factor of about 400, as compared to WASP-14b. This is because of the short circularization time-scale and the reportedly large eccentricity, as discussed later.

The measured eccentricity is based on fitting a Keplerian orbital motion on the radial velocity measurements collected by H09 with the SOPHIE spectrometer (Perruchot et al. 2008; Bouchy et al. 2009) together with transit photometry. Li et al. (2010) studied the case of WASP-12 with that value of eccentricity, and found a large implied mass-loss and dissipation of tidal energy in the planet.

In a transiting system, the time lag between the transit and the occultation has a strong dependence on the projected orbital eccentricity $e \cos \omega$, as shown by Winn et al. (2005):

$$e \cos \omega \simeq \frac{\pi}{2P} \left( t_2 - t_1 - \frac{P}{2} \right),$$

where $t_2 - t_1$ is the time difference between an occultation and a transit. Winn et al. (2005) also show that the component $e \sin \omega$ is dependent on a ratio involving the durations of the occultation and transit,

$$e \sin \omega \simeq \frac{T_{\text{trans}} - T_{\text{occ}}}{T_{\text{trans}} + T_{\text{occ}}},$$

where $T_{\text{trans}}$ and $T_{\text{occ}}$ are the transit and occultation durations, respectively, although this constraint is weaker than the one on $e \cos \omega$.

Therefore, if the occultation can be detected with sufficient significance, this provides a stringent test of the eccentricity. Lopez-Morales et al. (2009, hereafter L10) have measured the occultation of WASP-12b from the ground with SPICam on the ARC Telescope at Apache Point Observatory in the $z'$ band. Their best-fitting result initially indicated an occultation with a significant time lag ($e \cos \omega = 0.0156 \pm 0.0035$) compared to the epoch expected for a circular orbit, with a similar level of significance to H09.

Nevertheless, the presence of residual correlated noise is apparent in the L09 data (see Fig. 4), as expected for ground-based photometry at such a high accuracy – the depth of the occultation is only about 0.08 ± 0.02 per cent.

As a result, the issue remained inconclusive until a space-based measurement of the occultation with the *Spitzer Space Telescope* (Campo et al. 2011, hereafter C11) unambiguously showed that the timing of the occultation was consistent with a circular orbit. This result suggested that the L10 time lag was probably due to instrumental systematics, and that the orbit of WASP-12b was probably circular, since a fine-tuned alignment would be required to reconcile the *Spitzer* result with the H09 value of the eccentricity. Following this, L10 have reanalysed their data and revised their estimate to $e \cos \omega = 0.016^{+0.011}_{-0.009}$.

It is interesting to note that there is an inherent bias in eccentricity measurements from radial velocities, because a Keplerian orbit cannot get more circular than $e = 0$. Any noise applied to a circular orbit will result in an eccentric best-fitting orbit. Underestimating the noise will lead to spurious detections of small eccentricities. This was already recognized in the context of stellar binaries by Lucy & Sweeney (1971). These authors showed that spurious eccentricity detections tended to dominate for $e < 0.1$ for a typical precision at that time and stellar binary amplitudes. Four decades later, both companion masses and RV accuracies having changed by about three orders of magnitudes, and the same issue resurfaces for exoplanets. In the same way, Laughlin et al. (2005) showed that the measured orbital eccentricity of HD 209458b, $e = 0.14 \pm 0.009$ was consistent with the results of simulated data for a circular orbit. Shen & Turner (2008) also performed an extensive analysis involving simulated data to show that the estimation of eccentricities for exoplanets in the literature may be overestimated in about 10 per cent of cases. Recently, Zakamska, Pan & Ford (2010) studied this effect in the Butler et al. (2006) catalogue.

WASP-14b is, after WASP-12b, the known transiting planet having a reported non-circular orbit (Joshi et al. 2009, $e = 0.091 \pm 0.003$) with the second-shortest period ($P = 2.2$ d). This makes it another test case for tidal evolution of close-in gas giants. If its orbital eccentricity is indeed near 0.1, then this non-zero but relatively low value – in the context of the distribution of giant exoplanet eccentricities – makes it likely that this planet has undergone some degree of orbital evolution, and is still subject to strong tidal forces at present. Therefore its presence may be useful to constrain the tidal synchronization time-scale. It is also an important object when studying the issue of the anomalous radius of hot Jupiters because of its inflated size, with $R_p = 1.28R_J$. WASP-14b occupies a distinctive position in the relevant parameter space: irradiation, orbital distance, eccentricity and size.

