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Stellar activity of planetary host star HD 189733

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Abstract. Exoplanet search programs need to study how to disentangle radial-velocity (RV) variations due to Doppler motion and the noise induced by stellar activity. We monitored the active K2V HD 189733 with the high-resolution SOPHIE spectrograph (OHP, France). We refined the orbital parameters of HD 189733b and put limitations on the eccentricity and on a long-term velocity gradient. We subtracted the orbital motion of the planet and compared the variability of activity spectroscopic indices (HeI, Hα, Ca II H&K lines) to the evolution of the RV residuals and the shape of spectral lines. All are in agreement with an active stellar surface in rotation. We used such correlations to correct for the RV jitter due to stellar activity. This results in achieving a high precision on the orbital parameters, with a semi-amplitude: $K = 200.56 \pm 0.88\ m \cdot s^{-1}$ and a derived planet mass of $M_P = 1.13 \pm 0.03\ M_{Jup}$.

1. Introduction

The precision of RV searches for exoplanets is dependent on the noise induced by stellar photospheric luminosity variations due to active regions. Until now, most of the active stars are rejected from major RV surveys. In addition, planets around active stars found by new research instruments like CoRoT need RV follow-up. Monitoring activity on active planet host stars opens a way to disentangle radial-velocity variations due to Doppler motion from the noise induced by stellar activity.

HD 189733 (Bouchy *et al.* 2005) is one of the brightest transiting systems (V = 7.7) and thus its parameters are well constrained, thanks to detailed spectroscopic and photometric monitoring programs (e.g. Bakos *et al.* 2006b; Pont *et al.* 2007).

HD 189733 is a chromospherically active star. This dwarf star is classified as a variable type BY Dra, i.e. K stars with a short-term photometric variability but no long-period variations (spots evolve quickly). Moutou *et al.* (2007) have completed spectropolarimetric measurements of the star. They found that the chromospheric activity measured in Ca II H&K lines and Zeeman signatures is consistent with a magnetic field present at the surface of the star modulated with the rotation cycle.

Here, we monitor the activity using all the parameters available to searches for exoplanetary systems from high-precision spectroscopic measurements: RV, bisector of the lines and activity indices measured in HeI, Hα and Ca II H&K lines.

2. Measurements of the HD 189733 planetary system

2.1. *Observation and data reduction*

55 exposures were obtained with the high-resolution SOPHIE spectrograph (Bouchy *et al.* 2006) mounted on the 1.93-m telescope at the Observatoire de Haute-Provence, France between 12 July 2007 and 23 August 2007. We have gathered about two exposures per night in order to correctly sample the short orbital period ($\simeq 2.2$ d). Observations were conducted in the high-resolution mode ($R \sim 75'000$). The simultaneous Thorium-Argon (ThAr) lamp was used in order to have a better precision on RV measurements. The typical exposure time was 6 minutes, long enough to reach an average signal-to-noise ratio per pixel of about 80 at $\lambda = 5500$ Å. RVs were determined using a weighted cross-correlation method with a numerical G2 mask implemented in the automated reduction package provided for SOPHIE. Our average error is around 3.5 m$\cdot$s^{-1}; it is a quadratic sum of the photon-noise error, the uncertainty on the wavelength calibration and an estimation of the SOPHIE current systematics.

2.2. *Determination of system parameters*

We fixed the well-constrained orbital period $P = 2.2185733$ days and time at periastron $T_0 = 2453988.24876$ [BJD] (Winn *et al.* 2007). SOPHIE RV measurements are then best fitted with a Keplerian function with a semi-amplitude of K=200.6 $\pm$ 2.3 m$\cdot$s^{-1}, a mean radial velocity γ=-2.277 km$\cdot$s^{-1} and an eccentricity compatible with zero, in agreement with previous results (Bouchy *et al.* 2005; Winn *et al.* 2006).

We tested the detectability of an eccentricity for the orbit of HD 189733b. We used all the RVs measurements published (Bouchy *et al.* 2005; Winn *et al.* 2006) and ours, without those taken during the transit. We fit the data with a long term velocity gradient taking into account that HD 189733 has an M-dwarf stellar companion (Bakos *et al.* 2006a). The trend found between the three datasets does not require a long-period planetary companion to be explained and is not significant within the limit on eccentricity. Letting e and ω as free parameters, we do not detect a significant eccentricity larger than 0.008, in agreement with the values of Winn *et al.* (2007) and Knutson *et al.* (2007).

