

Disentangling stellar activity and planetary signals

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Abstract. Photospheric stellar activity (i.e. dark spots or bright plages) might be an important source of noise and confusion in the radial-velocity (RV) measurements. Radial-velocimetry planet search surveys as well as follow-up of photometric transit surveys require a deep understanding and precise characterization of the effects of stellar activity, in order to disentangle it from planetary signals.

We simulate dark spots on a rotating stellar photosphere. The variations of the RV are characterized and analyzed according to the stellar inclination, the latitude and the number of spots. The Lomb-Scargle periodograms of the RV variations induced by activity present power at the rotational period P_{rot} of the star and its two-first harmonics $P_{rot}/2$ and $P_{rot}/3$. Three adjusted sinusoids fixed at the fundamental period and its two-first harmonics allow to remove about 90% of the RV jitter amplitude. We apply and validate our approach on four known active planet-host stars: HD 189733, GJ 674, CoRoT-7 and ι Hor.

1. Introduction

High-precision radial-velocimetry is until now the more efficient way to discover planetary systems. However, an active star presents on its photosphere dark spots and/or bright plages rotating with the star. These inhomogeneities of the stellar surface can induce RV shifts due to changes in the spectral lines shape which may add confusion with the Doppler reflex-motion due to a planetary companion (e.g. Queloz et al. 2001; Huélamo et al. 2008). The amplitude of the RV shifts depends on the $v \sin i$ of the star, the spectrograph resolution, the size and the temperature of spots (Saar & Donahue 1997; Hatzes 1999; Desort et al. 2007). For these reasons, active stars are then usually discarded from RV surveys using criteria based on activity index R'_{HK} and/or $v \sin i$. However, photometric transit search missions (like CoRoT and Kepler) require RV measurements to establish the planetary nature of the transiting candidates and

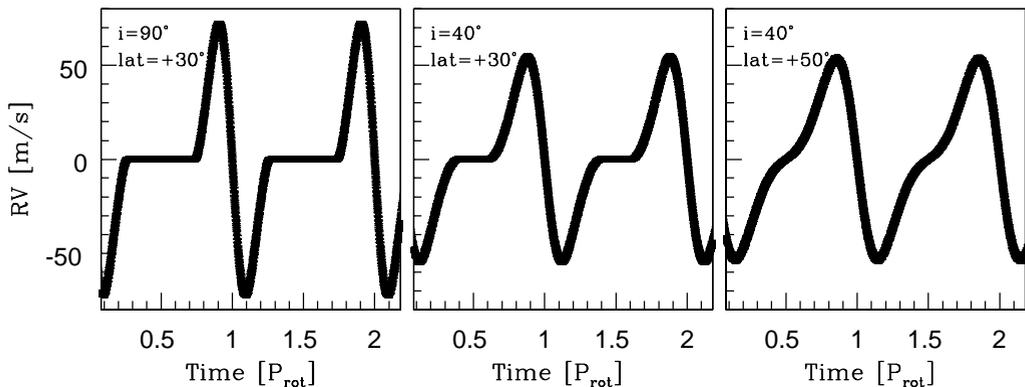


Figure 1: *RV modulations due to one spot as a function of time (expressed in rotational period unit). At $t=1$, the dark spot of 1% of the visible stellar surface is in front of the line of sight. The shape of the signal changes with the inclination i of the star and the latitude lat of the spot, labelled in the top left of each panel.*

to characterize their true masses. These candidates include active stars adding strong confusions and difficulties in the RV follow-up.

2. Dark spot simulations

SOAP is a program that calculates the photometric, RV and line shape modulations induced by one (or more) cool spots on a rotating stellar surface. SOAP computes the rotational broadening of a spectral line by sampling the stellar disk on a grid. For each grid cell, a Gaussian function represents the typical line of the emergent spectrum. The Gaussian is Doppler-shifted according to the projected rotational velocity ($v \sin i$) and weighted by a linear limb-darkening law. The stellar spectrum output by the program is the sum of all contributions from all grid cells. The spot is considered as a dark surface without emission of light, so we cannot compute different temperatures for the spot. For a given spot (defined by its latitude, longitude and size), SOAP computes which of the grid cells are obscured and removes their contribution to the integrated stellar spectrum.