In Section 2, we describe our new SOPHIE observations for WASP-12 and WASP-14. In Section 3, we describe the use of the Bayesian Information Criterion in this context and present the results of our analysis for each system, where we demonstrate that the data for WASP-12 is compatible with a circular orbit, while that for WASP-14 is compatible with an eccentric orbit. Finally in Section 4, we summarize the results presented in this paper and suggest there may be more transiting hot Jupiters for which the eccentricity has been overestimated in the literature due to limited data sets.

### 2 OBSERVATIONS

We obtained 29 radial velocity measurements for WASP-12 (16 during a single night, and 13 at various values of orbital phase, see Table 1) and 11 for WASP-14 (see Table 2), using the SOPHIE spectrograph installed on the 1.93-m telescope at OHP (France). The observations were gathered between 2009 January 17 and 2010 March 27. The 16 in-transit measurements for WASP-12 were initially obtained with the objective of constraining the spin-orbit angle via the Rossiter–McLaughlin effect. The typical exposure times were 1098 and 552 s for WASP-12 and WASP-14, respectively.

SOPHIE is a spectrograph optimized for precise radial velocity measurements and has participated in the detection of numerous transiting exoplanets in the Northern hemisphere, notably from the WASP and CoRoT transit searches. It reaches a stability of a few m s$^{-1}$ for bright targets. WASP-12 and WASP-14, however, are near the faint end of the capacity of the 1.93-m telescope, and were measured in the ‘High Efficiency’ mode of SOPHIE (see Perruchot et al. 2008; Bouchy et al. 2009). This mode has a higher throughput than the standard mode, the ‘High Resolution’ mode, thus allowing fainter targets to be measured, but is less optimized for radial velocity measurements. When considering the ensemble of data for known transiting planets obtained with SOPHIE on a time span of several months, significant excursions of the velocity zero-point with time were found, to the level of several dozen m s$^{-1}$ in some cases. As part of the constant improvement of the SOPHIE reduction pipeline, this effect is monitored and corrected for as far as possible (Bouchy et al. 2009), but the presence of relatively large instrumental systematics in the High Efficiency data is a possibility, especially with older data collected before we became aware of
the issue. This must be remembered when performing an orbital analysis based on data from the High Efficiency mode.

### 3 Analysis and Results

The orbital parameters of the two transiting planets were calculated from the radial velocity data, (together with published photometry data for the transit and occultation in the case of WASP-12b), with a Markov Chain Monte Carlo (MCMC) method using the Metropolis–Hastings algorithm. The use of MCMC in this context is described by, among others, Holman et al. (2006). Our implementation is described in Pont et al. (2009). We use a Bayesian treatment of the a priori constraints from stellar evolution models with the method of Pont & Eyer (2004). We model the radial velocity using a Keplerian orbit, the Rossiter–McLaughlin effect on the radial velocity using Giménez (2006) and the transit and occultation light curves using Mandel & Agol (2002). For the occultation, we include a multiplicative term for the depth in the transit code, as well as zero limb darkening. For each target, we run an initial chain (100 000 steps) to obtain the median values for the parameters. These are then used as the starting point for the final run, which is executed for 400 000 steps. The whole second chain is kept, and we verify that the autocorrelation length of each chain is much shorter than the chain length to ensure the relevant region of parameter space is properly explored.

MCMC methods are powerful, but they also tend to obscure the relation between the uncertainties on the measured data and the calculated uncertainties on the final system parameters. Neglecting non-random sources of noise in the data (such as instrumental systematics and stellar variability) can lead to an underestimation of the uncertainties in the final system parameters by a large factor (Pont, Zucker & Queloz 2006), and, in the case of orbital eccentricities, to a systematic bias (Lucy & Sweeney 1971). We account for the presence of correlated noise in both the photometric and radial velocity data by modifying the merit function used in the MCMC to include the possible presence of non-random noise.

