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LETTER TO THE EDITOR

WASP-33: The first δ Scuti exoplanet host star and evidence of star-planet interactions

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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 both in transit and out-of-transit phases from the Montcabrer (0.3-m telescope) and Montsec (0.8-m telescope) observatories. Proper fitting and subsequent removal of the transit signal reveals stellar photometric variations with an amplitude of about 1 mmag and a period of 67.57 ± 0.08 min, which is typical of δ Scuti-type variable stars. Furthermore, the oscillation period is commensurable with the orbital period of the planet with a factor of 26. These findings make WASP-33 the first transiting exoplanet host star with pulsation variability and possibly experiencing tidally induced planet-star interactions. Several possible explanations for the existence of the observed high-order ressonance such as perturbations due to an eccentric orbit, rotational distortion of the star or tidal locking during planet migration are proposed.

Key words. Stars: variables: delta Scuti - Stars: oscillations (including pulsations) - Techniques: photometric

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 a singular case that offers the possibility of studying an intermediate-mass planet host. 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 showed evidence of non-radial pulsations in the star and suggested γ Dor-type variability. Futhermore, they also found that WASP-33 b orbits the star in retrograde motion and that the orbit is inclined relative to the stellar equator.

In recent times, modern low-cost CCDs capable of high-precision photometry are becoming increasingly common among amateur astronomers and this is resulting in large databases of exoplanet transit and variable star photometry. The availability of amateur observatories represents a great advantadge for works that do not require large telescopes. Moreover, the quality of the photometric time series observations may sometimes be enough to unravel interesting phenomena for exoplanet or asteroseismology studies. Additionally, professional robotic observatories are showing their potential at acquiring large amunts of time-series data and thus permitting studies of time-domain astrophysics.

Here we use observations taken at the amateur-run Montcabrer Observatory and the professional robotic Montsec Astronomical Observatory (Colomé et al. 2010a,b), 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 analize their amplitude and periodicity. The presence of a large planet close to a star may cause tidal effects responsible of multiperiodic non-radial pulsations, and in special cases radial pulsations, on its host star (Schuh 2010). However, there is only one known exoplanet orbiting a pulsating star, V391 Pegasi (sdB type), which 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, showing 43 p-modes. 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 non solar-like photometric pulsations have been observed on a known transiting exoplanet host star.

2. Observations and photometry

The first observations in our dataset were obtained from Montcabrer Observatory on UT dates September 2, 7 & 14, 2010, 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 having Minor Planet Center code 213 located in the suburbs of Barcelona, Spain. Photometry in two additional nights with very good photometric conditions (September 21 & 28, 2010) was obtained from Montsec Astronomical Observatory using a robotic 80-cm Ritchey-Chretien telescope and a FLI PL4240 2k×2k camera with a plate scale of 0.36″per pixel. All the photometry described above was carried out in the Johnson *R* band and by defocussing the images to increase the photo-

Table 1. Photometric datasets used in this work. Montcabrer Observatory and Montsec Astronomical Observatory 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 rms per measurement and the transit timing residual with respect to the mid-transit ephemeris (see text) are calculated from the fits represented in Figure 2.

Author/ Observatory	Date	Transit / Out of tr.	RMS (mmag)	O-C (min)
K. Hose	23 Aug	T	3.6	4.37 ± 0.75
Montcab. Obs.	26 Aug(a)	T	2.9	9.14 ± 1.22
F. Hormuth	26 Aug(b)	T	3.0	3.09 ± 0.97
Montcab. Obs.	7 Sept	OOT	3.6	
C. Lopresti	11 Sept	T	3.8	−4.97 ± 2.62
Montcab. Obs.	14 Sept	OOT	2.6	
Montsec Obs.	21 Sept	OOT	1.7	
Montsec Obs.	28 Sept	T	1.9	2.60 ± 0.54

metric precision. Aperture photometry was performed to 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 analysis of each transit. WASP-33 b transit *R*-band photometric data from K. Hose (September 1, 2010), F. Hormuth (September 2, 2010) and C. Lopresti (September 13, 2010) were used in our analysis. All the photometry datasets used in this study are listed in Table 1.

3. Data analysis and discussion

The transit photometry datasets were analysed using 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 and preliminary fits were run using JKTEBOP by solving for the sum of the relative radii (star + planet), ratio of radii, inclination, and time of transit. The effect of gravity darkening has also to be taken into account for transiting systems since it may alter the light curves in the case of rapidly rotating stars (Barnes 2009). Nevertheless, this only affects the bottom part of the transit curve and would only attain mmag-scale effects in the case of a planet with an almost polar orbit. Figure 1 illustrates the combination of all the analyzed transits with a binned representation at steps of 0.001 phase while Figure 2 shows all the transit light curves with their corresponding fits. It is already apparent to the eye that all the curves (some of them separated by 30 days) show obvious “bumps” and that such bumps always appear at the same orbital phases (note, e.g., the phases just after the egress), thus suggesting the existence of photometric pulsations and that these seem to be somehow associated to the planet’s orbital period.