RV variations due to dark spots. Fig. 1 shows the RV modulations due to a spot as a function of time for different inclinations i of the star with the line of sight and different spot latitudes lat . These two parameters clearly modify the pattern of the RV modulation. Fig. 2 shows the Lomb-Scargle periodograms of the three cases shown in Fig. 1. Main peaks are clearly detected at the rotational period of the star P_{rot} , as well as the two-first harmonics $P_{rot}/2$ and $P_{rot}/3$. We noticed that the energy in each peak varies with the shape of the RV modulation. Multiples of the rotational period are never found.

Finally, the periods detected in the periodogram are the same for the following configurations : 1) a star with different inclinations, 2) spots at different latitudes, 3) spot size and/or temperature varying with time, 4) several spots on the stellar surface.

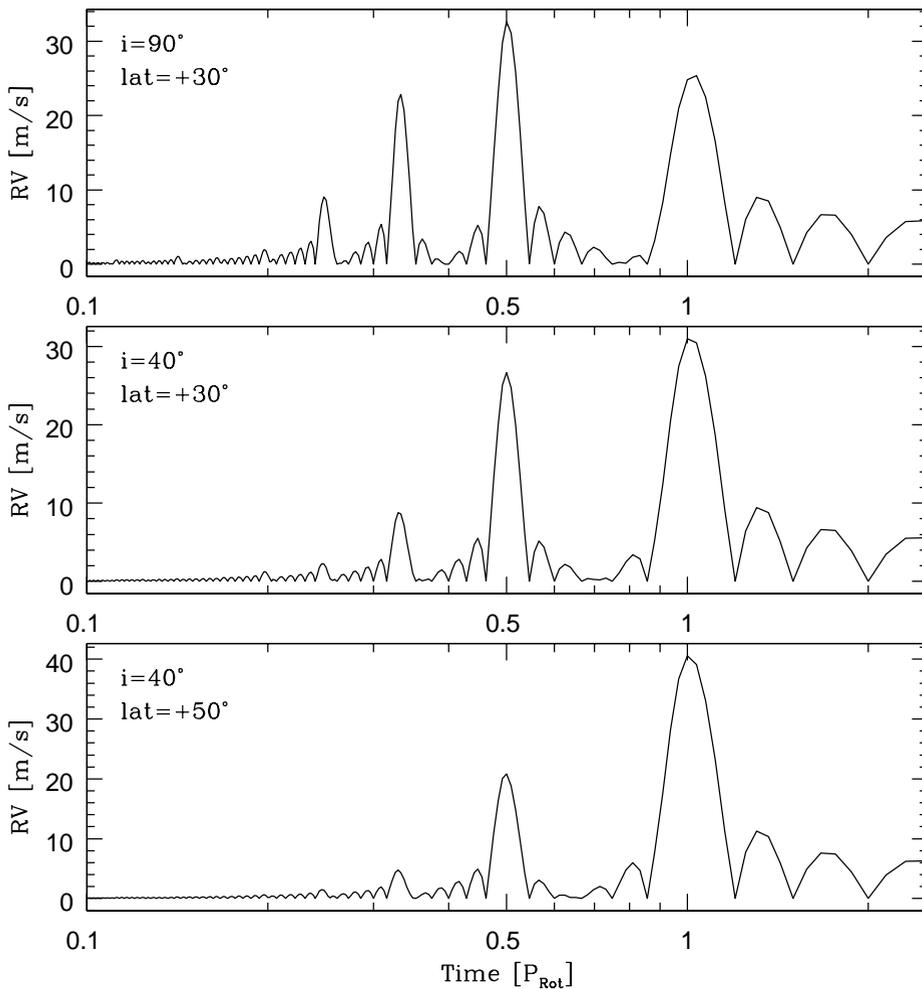


Figure 2: *Lomb-Scargle periodograms of the three RV modulations shown in Fig. 1. The fundamental frequency, P_{rot} , and its first harmonics are detected.*

RV fit of dark spots. The purpose is to remove or at least to reduce the stellar activity signal in order to identify a planetary signal hidden in the RV jitter. The Lomb-Scargle periodogram corresponds to sinusoidal decompositions of the data. Three sinusoids with periods fixed at the rotational period P_{rot} , and its two first harmonics $P_{\text{rot}}/2$ and $P_{\text{rot}}/3$ reduce the semi-amplitude of the RV jitter by more than 87%.