#### 3.1 Bayesian Information Criterion

Deciding between a circular orbit (Model 1) or an eccentric one (Model 2), is an exercise in model selection — we want to compare Model 1 to Model 2. To do this, we need the posterior distribution ratio \( P(\text{Model}_1|\text{data})/P(\text{Model}_2|\text{data}) \), and we could use Bayes’ theorem,

\[
P(\text{Model}_1|\text{data}) = \frac{P(\text{data}|\text{Model}_1)P(\text{Model}_1)}{P(\text{data})},
\]

where the term \( P(\text{Model}_1) \) on the RHS is the prior. This is not known, so we choose instead to use the Bayesian Information Criterion BIC as described by (Liddle 2007):

\[
\text{BIC} = -2 \ln L_{\text{max}} + k \ln M,
\]

where \( L_{\text{max}} \) is the maximum likelihood achievable in the model (circular or eccentric), and this is calculated from \( e^{-\chi^2/2} \), and

\[
\chi^2 = \sum_i \left( \frac{v_{i,1} - v_{i,\text{mod}}}{\sigma_i} \right)^2,
\]

where \( v_{i,j} \) is the observed value of the radial velocity, \( v_{i,\text{mod}} \) is the model value, \( \sigma_i \) is the uncertainty, including the red noise (see later) and \( M \) is the number of parameters. \( k \) is the number of parameters in the model used (4 for a circular orbit and 6 for an eccentric orbit). The term \( k \ln M \) thus penalizes a model with a larger number of parameters (say, an eccentric orbit), and we seek the model with smallest BIC. In this paper, we only use the radial velocity data to do the BIC testing in both the case of WASP-12 and WASP-14.

#### 3.2 The orbital eccentricity of WASP-12b

Figs 1 and 2 display our radial velocity data for WASP-12, together with a circular orbital solution (solid line, residuals shown in the lower panel) and the eccentric-orbit fit of H09 (dotted). Our radial velocities are the observed value of the radial velocity, \( k^{-1} = 19.113 \). The number of points, \( P \), is the maximum likelihood achievable in the model, \( \pm \sigma \), and we find \( V_0 = 19.113 \pm 0.014 \) km s\(^{-1}\).
velocity data are shown together with the H09 data in the right-hand panel. As the figure clearly shows, the radial velocity signal cannot be adequately modelled by a periodic orbital signal affected by random noise. The presence of a correlated non-periodic component is especially obvious during the in-transit sequence. This could be due to instrumental noise, stellar variability or an unaccounted planetary companion in the system, all of which would behave in the same way as far as the orbital fit is concerned. Given our experience with SOPHIE in High Efficiency mode, we consider the first cause as likely.

We use the transit light curve from H09 and the occultation light curves from L10 and C11 with our own radial velocity measurements to perform a global fit with a Keplerian orbit, and we account for the effect of red noise by modifying the uncertainties on the data using \( \sigma' = (\sigma^2 + N\sigma_r^2)^{1/2} \), where \( \sigma \) is the random error, \( \sigma' \) the modified error used to compute the merit function for the MCMC, \( \sigma_r \) the red-noise factor and \( N \) the number of data points over a typical correlation timespan. The reader is referred to Pont et al. (2006) and Pont et al. (2009) for more details on this approach.

For the H09 photometric transit, we estimate \( \sigma_r = 0.0005 \) (out of transit flux normalized to 1.0) and \( N = 20 \). Similarly, for the L10 data, we set \( \sigma_r = 0.0002 \) (out of transit flux normalized to 1.0) and \( N = 9 \). For the C11 data, we set \( \sigma_r = 0.0005 \) (out of transit flux normalized to 1.0) and \( N = 9 \). For our own radial velocity data, we estimate the red noise parameter to be 9 m s\(^{-1}\), and \( N = 16 \) during the transit and \( N = 1 \) outside the transit. The former measurements are taken on the same night, so \( N = 16 \) guards against the possibility these points were shifted together due to instrumental systematics or other effects, while the other points are taken in different nights so that the uncertainties are not expected to be correlated.