To determine the characteristic period of these pulsations, the transits were combined in a single phase-folded transit by shifting their magnitudes according to the out-of-transit level of the preliminary model fits. To calculate the orbital phases we employed the ephemeris given by Collier Cameron et al. (2010): $T = 2454163.22373 + 1.2198669E$ (HJD). The best fit to the overall transit photometry is shown in Fig. 1 and the associated parameters are given in Table 2. We decided, however, to carry 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 due to unknown third bodies in the system on the residuals and the effect of trend corrections on the transit depth. Nevertheless, it was reassuring to find that the inclination of each individual fit is well within the uncertainty of that determined for the combination of the transits.

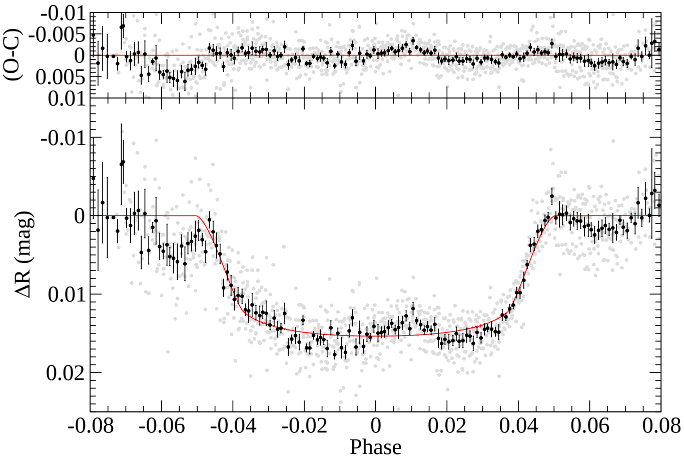

Fig. 1. Best fit to the overall *R*-band transit photometry phase-pholded (grey symbols) and binned in steps of 0.001 in phase (black symbols). The top panel shows the residuals of this fit.

Table 2. Transit parameters fitted using JKTEBOP.

Parameters	Value
$r_1 + r_2$	0.303 ± 0.010
r_2/r_1	0.1063 ± 0.0012
i (°)	81.5 ± 1.3
$T_0 - 2450000$	5431.88725 ± 0.00021
Depth (mmag)^a	15.7 ± 0.3
RMS (mmag)	3.34

^{a}Computed from the fit.

The residuals of the transit fits show a clear oscillation pattern that is also present on the out-of-transit photometry of WASP-33. We combined the residuals from transit fits and the out-of-transit light curves in the single light curve shown in Fig. 3 to better determine the period of the oscillations. A Lomb-Scargle periodogram (Scargle 1982) was subsequently performed on these data. The results are shown in Fig. 4.

Two main periodicities are found for frequencies of 21.31 days^{-1} and 6.73 days^{-1}, corresponding to periods of roughly 1.1 hours and 3.6 hours. The later is similar to the length of each observed light curve and thus its significance can be spurious. The highest peak of the periodogram corresponds to a main pulsation period of 67.57 ± 0.08 minutes. Figure 5 shows the the overall residuals and out-of-eclipse photometry phase-folded according to this period. The best sinusoidal fit to this data reveals a modulation with an amplitude of 0.9 mmag. Interestingly, the ratio of the pulsation period to the orbital period of the planet WASP-33 b is 26.00 ± 0.03. This surprising commensurability, albeit of very high order, seems to provide evidence for star-planet interactions. Some form of tidal resso-

