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LETTER TO THE EDITOR

WASP-33: the first δ Scuti exoplanet host star[⋆]

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ABSTRACT

We report the discovery of photometric oscillations in the host star of the exoplanet WASP-33 b (HD 15082). The data were obtained in the R band in both transit and out-of-transit phases from the 0.3-m telescope and the Montcabrer Observatory and the 0.8-m telescope at the Montsec Astronomical Observatory. Proper fitting and subsequent removal of the transit signal reveals stellar photometric variations with a semi-amplitude of about 1 mmag. The detailed analysis of the periodogram yields a structure of significant signals around a frequency of 21 cyc d^{-1}, which is typical of δ Scuti-type variable stars. An accurate study of the power spectrum reveals a possible commensurability with the planet orbital motion with a factor of 26, but this remains to be confirmed with additional time-series data that will permit the identification of the significant frequencies. These findings make WASP-33 the first transiting exoplanet host star with δ Sct variability and a very interesting candidate to search for star-planet interactions.

Key words. stars: variables: δ Scuti – stars: oscillations – techniques: photometric – asteroseimology

1. Introduction

Over 100 transiting exoplanets have been confirmed to date, most of them orbiting solar-type or late-type stars. WASP-33 b, a gas giant planet showing transits on a fast-rotating main-sequence A5 star, represents an uncommon case that offers the possibility of studying an intermediate-mass main-sequence star. WASP-33 b was first reported as a transiting planet candidate by Christian et al. (2006), but it was not officially announced as an exoplanet until the study of Collier Cameron et al. (2010). The relatively long time lapse may be explained because the host star (HD 15082, $V = 8.3$) is a fast rotator ($v \sin i = 86$ kms^{-1}) and this hampers precise radial velocity work. Collier Cameron et al. (2010) carried out a detailed study considering both photometry and spectral line profile variations during transits and established an upper mass limit of 4.1 M_J for the planet. In addition, the authors presented evidence of non-radial pulsations in the star and suggested γ Dor-type variability. Furthermore, they also found that WASP-33 b orbits the star in retrograde motion and that the orbit is inclined relative to the stellar equator.

Here we use observations taken at the amateur Montcabrer Observatory and the professional fully robotic Montsec Astronomical Observatory – OAdM (Colomé et al. 2008), as well as additional observations from the Exoplanet Transit Database (hereafter ETD, `http://var2.astro.cz/ETD`). These allow us to provide the first evidence for photometric oscillations on the star WASP-33, and to analyse their amplitude and periodicity. The presence of a large planet close to a star may cause tidal effects that are responsible for multi-periodic non-radial pulsations, and in special cases radial pulsations, on its host star (Schuh 2010). However, there are only a few known exoplanets orbiting pulsating stars, such as V391 Pegasi (sdB type), whose planet was discovered using the timing method (Silvotti et al. 2007). Bazot et al. (2005) performed the first asteroseismic analysis for a solar-like planet host star, μ Arae, modelling 43 p-modes which were previously identified by Bouchy et al. (2005). Recently, Kepler data were used to characterize the exoplanet host HAT-P-7 through an analysis of its simultaneously discovered solar-like oscillations (Christensen-Dalsgaard et al. 2010). WASP-33 is the first case where δ Sct pulsations have been observed in a known transiting exoplanet host star.

2. Observations and photometry

The first observations in our dataset were obtained from Montcabrer Observatory on 2010 August 26, September 7 and 14 and October 20, using a 0.3-m Schmidt-Cassegrain telescope and a SBIG ST8-XME camera with an AO-8 adaptive optics system, working at a 1.03″ per pixel scale. This is an amateur private observatory with the Minor Planet Center code 213, which is located in the suburbs of Barcelona, Spain. Photometry on two additional nights with very good photometric conditions (September 21 and 28, 2010) was obtained from OAdM and with a fully robotic 80-cm Ritchey-Chrétien telescope and a FLI PL4240 2k × 2k camera with a plate scale of 0.36″ per pixel. All photometry described above was carried out in the Johnson R band and by defocusing the images to increase the photometric precision. Aperture photometry was performed on the images, using three or four comparison stars, as available. The first transit was observed with the aim of improving the definition of the existing light curves, most of them incomplete so far (Collier Cameron et al. 2010), whereas the follow-up photometry was obtained at several orbital phases in order to further study the oscillations that the first photometric dataset seemed to suggest.