We vary the period \( P \), mid-transit time \( T_{tr} \), system velocity \( v_0 \), eccentricity components \( e \cos \omega \) and \( e \sin \omega \), semi-amplitude \( K \), impact parameter \( b \), scaled planetary radius \( R_p/R_s \), the stellar mass \( M_s \), stellar radius \( R_s \) and effective temperature \( T_{eff} \) of the star. The scaled semimajor axis \( a/R_s \) is calculated from the assumption of a Keplerian orbit using the period \( P \). We also include a separate term for the depth of each occultation data set, because the depth varies with wavelength.

We set the quadratic limb darkening parameters for the H09 transit to \( u_a = 0.1274 \) and \( u_b = 0.3735 \) according to Claret (2004). We ran the MCMC code for 800,000 steps, and found 18 per cent of the steps were accepted.

Although our data cover a complete spectroscopic transit, and thus potentially constrain the projected spin-orbit angle of the WASP-12 system through the Rossiter–McLaughlin effect, the constraint is weak once the possible presence of non-random noise is taken into account. The distribution of the spin-orbit angle from our MCMC exploration spans a wide interval extending from a prograde
orbit to a projected spin-orbit angle larger than 90°, as shown in Fig. 3. The data marginally favour a prograde rather than retrograde orbit, with the odds, i.e. the ratio of prograde to retrograde orbits, at 1.05. We therefore allow $\lambda$ to be free in subsequent calculations.

This does not appreciably alter the orbital parameters (for example the derived eccentricity in the case of using a free parameter $\lambda$ is $e = 0.018^{+0.024}_{-0.014}$, while fixing $\lambda = 0$ yields $e = 0.017^{+0.015}_{-0.010}$).

The best solution with our radial velocity data and the constrains from the transit and occultation light curves gives $e = 0.018^{+0.024}_{-0.014}$. The value of $\chi^2$ for the circular orbit is $\chi^2_c = 33.60$ and the value for an eccentric orbit is $\chi^2_e = 32.19$. When these are entered into equation (4) using $k = 4(P, T_{tr}, V_0, K)$ and 6 (i.e. including $e \sin \omega$ and $e \cos \omega$) respectively, and $M = 29$, we obtain the BICs as $\text{BIC}_c = 47.07$ and $\text{BIC}_e = 52.40$. This means that the circular orbit is preferred, because the ‘gain’ in minimizing $\chi^2$ is offset by the penalty for including two additional parameters $e$ and $\omega$ and that according to the data, we do not have the evidence to reasonably maintain that the orbit is eccentric. Using the Lucy & Sweeney test, the significance of the eccentricity is $p = 0.61$, corresponding to a $0.51\sigma$ result.

Our results for the orbital parameters of the WASP-12 system are shown in Table 3, with the results of the analysis of our new SOPHIE RV data used in combination with the H09 transit light curve, and the L10 and C11 occultation light curves, compared to the H09 parameters.

The H09 radial velocity data forces the solution towards a higher eccentricity, significant at the $\sim3\sigma$ level, but Fig. 2 suggests that this is probably an artefact due to an excursion of the zero-point between different nights.
It is interesting to compare the situation in radial velocity with the similar sequence of events regarding the occultation photometric data. Fig. 4 (left-hand panel) shows the occultation data for both L10 (top two panels) and C11 (bottom two panels). The solid line shows a circular orbit, from a global fit assuming $e = 0$. The dotted line represents the L10 solution (eccentricity $e = 0.057$, and the residuals are plotted for both data sets for the L10 (eccentric) solution. This shows that the L10 eccentric solution is somewhat plausible for the L10 data but definitely not for the C11 data. Fig. 4 (right-hand panel) shows the same data, and the solid line is still a circular orbit $e = 0$. The residuals for both data sets are now plotted for the circular solution $e = 0$. It is clear that the circular solution fits the C11 data set better and remains reasonable for the L10 data set. This could be explained if the effects of instrumental systematics had been underestimated in the original L10.