2.3. *Residuals (O-C) and bisectors analysis*

The large observed minus calculated (O-C) residuals around the solution are explained by activity-induced "jitter" of the star. Our dispersion value, 9.1 m$\cdot$s^{-1}, is smaller than the 12 m$\cdot$s^{-1} measured by Winn *et al.* (2006) and the 15 m.s^{-1} found in Bouchy *et al.* (2005). This larger (O-C) might be due to the lowest accuracy of the ELODIE spectrograph and to the amplitude of the activity jitter decreasing with time.

The cross-correlation function (CCF), calculated when measuring the RVs of the star, corresponds to an average of all the spectral lines. We analyse the bisector velocity span (Vspan), a measurement of the shape of the CCF as defined in Queloz *et al.* (2001). On Fig. 1, both the residual RV jitter and Vspan seem to present periodic variations close to the rotation period of the star, 12 days. Active regions on the stellar surface, such as dark spots or bright plages, induce an asymetry in the emitted light of the star changing periodically as they move in and out of view with stellar rotation. This then induces an asymetry in the line profile that can be measured by the Vspan. An activity phenomenon is characterized by an anticorrelation between the observed RV (here, the O-C) and the Vspan, as visible on Fig. 2.

2.4. *Spectroscopic indices of stellar activity*

The CaII H and K lines (3968.47 Å and 3933.66 Å), the HeI line (5875.62 Å) and the Hα line (6562.808 Å) are known to be sensitive to the non-radiative heating of the

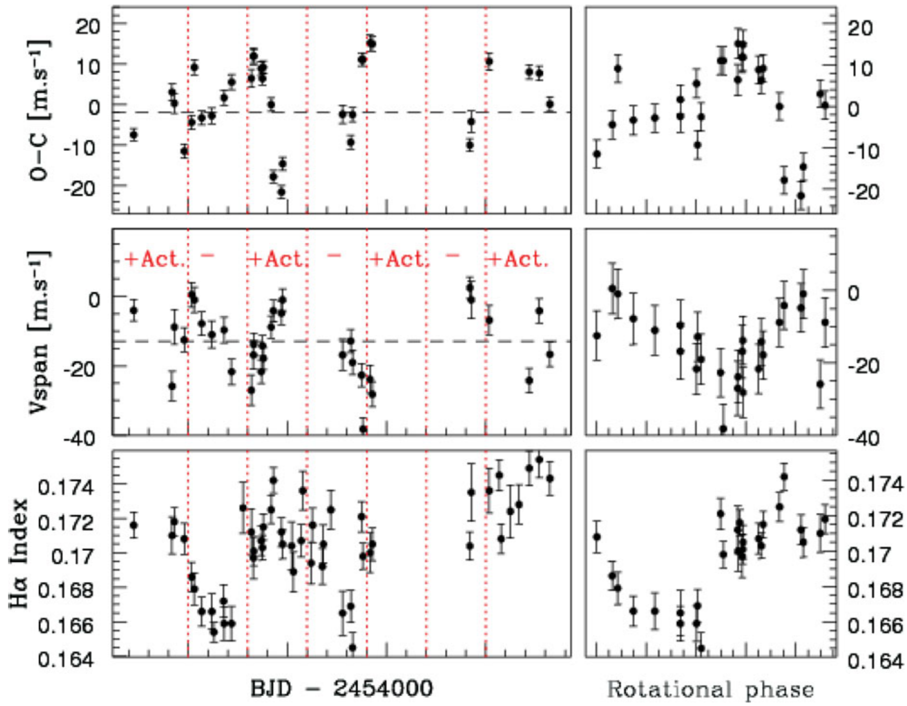

Figure 1. Residuals of the Keplerian fit *(top)*, bisector span of the CCF profile *(middle)* and Hα activity index *(bottom)* as a function of time *(left)* and as a function of the star rotational phase *(right)* without those for BJD-2454000 $\geqslant$ 320. T_0=2453988.8034[BJD] and P_{rot} = 11.953 d. The red dashed lines are based on the minimum activity index separated by 6 days ($\approx P_{rot}/2.$). The plus (minus) signs indicate star maximum (minimum) level of activity. (O-C) and Vspan are anticorrelated and the Hα index variation is quater-phase shifted.

chromosphere due to active regions. Here, the Hα index is the most sensitive of our indices. It is defined as in Bonfils *et al.* (2007): $Index = \frac{F_{H\alpha}}{F_1+F_2}$ with $F_{H\alpha}$ sampling the $H\alpha$ line and F_1 and F_2 the continuum on both sides of the line. The $F_{H\alpha}$ interval is 31 km.s^{-1} wide and centered on 6562.808 Å, while F_1 and F_2 are respectively integrated over [6545.495:6556.245] Åand [6575.934:6584.684] Å. The errors bars take into account the CCD readout and photonic noise. Two decreases of the activity index are observed on Fig. 1, centered near $BJD - 2454000 \cong 303$ and 315 days.