Additional recent transit photometry of WASP-33 is available at the ETD, including some diagrams and a parameter

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[⋆] Photometric data is only available in electronic form at CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/526/L10`

Table 1. Photometric datasets used in this work.

Author/ observatory	Date	Transit/ out of tr.	rms (mmag)	TTD (min)
Hose	23/08/2010	T	3.7	4.10 ± 1.31
Montcabrer	26/08/2010a	T	2.8	9.76 ± 1.01
Hormuth	26/08/2010b	T	2.7	3.18 ± 0.86
Montcabrer	07/09/2010	OOT	3.1	
Lopresti	11/09/2010	T	3.9	−1.66 ± 1.62
Montcabrer	14/09/2010	OOT	2.3	
OAdM	21/09/2010	OOT	1.6	
OAdM	28/09/2010	T	2.1	2.83 ± 0.50
Montcabrer	20/10/2010	T	1.8	7.55 ± 0.86

Notes. Montcabrer Observatory and OAdM data were specially acquired during the course of this work. The rest of the photometry is public at the ETD. In transit observations, the photometric root mean square (rms) residual per measurement and the transit time deviation (TTD) with respect to the mid-transit ephemeris given in Collier Cameron et al. (2010) are calculated from the fits represented in Fig. 2.

analysis of each transit. WASP-33 b transit R-band photometric data from Hose (August 23, 2010), Hormuth (August 26, 2010) and Lopresti (September 11, 2010) were used in our analysis. All photometry datasets used in this study are listed in Table 1. The root mean square (rms) residuals given in the third column, even thoughthey are affected by the pulsations, give an idea of the precision of the photometry from each observatory.

3. Data analysis and discussion

The transit photometry datasets were analysed with the JKTEBOP code (Southworth et al. 2004a,b), which is based on the EBOP code written by Paul B. Etzel (Popper & Etzel 1981). Each transit light curve was corrected for a slight trend using low-order polynomials. Preliminary fits were run with the JKTEBOP by solving for the sum of the radii relative to the orbital semi-major axis (star + planet; $r_1 + r_2$), ratio of radii (r_2/r_1), inclination, and time of transit. This was done before combining all transits by including a shift to normalize their out-of-transit level, so that consistent parameters were obtained for all the transits. The period was fixed to that given in Collier Cameron et al. (2010), $P_{\rm orb} = 1.2198669$ d. To properly weigh the observations from different authors, we performed a running average of the residuals from a preliminary fit in bins of 20 minutes, selecting as individual error for each point the standard deviation of its bin. The best fit to the overall transit photometry is shown in Fig. 1 and the associated parameters are given in Table 2. All parameters are consistent within the uncertainties with those in Collier Cameron et al. (2010). A pulsation trend is clearly present on the residuals of this fit, and as Fig. 2 illustrates, it is already apparent to the eye that all the curves (some of them separated by almost 60 d) show "bumps" that always appear at the similar orbital phases (note, e.g., the phases just after the egress).