We also looked for possible evidence for a second planetary companion in the system by examining the residuals as function of time, by including a linear trend in the fitting process:

$$v(t) = v_{\text{planet}}(t) + \dot{\gamma}(t - t_0),$$

setting $t_0 = 2454900$ (to allow the MCMC to explore values of $\dot{\gamma}$ and reran the MCMC twice: once for a circular orbit and once for an eccentric orbit. For the circular orbit, we found that the limits on the gradient are $\dot{\gamma} = 0.052 \pm 0.054 \text{ m s}^{-1} \text{ d}^{-1}$ and $\chi^2 = 27.50$, giving $\text{BIC}_{\text{linear trend}} = 44.34$, using $k = 5$ to penalize this circular model for the extra term. For the eccentric orbit, we found that the limits on the gradient are $\dot{\gamma} = 0.050 \pm 0.054 \text{ m s}^{-1} \text{ d}^{-1}$ and $\chi^2 = 27.39$, giving $\text{BIC}_{\text{linear trend, eccentric}} = 50.96$, using $k = 7$ to penalize this eccentric model for the extra term. This would appear to favour the circular model with a trend of $\dot{\gamma} = 0.052 \pm 0.054 \text{ m s}^{-1} \text{ d}^{-1}$, but since this result is consistent with no trend, and we know from experience that it is possible to obtain this magnitude of a trend ($\sim 20 \text{ m s}^{-1}$ over 400 d) with SOPHIE, we do not consider this trend to be significant.

For completeness, we include a discussion of the light travel time across the system. The negligible delay in the occultation as detected by C11, $(0.0012 \pm 0.0006)$ $P$ would be significant if the light travel time across the system (in reality, only $\sim 10$ s) were much longer than the measured delay ($\sim 110$ s) and the uncertainties $\sim 60$ s. In that case, the light travel time would induce a delay in the occultation detection, and a measurement showing a negligible delay would suggest an eccentric orbit was giving an offset that exactly cancelled the light travel time. This is not supported here, however, because the light travel time is smaller than both the shift

**Table 3.** System parameters for WASP-12. Left: H09. Right: our SOPHIE radial velocity data, H09 transit photometry data and L10 and C11 occultation photometry data. Median values are quoted as well as 68.3 per cent confidence limits.

| Parameter                        | H09            | New SOPHIE RV and photometry |
|----------------------------------|----------------|-------------------------------|
| Centre-of-mass velocity $V_0$ (km s$^{-1}$) | $19.085 \pm 0.002$ | $19.061 \pm 0.014$            |
| Orbital eccentricity $e$         | $0.049 \pm 0.015$ | $0.018 - 0.014$               |
| Argument of periastron $\omega$ (°) | $-74^{+13}_{-10}$ | 0 (unconstrained)            |
| $e \cos \omega$                 | $0.0035 \pm 0.0034$ | $0.0177 \pm 0.028$           |
| $e \sin \omega$                 | $0.0021$         |                               |
| Velocity semi-amplitude $K$ (m s$^{-1}$) | $226 \pm 4$   | $238 \pm 11$              |
Figure 5. The new SOPHIE radial velocity data for WASP-14 are shown with squares, while the Joshi et al. (2009) data from FIES and SOPHIE are shown with points and crosses, respectively. The solid line is the best solution with $e = 0.0877$, and the dotted line is a circular orbit. The middle panel shows residuals plotted for the best-fitting orbit $e = 0.087$, while the bottom panel shows residuals for a circular orbit (using the parameters of Joshi et al. 2009, for the spectroscopic transit).

and the uncertainty in the timing of the occultation according to the Spitzer measurements.

3.3 The orbital eccentricity of WASP-14b

Fig. 5 shows our SOPHIE data and the FIES and SOPHIE data from Joshi et al. (2009) along with with the best-fitting orbit and a circular orbit. We adopt the prior distribution on the period $P$ from photometric data by Johnson et al. (2009) and that on the mid-transit time $T_{\text{tr}}$ from Joshi et al. (2009). We work out the orbital parameters using both our radial velocity data and that published in the discovery paper. We include the effect of red noise in a similar manner explained above, adding 8 m s$^{-1}$ of correlated uncertainties to each single data point and $\sqrt{N} \times 8$ m s$^{-1}$ to each point in each group where $N$ is the number of points taken on the same night (determined from the timestamps).

We ran the MCMC code for 800 000 steps, and found 16 per cent of the steps were accepted. Our results are shown in Table 4. Our best-fitting value for the orbital eccentricity is $e = 0.0877 \pm 0.0030$, in good agreement with the value found by Joshi et al. (2009) ($e = 0.091 \pm 0.003$).