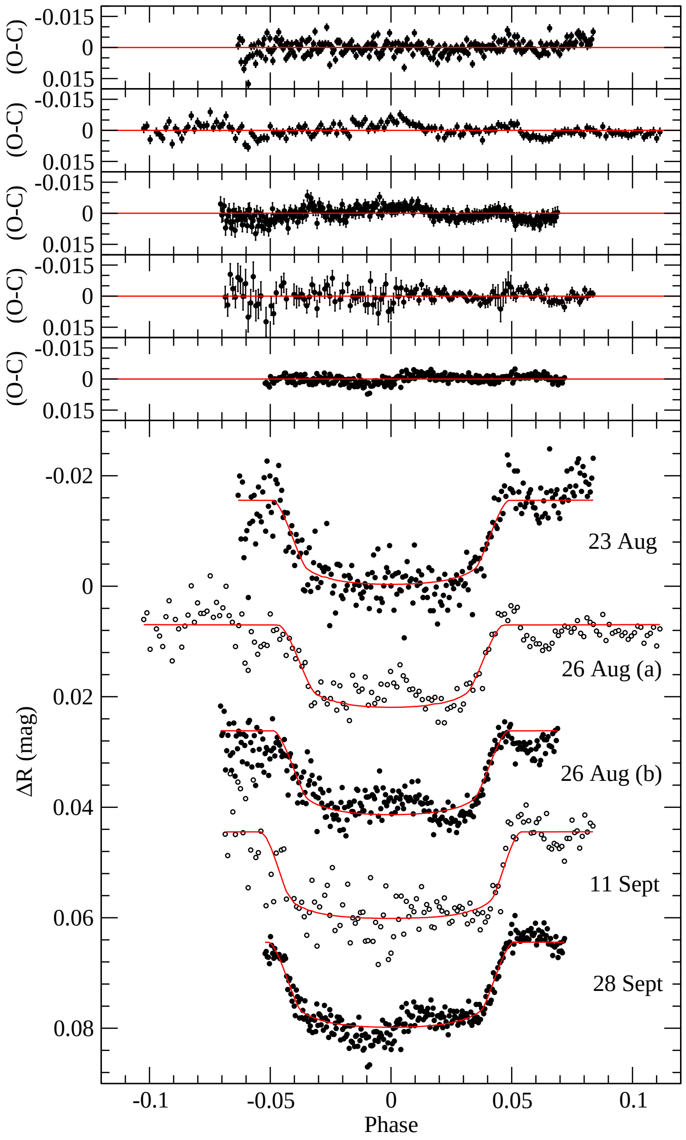

Fig. 2. *R*-band transit photometry of WASP-33. The solid line is the best simultaneous fit to all the transits using the JKTEBOP code. The residuals are shown in the upper panels in the same order as transits are displayed. See Table 1 for reference.

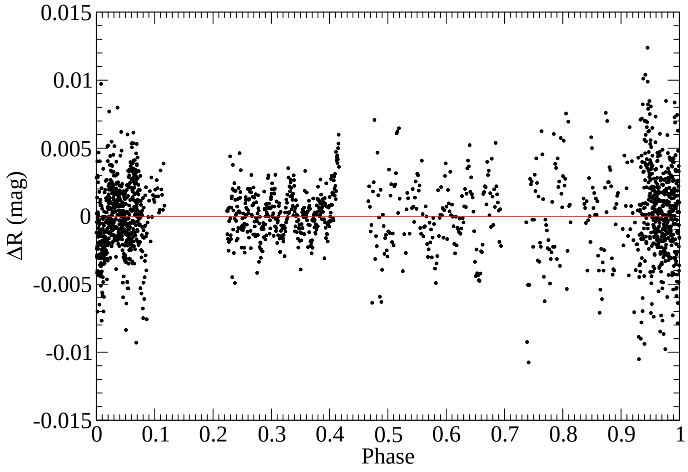

Fig. 3. *R*-band photometric light curve of WASP-33 composed of the residuals of the transit fits and the out-of-transit observations and phase-folded according to the orbital period of the planet.

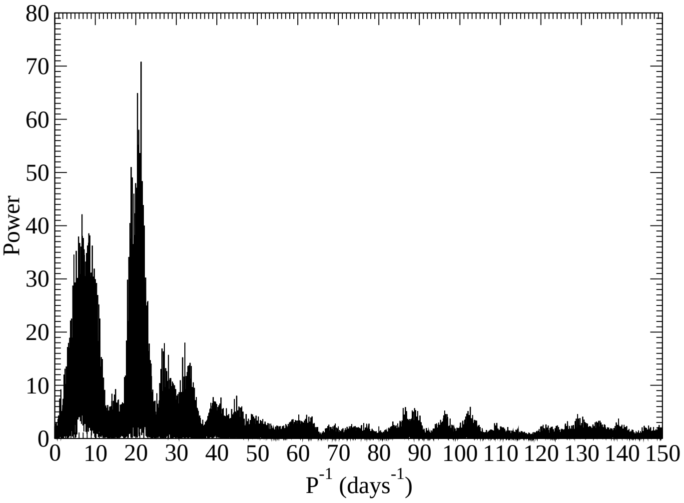

Fig. 4. Lomb-Scargle periodogram of the transit residuals and out-of-eclipse phases of WASP-33.