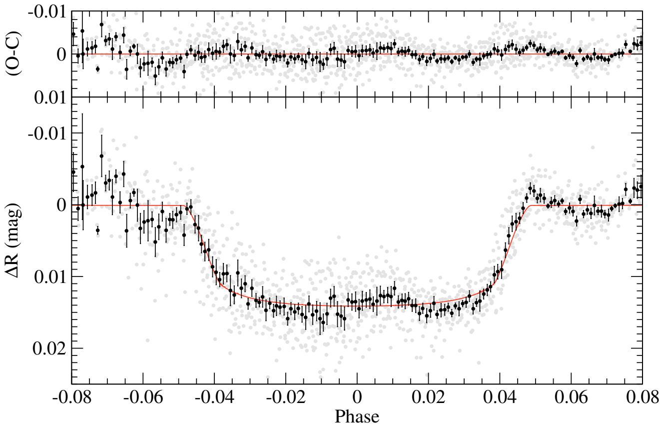

Fig. 1. Best fit to the overall R-band transit photometry phase-folded (grey symbols) and binned in steps of 0.001 in phase (black symbols) for better visualization. The top panel shows the residuals of this fit. Error bars are computed as the mean value error of each bin.

Table 2. Transit parameters fitted using JKTEBOP.

Parameter	Value
$r_1 + r_2$	0.309 ± 0.007
r_2/r_1	0.1066 ± 0.0008
i (°)	85.8 ± 2.0
T_0 − 2450000	5431.8879 ± 0.0003
rms (mmag)	3.44
Depth (mmag)	14.3 ± 0.2

Notes. The transit depth was computed from the fit. The error bars are 1-σ uncertainties.

To better determine the characteristic period of the observed pulsations, we carried out individual fits to each transit by leaving the inclination and transit time as free parameters and fixing the relative radii of the star and the planet according to the global result. This was done to minimize the possible effects of transit time variations caused by unknown third bodies in the system on the residuals and the effect of trend corrections on the transit depth. We find that the inclination of each individual fit is well within the uncertainty of that determined for the combination of the transits. In Table 1 the transit time deviations of each transit are also listed, however, their scarcity and possible systematics caused by the pulsation precludes us of drawing any conclusions about the presence of additional planets in the system.

As already shown, the residuals of the transit fits show a clear oscillation pattern that is also present in the out-of-transit photometry obtained for WASP-33. The presence of oscillations during the entire orbital period, including out-of-transit phases as shown in Fig. 3, rules out the possibility of the "bumps" seen in transit as being caused by the effect of the gravity darkening in a rapidly rotating star such as WASP-33 (Barnes 2009). Thus, we combined the residuals from the transit fits and the out-of-transit light curves in a single curve to better determine the period of the oscillations. Figure 4 shows the results of running a periodogram on these data with the PERIOD04 code (Lenz & Breger 2005, `http://www.univie.ac.at/tops/period04/`) that is based on the discrete Fourier transform algorithm. A main peak around a frequency of 21 d^{-1} is clearly present in this figure, corresponding to a period of about 68 min. However, a close inspection of this peak reveals that it is composed of several other peaks that are an imprint of the window function associated to our data. The second structure around 6 d^{-1}, which is similar to the typical length of the individual photometric series, is probably spurious and may be related to the detrending and the flux-shift of the different light curves.

To better analyse the structure of this peak, we fitted the theoretical transit light curve to the original data by adding a sinusoidal modulation of the light of the system, thus performing a phase dispersion minimization algorithm (Stellingwerf 1978). The minimization of this parametric fit was performed by means of a Levenberg-Marquardt algorithm (Press et al. 1992). Because of the degeneracy on the solutions, we fitted the amplitude of the modulation and tested a grid of frequency and phase difference values. A key element to consider is the weighing of each data point. At the high precision of our photometry, photon