3. Discussion

An active region is not expected to rotate at exactly the rotation period, since the star may undergo differential rotation, with the poles rotating more slowly than the equator. The stellar rotation period is better determined by Henry & Winn (2008) with P_{rot} = 11.953±0.009 days. According to Fig. 1, (O-C), Vspan and the $H\alpha$ index present periodic variation of about 12 days. Moreover, correlations between parameters are consistent with one main active region rotating on the stellar surface. The activity variations exhibit a roughly one-quarter phase shift compared to the RVs and Vspan. On Fig. 2, the (O-C) as a function of the $H\alpha$ index plot a loop pattern, as expected for an active region rotating on the stellar surface carried in and out of view: when a spot appears or disappears on the line of sight, it lies on the rotationally blue-shifted or red-shifted half part of the stellar surface and induces an asymetry in the velocity distribution of the emitted flux.

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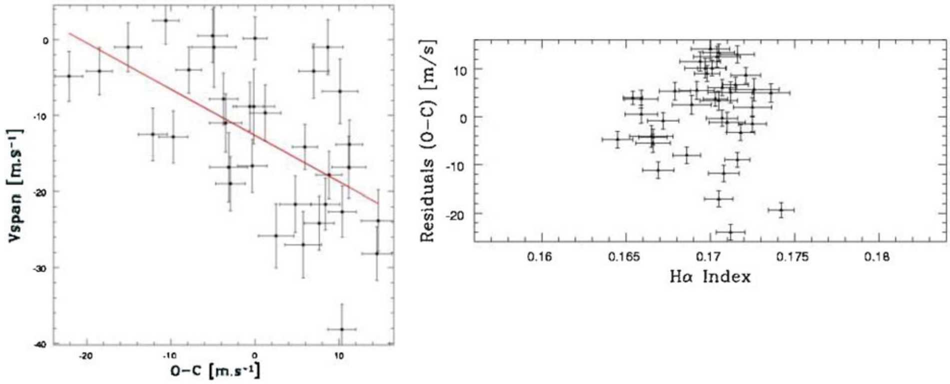

Figure 2. *Left:* The residuals (O-C) of the Keplerian fit versus bisector span of the CCF profile. The linear correlation coefficient is -0.58. An anticorrelation is expected in the case of RVs variations induced by stellar activity. *Right:* (O-C) as a function of Hα spectral index. The loop pattern is a signature of a stellar surface with one main active region in rotation.

When the activity level is maximum, a spot hides symmetrically the approaching and the receeding halves of the stellar disk and the effect is null in RV and Vspan.

We corrected the RV measurements from the stellar activity and refined the orbital parameters. We used the best linear adjustement between (O-C) and Vspan according to Fig. 2 and added it to the (O-C) (Melo *et al.* 2008). The best keplerian fit of the corrected RVs had lower residuals: 3.7 m$\cdot$s^{-1}, compared to 9.1 m$\cdot$s^{-1}, and lower error bar on the semi-amplitude: K=200.6 $\pm$ 0.9 m$\cdot$s^{-1}, compared to K=200.6 $\pm$ 2.3 m$\cdot$s^{-1}. Using the stellar mass $M_\star$=0.82 $\pm$ 0.03 M$_\odot$ given by Bouchy *et al.* (2005), we found a planet mass of M_P=1.13 $\pm$ 0.03 M$_{Jup}$. This value agrees exactly with the value reported by Winn *et al.* (2006) and is also in agreement with the Bouchy *et al.* (2005) value of 1.15 $\pm$ 0.04 M$_{Jup}$. The current uncertainty in M_P is dominated by the error in M_*.

This result is promising for RVs surveys. The error on the derived semi-amplitude of the orbit is divided by 2.5 after applying the correction law and brought down near the instrumental limit, allowing a more precise estimate of the companion's mass. This method has to be further tested on other systems, to estimate the confidence in the corrected RVs and, subsequently, to apply such analyses in planet-search programs.

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