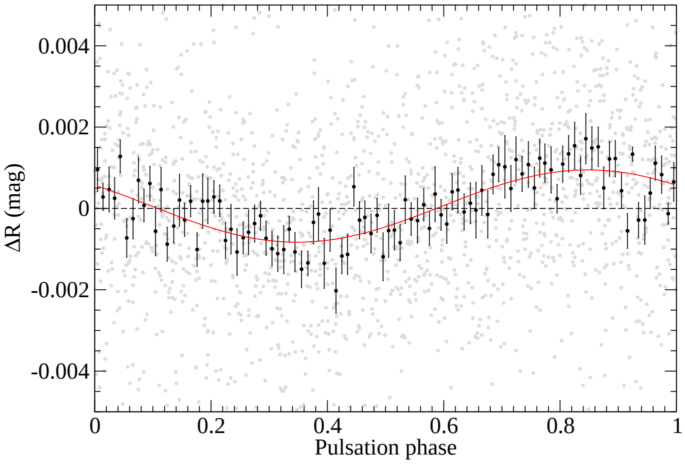

Fig. 5. Residuals and out-of-eclipse photometry of WASP-33 phase-folded according to the period of the pulsation found in this work, i.e., 67.57±0.08 min, (grey symbols) and 0.01 phase binning (black symbols). The solid curve is the best fit sinusoidal modulation with an amplitude of 0.9 mmag.

nance may be at play in this system. The best described case for tidally-induced ocillations 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).

Line-profile tomography in Collier Cameron et al. (2010) provided strong evidence for non-radial pulsations in WASP-33 as usually found in γ Dor stars, which have periods typically around one day. Also, the authors question the possibility that the retrograde orbiting planet could be tidally inducing them. However, 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, as so does its pulsation period of a little over an hour. 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 pusaltion 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 is the case of WASP-33.

One initial consideration that must be made in spite of all the (massive) evidence is the possibility of the photometric variations being ellipsoidal in nature and not caused by pulsations. Indeed, the tidal bulge travels specially fast over the stellar surface as 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 granted to assume that the inclination of the stellar spin axis corresponds to the planet's orbital inclination. But a simple calculation 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 at about 2 days^{-1}, which is the net combination of the orbital and rotation frequencies, and far from the frequencies we find relevant in the periodogram.

The δ Sct-type nature of the pulsations and the consequent evidence for star-planet interactions seems well established given all the indications. No straightforward explanation can be immediately put forward to give account of the high-orbital resonance between the planet's orbit and the pulsation but we have considered a few speculative and qualitative ideas. A first scenario that must be considered is the possibility that the stellar radial pulsations are tidally induced, or at least influenced, by the presence of the planet. Indeed, the planet can be relatively massive ($\sim$4 M_J) and it orbits the star at a very close distance (a = 0.026 AU). Willems & Aerts (2002) suggested that close binary companions could excite stellar pulsation modes by resonant tidal forcing, but the authors mainly consider non-radial pulsations. A possible excentric orbit for the close companion could cause ressonant tidal forces on the primary star that select certain p-modes with frequencies commensurable to the companion's orbital period. Unfortunately, the orbital parameters of WASP-33 b are still poorly defined because of the absence of a radial velocity curve and the lack (so far) of secondary eclipse observations that could provide constraints on the eccentricity. An alternative explanation compatible with the previous one is the fact that the star is not rotating synchronously with the orbit and thus the tidal bulge travels over the stellar surface potentially giving raise to radial displacements. Further, the planet follows an inclined orbit with respect to the stellar spin axis. Both effects can lead to the shape of the star deviating notably from sphericity (Iorio 2010) and thus potentially extice certain pulsation modes or block others. A third possible scenario is that the orbital period of the planet has been locked at a high-order ressonance with an inherent and already excited stellar pulsation period during its migration inwards.

4. Conclusions

High-precision R-band photometry has allowed us to present the discovery of photometric oscillations in WASP-33, thus becoming the first planet host with δ Sct pulsations. Further, the (high-order) commensurability with the orbital period yields strong evidence for the existence of planet-star interactions. The explanation for the observed period multiplicity remains elusive, but this is a rather peculiar system in which the orbital motion of the planet is retrograde and inclined relative to the stellar equator. The stellar oblateness and unknown planet orbital eccentricity could play an important role in producing tidally-induced forces that select or block certain p-mode pulsations from the δ Sct host star. Or perhaps tidal locking has worked in the opposite way and the planet has become stuck in a high-order ressonance mode during orbital migration. In any case, gaining insight to rule out or confirm any of the presented scenarios (or further ones) will necessarily require the collection of additional data (possibly multi-color) 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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