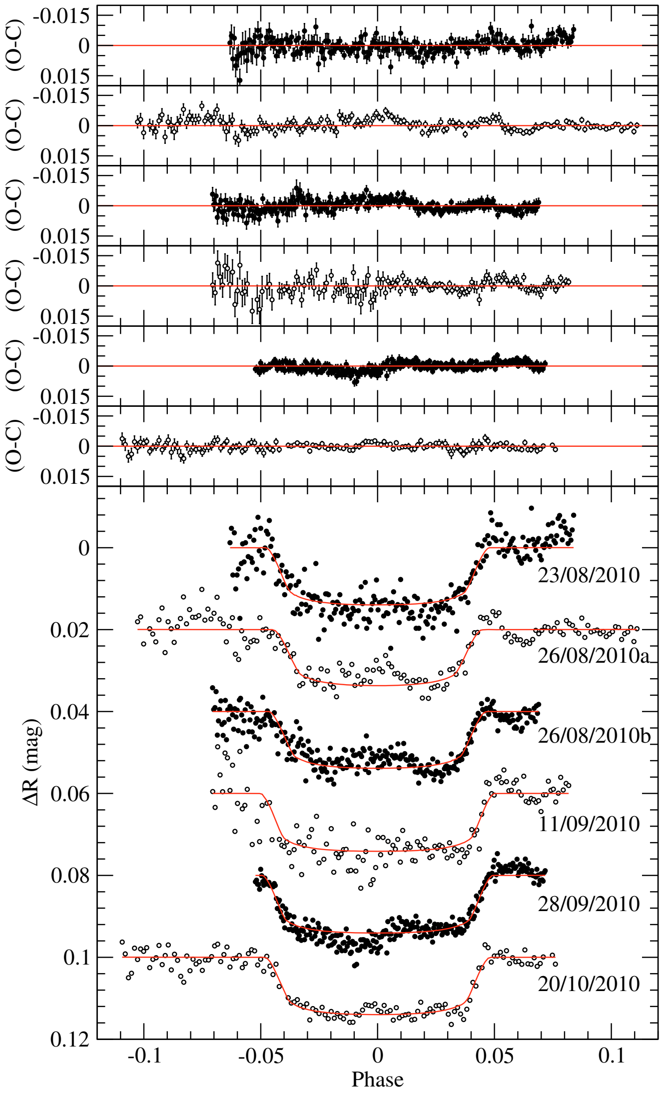

Fig. 2. *R*-band transit photometry of WASP-33. The solid line is the best fit to each curve with the relative radii of the star and the planet fixed to those found in the global fit using the JKTEBOP code. The residuals are shown in the upper panels in the same order as transits are displayed. See Table 1 for reference.

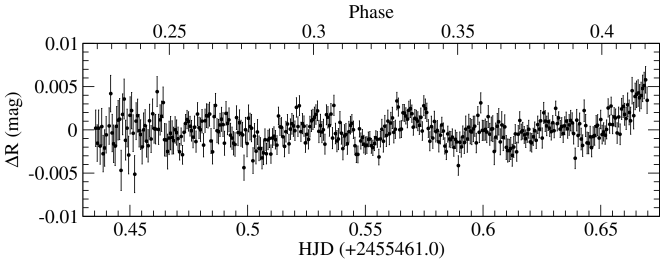

Fig. 3. Out-of-transit photometry of WASP-33 obtained from OAdM on 21 September, 2010.

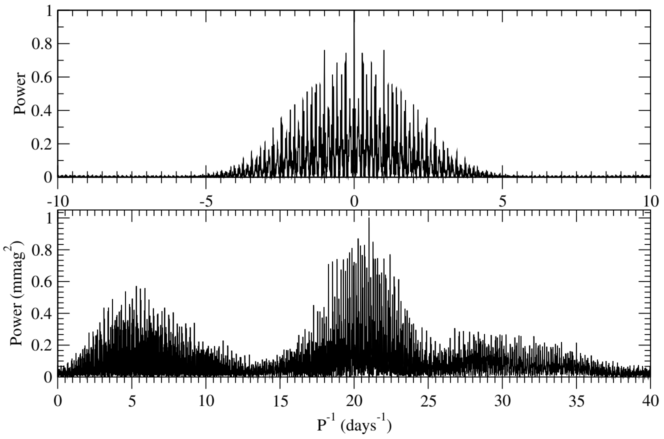

Fig. 4. Periodogram of the transit residuals and out-of-eclipse phases of WASP-33 using PERIOD04 code. Top panel displays the window function.