3. Application to real data

HD 189733. The active K2V star HD 189733 and its transiting planetary companion was monitored by Boisse et al. (2009) with the high-resolution spectrograph *SOPHIE* mounted on the 1.93-m telescope at the Observatoire de Haute-Provence. The residual RV measurements, after subtracting the fit of the planetary companion, are due to the

activity of the star. We computed the Lomb-Scargle periodogram of the residuals from the Keplerian fit. The fundamental period at P_{rot} (~ 12 d) and its first two harmonics are detected with false alarm probability lower than 10^{-1} .

GJ 674. GJ 674 is a moderately active M2.5V dwarf hosting a planet with 4.69-day period (Bonfils et al. 2007). A superimposed signal with a periodicity of 35 days due to stellar activity is also visible in the HARPS RV measurements. We fit the RV with three sinusoids with periods fixed at the rotational period and the first two harmonics and one Keplerian that gives the planetary parameters. These are in agreement with Bonfils et al. (2007) and we obtained a weaker dispersion of the residuals closest to the current HARPS accuracy and equal to the uncertainty on each measurement.

CoRoT-7. The photometric transit search with the CoRoT satellite has reported the discovery of a planetary companion CoRoT-7b around an active $V=11.7$ G9V star (Léger et al. 2009) with an orbital period of 0.85 day. Queloz et al. (2009) (Q09) reported the intensive campaign carried out with HARPS at 3.6-m telescope at La Silla. The RV variations are dominated by the activity of the star with an estimated period of 23 days. The second of the two approaches used in Q09 is a modeling of the active jitter by an harmonic decomposition of the rotational period. The authors subtract their model from the RV data before to detect and characterize the planetary system. Here, we want to simultaneously fit the effect of activity and the planetary system as we have previously done for GJ674.

We use the 37 last days of HARPS data in order for the distribution of spots on the stellar surface not to change too much. We simultaneously fit three sinusoids for the active jitter with periods fixed at the rotational period and its first two harmonics. The Lomb-Scargle of the residuals shows a clear peak near 3.69 d and another one near 0.85 d with false alarm probabilities lower than $5 \cdot 10^{-4}$. We then simultaneously fit three sinusoids for the active jitter and two Keplerians for the possible companions with no parameters fixed for the Keplerians except the eccentricities ($e=0$). The differences with the published values on the periods are below 0.5% compared to the values published by Queloz et al (2009) and the difference on the transit phase of CoRoT-7b is less than 0.2% as compared to the value of Léger et al (2009). To measure the semi-amplitude and then the mass of the planets, we fixed the period and the T0 of the transiting companion. The period of 3.70 ± 0.02 d found for CoRoT-7c is in agreement with the value of 3.698 ± 0.003 d from Q09. For comparison, the same study is done on another data set. Our method is robust but the differences in the parameters of the fit illustrate the difficulty to measure the amplitudes accurately in presence of activity. We then estimate that a systematic noise due to active jitter of 1.5 ms^{-1} must be added quadratically to the error bars. We then find for the masses $5.7 \pm 2.5 M_{Earth}$ for CoRoT-7b agreeing with the value of Q09 and $13.2 \pm 4.1 M_{Earth}$, slightly higher than the published value, for CoRoT-7c.

ι Hor. ι Hor, or HD 17051 is a young G0V star. A 320.1-d period planet ι Hor b was reported by Kürster et al. (2000). They noted an excess RV scatter of 27 ms^{-1} due to stellar activity. Asteroseismologic observations were made with the high-precision spectrograph HARPS (Vauclair et al. 2008). We studied these data to characterize the active jitter and to search for a possible hidden Doppler motion. Before studying the RV variations due to stellar activity, we subtract the long-period planet Doppler motion and we averaged the data by group of 20 measurements in order to average the p-modes signature. The mean RV photon noise uncertainty on averaged points is then about 26 cms^{-1} , but the actual precision is limited by the instrumental accuracy $\approx 80 \text{ cms}^{-1}$.