We examined the possibility of a scenario similar to that of WASP-12b, with correlated noise causing a spurious eccentricity detection. The lower panel of Fig. 5 shows the residuals around the best-fitting circular orbit (given by a MCMC run with $e = 0$ fixed). We find that, in contrast to the case of WASP-12b, the differences between observation and model assuming a circular solution are periodic and regular, which would not be the case for correlated noise. The value of $\chi^2$ for a circular orbit is $\chi^2_{c} = 865$ and that for an eccentric orbit is $\chi^2_{e} = 29$. When these are entered into equation (4) using $k = 3$ (two values of $V_0$, one for our data with SOPHIE

| Parameter               | Joshi et al.     | This paper         |
|-------------------------|------------------|--------------------|
| Centre-of-mass velocity $V_0$ (km s$^{-1}$) | $-4.985 \pm 0.003$ | $-4.985 \pm 0.003$ |
| Orbital eccentricity $e$ | $0.091 \pm 0.003$ | $0.0877 \pm 0.0030$ |
| Argument of periastron $\omega$ (°) | $-106.6 \pm 0.7$ | $-107 \pm 1$ |
| $e \cos \omega$         | $-0.026 \pm 0.002$ | $-0.026 \pm 0.002$ |
| $e \sin \omega$         | $-0.082 \pm 0.003$ | $-0.082 \pm 0.003$ |
| Semi-amplitude K (m s$^{-1}$) | $993 \pm 3$ | $991 \pm 3$ |
and one for the data from Joshi et al. (2009), using SOPHIE, and the semi-amplitude $K_2$ and $k = 5$ (two additional parameters, the eccentricity $e$ and the argument of periastron $\omega$) respectively, and $M = 38$ (we used both the Joshi et al. 2009 SOPHIE data and our own RV), we obtain the BICs as $\text{BIC}_c = 876$ and $\text{BIC}_c = 47.5$. The circular orbit is thus overwhelmingly rejected. Using the Lucy & Sweeney test, the significance is $p = 5.53 \times 10^{-25}$, corresponding to a 10.3σ detection.

In the same manner as for WASP-12b, we looked for possible evidence for a second planetary companion in the system by examining the residuals as function of time, by including a linear trend in the fitting process according to equation (6) and reran the MCMC for both a circular and an eccentric orbit. This time we set $t_0 = 2454460$ HJD. For the circular orbit, we found that the limits on the gradient are $\dot{\gamma} = 0.070^{+0.004}_{-0.004}$ m s$^{-1}$ d$^{-1}$ and $\chi^2 = 852$, giving $\text{BIC}_{\text{linear trend, circular}} = 867$, using $k = 4$ to penalize this circular model for the extra term. For the eccentric orbit, we found that the limits on the gradient are $\dot{\gamma} = 0.078^{+0.006}_{-0.006}$ m s$^{-1}$ d$^{-1}$ and $\chi^2 = 27.5$, giving $\text{BIC}_{\text{linear trend, eccentric}} = 49.3$, using $k = 6$ to penalize this eccentric model for the extra term. The eccentric orbit without any linear trend is thus favoured, because it had the lowest BIC.

4 DISCUSSION

From Mazeh (2008), we can work out the circularization time-scale for a system, using

$$\tau_{\text{circ}} = \frac{P}{2 \ln(\frac{Q}{k})} \left( \frac{M_2}{M_1} \right) \left( \frac{a}{r_p} \right)^5,$$

(7)

which yields about $10^7$ yr for WASP-12b, and $5 \times 10^7$ yr for WASP-14b if we assume $Q_s/k = 10^5$ from Goldreich & Soter (1966). This should be compared to the ages of the systems, $2.4 \times 10^9$ (H09) and $0.5-1 \times 10^9$ yr (Joshi et al. 2009) respectively. The circularization time-scale (e.g. Lecar, Wheeler & McKee 1976; Jackson, Greenberg & Barnes 2008) is given by

$$\frac{1}{e} \frac{de}{dr} = -1 \tau_{\text{circ}},$$

(8)

up to a factor of 2, from which we can estimate that WASP-12b’s orbit should be subject to tidal effects at a factor of $\sim 400$ larger than WASP-14b if it really had an eccentric orbit.