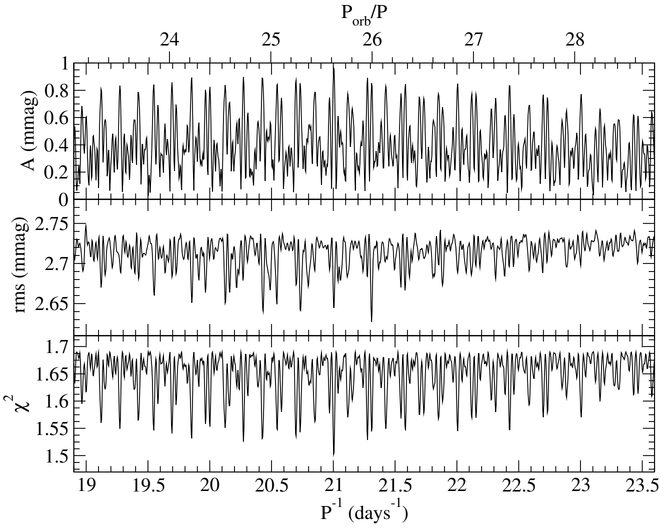

Fig. 5. Results from the Levenberg-Marquardt algorithm method displaying the structure of the main periodogram peak. Both amplitude and χ^2 give best fits for 21.00 d^{-1}, while the rms is minimized for a pulsation of frequency 21.31 d^{-1}, which is commensurable with the planet's orbital period.

noise is not a good measure of the uncertainty of the measurement because systematic effects in the form of correlated noise dominate (e.g., Pont et al. 2006). Therefore, we applied a two-step process in which we performed the analysis assuming an initial constant arbitrary value of the standard deviation $\sigma = 1$ for each data point. The best-fitting solution was then used to calculate a new value for σ as the local value of the rms residual (computed as the running average of the residuals in bins of 20 minutes), and a final fit was run with weights set accordingly. As can be seen in Fig. 5, the lowest χ^2 is found for a pulsation with a semi-amplitude of 0.98 ± 0.05 mmag and a frequency of 21.004 ± 0.004 d^{-1} at a phase difference with the mid-transit time of 264 ± 12° (at reference epoch from Table 2). This corresponds to a period of $P = 68.56 \pm 0.02$ min. Figure 6 shows the overall residuals and the out-of-eclipse photometry phase-folded according to this best-fitting period. As a result of the separation between observing nights, the main feature in Fig. 5 is composed of many equidistant peaks with similar χ^2. Interestingly, the periodogram peak with lower resulting rms differs from the one above as it occurs for a pulsation of about 0.86 mmag in semi-amplitude with frequency of 21.311 ± 0.004 d^{-1} corresponding to a pulsation period of 67.57 ± 0.02 min. This illustrates the relatively strong impact of the weighing scheme because the signal is weak and our time series is relatively short. The latter frequency is especially interesting as is happens to be commensurable with the planet's orbital motion with a factor of 25.997 ± 0.005.

Line-profile tomography in Collier Cameron et al. (2010) provided strong evidence for non-radial pulsations in WASP-33

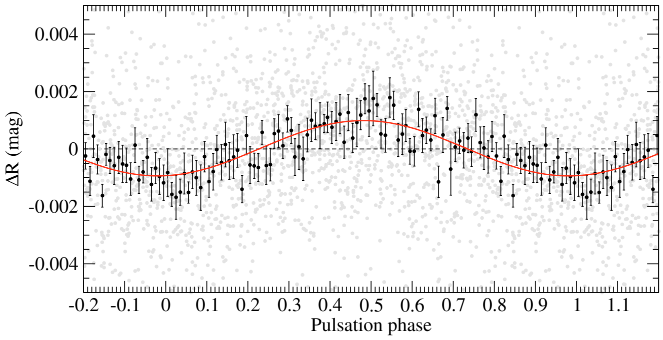

Fig. 6. Residuals of the transit fits and out-of-eclipse photometry of WASP-33 phase-folded according to the period of the pulsation found in this work, i.e., 68.56 ± 0.02 min, (grey symbols) and 0.01 phase binning (black symbols). The solid curve is the best fit sinusoidal modulation with an amplitude of 0.98 mmag.