Detection and Dynamics of Transiting Exoplanets

The ι Hor RV modulations are well explained by dark spots rotating with the photosphere with a rotational period in the range [7.9-8.4] days (Fig. 3). The residuals are equal to $\sigma = 1.03\text{ms}^{-1}$ reaching almost the instrumental accuracy. We do not detect in the ι Hor data a short-period companion. Nevertheless, we tested whether we have subtracted the RV shift due to a companion by subtracting the effect of activity. We ran simulations and added RV modulations due to fake planets to the ι Hor data, considering the case of circular orbits only. We fit the active jitter with three sinusoids with periods fixed at the rotational period and its first two harmonics and then look at the Lomb-Scargle periodogram of the residuals. If a peak at the planetary period is detected, we simultaneously fit a Keplerian with null-eccentricity to obtain the planetary parameters. We consider that a peak is significant if its false-alarm probability is smaller than 10^{-2} . We can exclude low-mass planets with periods between 0.7 and 2.4 days with semi-amplitude greater than 4ms^{-1} , which corresponds to a minimum mass of, respectively, 6 to $10 M_{\text{Earth}}$.

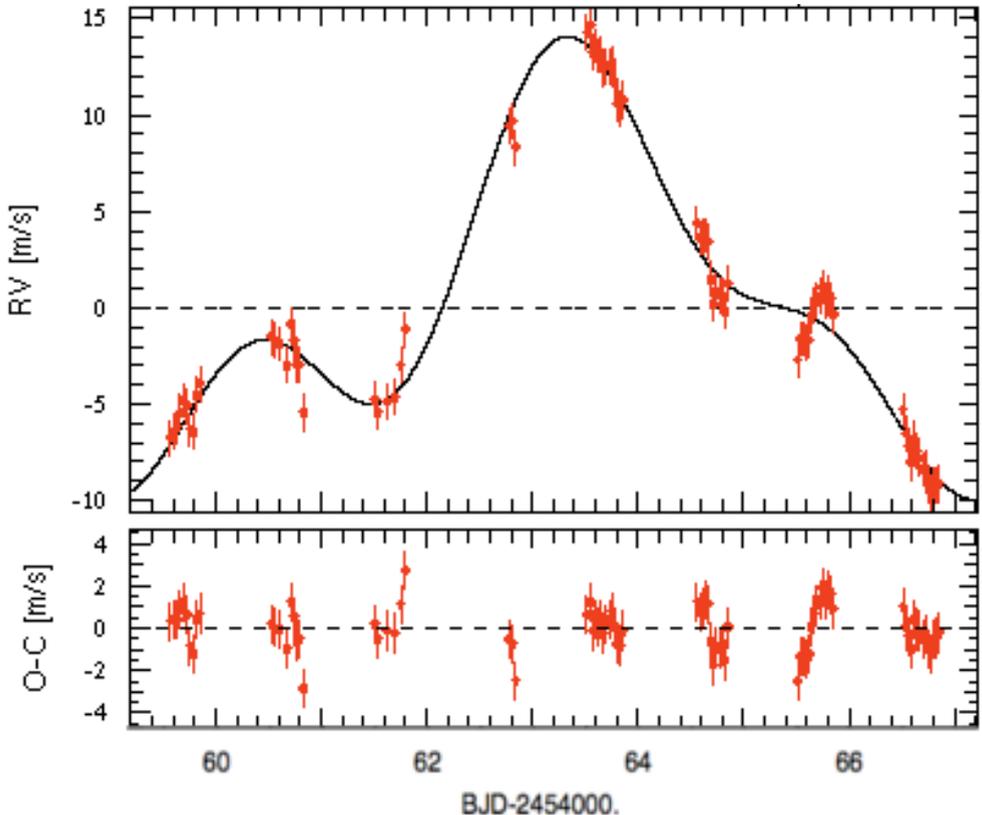


Figure 3: *Top: RV of ι Hor derived from HARPS spectra as a function of time. The three-sinusoid fit, with periods fixed at the rotational period of the star and its first two harmonics, is plotted as a solid line. The rotational period is chosen equal to 8.2 days. Bottom: Residuals from the fit as a function of time. The dispersion value equals 1.03ms^{-1} .*

4. Conclusion

We succeed in simultaneously fitting activity and planetary signals on GJ674 and CoRoT-7. It leads to slightly larger masses of CoRoT-7b and c: respectively, $5.7 \pm 2.5 M_{Earth}$ and $13.1 \pm 4.1 M_{Earth}$. The larger uncertainties properly take into account the stellar active jitter. We excluded short-period low-mass exoplanets around ι Hor. Our approach is efficient to disentangle reflex-motion due to a planetary companion and stellar-activity induced-RV variations provided that 1) the planetary orbital period is not close to that of the stellar rotation or one of its first two harmonics, 2) the rotational period of the star is accurately known, 3) the data cover more than one stellar rotational period.

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