Our results, on the other hand, confirm the strong indications of C11 that all the available data for WASP-12b is compatible with a circular orbit, and that the eccentricity of the best-fitting orbit to the radial velocity of H09 and subsequently the occultation data of L10 may be due to correlated noise. Not accounting for this noise in the statistical analysis could lead to an apparent $\sim 3σ$ significance for the rejection of the null hypothesis ($e = 0$), but the new data strongly suggest that the orbit of WASP-12b is indeed circular.

C11 suggested that, for an eccentric orbit, the difference between the occultation phase in C11 and L10 could be due to apsidal precession. This would require that the argument of periastron had changed from $\omega = -74^{+13}_{-10}$ in 2008 February (H09) to $\omega = -90^\circ$ in 2008 October (C11). In terms of the projected component of the eccentricity, $e \cos \omega$, one obtains $e \cos \omega = 0.014 \pm 0.004$ in 2008 February using the H09 orbital parameters, C11 found $e \cos \omega = 0.0019 \pm 0.0007$ in 2008 October, L10 found $e \cos \omega = 0.0156 \pm 0.0035$ in 2009 February to October, and our result is $e \cos \omega = 0.0037 \pm 0.0035$ for 2009 January to 2010 March. When considered in the order that observations were made, these values do not support the hypothesis of apsidal precession.

A circular orbit for WASP-12b removes the need for models to explain the survival of such an eccentricity at this very short period, in face of what would have been extremely strong tidal effects. In particular, the scenario of Li et al. (2010), using the eccentricity from H09 to infer values of mass-loss and tidal dissipation for WASP-12b, loses its principal empirical support.

The eccentricity of WASP-14b, in contrast, is confirmed by our measurements. This illustrates the capacity of SOPHIE to measure accurate values of orbital eccentricity for transiting planets, given a sufficient number of measurements well distributed in phase and spread over different nights (the measurements for WASP-12 having most weight towards an eccentric solution were gathered during only two different nights).

4.1 Eccentricity distribution and tidal circularization for hot Jupiters

Fig. 6 shows a plot of the eccentricity of known transiting planets with $a < 0.1$ au against their semimajor axis $a$ (log scale). This has been studied before by others, for example see Jackson et al. (2008) for exoplanets and Mathieu & Mazeh (1988) for stellar binaries. There is a well-known trend for the inner planets to have circular orbits, due to tidal orbital decay. If the WASP-12 system follows a circular orbit, the WASP-14 system establishes a new lower limit for the point at which orbital eccentricity can survive tidal evolution for a sufficiently long time to be observed in a sample not selected by age. The fact that the eccentricity of WASP-14b is clearly non-zero, but also near the lower end of the eccentricity distribution for planets out of reach of tidal evolution (broadly distributed between 0 and 1) probably indicates that this object has already undergone some tidal evolution. As a result, WASP-14b is an interesting object to constrain the tidal evolution, intensity of tidal torque and relation between tides and size, for gas giant planets.

WASP-10 is a third known transiting planet closer than 0.04 au with a possible non-circular orbit. Christian et al. (2009) found an eccentricity of $e = 0.059^{+0.004}_{-0.004}$, which is at a similar level of significance as the H09 result for WASP-12. Recently, however, Maciejewski et al. (2010) revisited this system and concluded that it was important to take stellar activity into account when using the original radial velocity measurements to compute the orbital eccentricity. This led Maciejewski et al. (2010) to conclude the orbit of WASP-10 was probably circular.

The fact that WASP-12b has a large size ($R_p = 1.79 R_\text{J}$, for $a = 0.0229$ and $e \sim 0$) and WASP-14b a smaller but still markedly inflated size ($R_p = 1.28 R_\text{J}$, for $a = 0.037$ au and $e \sim 0.09$), provides a challenging test for theories attempting to account for the anomalous radii of some hot Jupiters.

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Figure 6. Plot of eccentricity $e$ against semimajor axis $a$ (log scale) for close-in transiting planets. Orbits with measured eccentricities are shown with a plus sign, and orbits with assumed zero eccentricities with a cross.

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