with a period around one day, similar to those usually found in γ Dor stars. Moreover, the authors point out the possibility that the retrograde orbiting planet could be tidally inducing them. Both the period of the photometric oscillations presented here and the stellar properties from Collier Cameron et al. (2010) ($T_{\rm eff}$ = 7400 ± 200 K, $\log g$ = 4.3 ± 0.2) locate WASP-33 well within the δ Sct instability strip. Handler & Shobbrook (2002) present a discussion on the different properties of δ Sct and γ Dor pulsators. Using the formalism there it can be shown that the pulsation constant of WASP-33 ($\log Q_{\rm WASP-33} = -1.45$) perfectly corresponds to the δ Sct domain. The power spectrum of δ Sct pulsators is usually very rich, as illustrated by the 75+ frequencies identified for FG Vir (Breger et al. 2005), but asteroseismic modelling is especially difficult for fast rotators as WASP-33. Given this evidence, a different scenario considering that WASP-33 belongs to the relatively rare class of hybrid pulsators, showing simultaneous δ Sct and γ Dor oscillations (Handler et al. 2002; Handler 2009), may be possible.

One scenario that should be explored in spite of all the evidence is the possibility that the photometric variations are ellipsoidal in nature and are not caused by pulsations. Indeed, the tidal bulge travels particularly fast over the stellar surface, because the orbital motion of the planet is retrograde with respect to the stellar rotation. Note that there is an indeterminacy in the stellar rotation velocity because it is not a given assumption that the inclination of the stellar spin axis corresponds to the planet's orbital inclination. But a simple calculation, equalling the pulsation frequency found here to that of the relative orbital motion of WASP-33 b above the star surface, renders the ellipsoidal variation scenario as physically not valid since the star would have to rotate at a largely super-critical speed in terms of gravitational break-up. It is more likely that the tidal bulge rotates over the stellar surface with a frequency of about 2 d^{-1}, which is the net combination of the orbital and rotation frequencies, and is far from the frequencies we find relevant in the periodogram.

As seen above, the periodogram is still not defined sufficiently well to assess the true pulsation spectrum of WASP-33. However, given the potential interest, we find it appropriate to briefly address here the possibility of the coupling between the pulsation and the orbit. If the pulsation frequency of 21.311 ± 0.004 d^{-1} turned out to be real, this could suggest the existence of some kind of star-planet interactions that lead to a high-order commensurability of 26 between the pulsation and orbital periods. Very few cases are known to date of a δ Sct variable belonging to a close binary system (Willems & Claret 2005). The best described candidate for tidally-induced oscillations is HD 209295, which simultaneously presents γ Dor and δ Sct-type pulsations, and which was photometrically found to show several p-modes directly related to the orbital motion of its companion (Handler et al. 2002). This poses the tantalizing possibility of a similar situation occurring in WASP-33, which will certainly be much clearer when additional photometry is acquired and puts constraints on the δ Sct frequency spectrum.

4. Conclusions

High-precision R-band photometry has allowed us to present the discovery of photometric oscillations in WASP-33, thus becoming the first transiting planet host with δ Sct pulsations. These oscillations have a period of about 68 minutes and a semi-amplitude of 1 mmag. The frequency spectrum of WASP-33 is still not well defined because the size and significance of the peaks depends on the scheme used to weigh the data. In a particular weighing criterion, the most significant period comes out to be commensurable with the orbital period at a factor of 26. If this association is assumed to be physically relevant, the multiplicity hints at the existence of planet-star interactions. In any case, gaining insight into the nature of WASP-33 will necessarily require the collection of additional data (possibly multi-colour) with longer time baseline and to carry out pulsation and dynamical modelling. The WASP-33 system now represents a new benchmark in the world of exoplanets that can provide valuable information on stellar pulsations (through, e.g., transit surface mapping), on the tidal interactions between planets and stars, and on the dynamical evolution of planetary systems.

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