The Physics of the Sun and Star Spots
Proceedings IAU Symposium No. 273, 2010
D. P. Choudhary and K. G. Strassmeier, eds.
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doi:10.1017/S1743921311015389

Disentangling between stellar activity and planetary signals

Isabelle Boisse[1,5], François Bouchy[1,2], Guillaume Hébrard[1,2], Xavier Bonfils[3,4], Nuno Santos[5] and Sylvie Vauclair[6]

[1]Institut d'Astrophysique de Paris, Université Pierre et Marie Curie, UMR7095 CNRS, 98bis bd. Arago, 75014 Paris, France
email: iboisse@iap.fr

[2]Observatoire de Haute Provence, CNRS/OAMP, 04870 St Michel l'Observatoire, France
[3]Laboratoire d'Astrophysique de Grenoble, Observatoire de Grenoble, Université Joseph Fourier, CNRS, UMR 5571, 38041, Grenoble Cedex 09, France
[4]Observatoire de Genève, Université de Genève, 51 Ch. des Maillettes, 1290 Sauverny, Switzerland
[5]Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
[6]LATT-UMR 5572, CNRS & Université P. Sabatier, 14 Av. E. Belin, F-31400 Toulouse, France

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 deeper understanding and characterization of the effects of stellar activities 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. We succeed in fitting simultaneously activity and planetary signals on GJ674 and CoRoT-7. 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 two-first harmonics, 2) the rotational period of the star is accurately known, 3) the data cover more than one stellar rotational period.

Keywords. techniques: radial velocities - planetary systems - stars: activity - stars: individual: ι Hor, HD 189733, GJ 674, CoRoT-7

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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 confusions 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 depend on the $v \sin i$ of the star, the spectrograph resolution, the size and temperature of spot (Saar & Donahue 1997; Hatzes

https://doi.org/10.1017/S1743921311015389 Published online by Cambridge University Press

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 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 consider as a dark surface without emission of light, so we cannot compute different temperature 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 showed 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.

RV fit of dark spots. The purpose is to remove or at least to reduce the stellar activity signals 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 $P_{rot}/2$ and $P_{rot}/3$ reduce the semi-amplitude of the RV jitter by more than 87%.

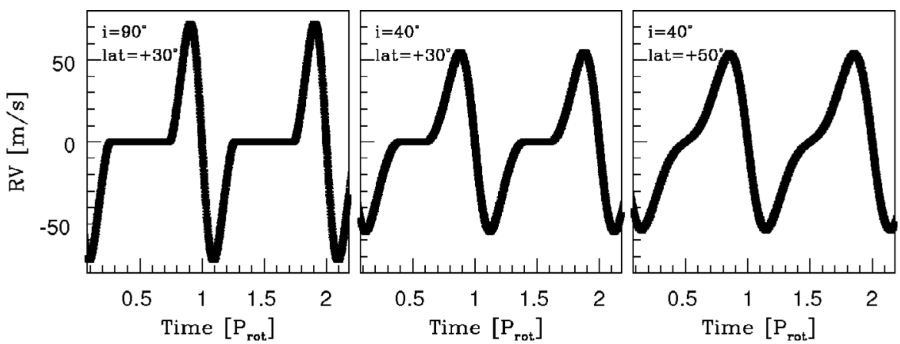

Figure 1. RV modulations due to one spot as a function of time (expressed in rotational period unit). At t=0, the dark spot of 1% of the visible stellar surface is in front of the line of sight. The shape of the signal changes with the inclination i of the star and the latitude *lat* of the spot, labelled in the top left of each panel.

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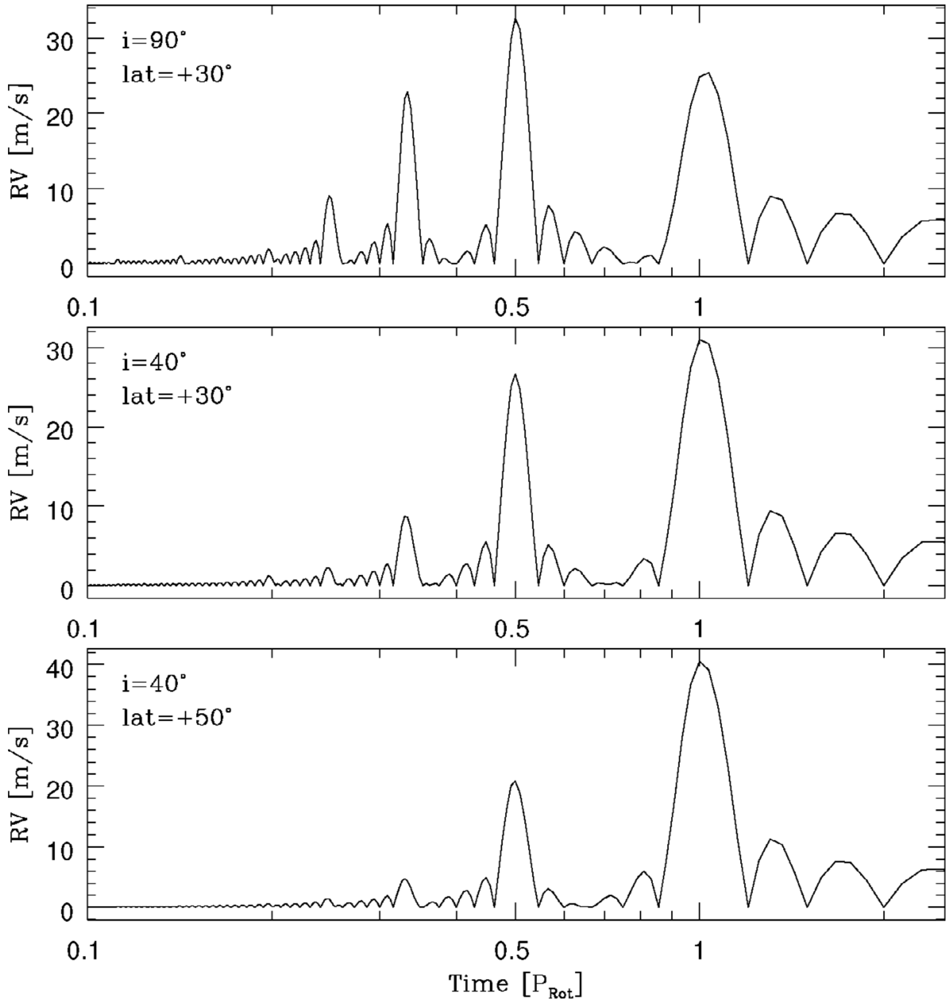

Figure 2. Lomb-Scargle periodograms of the three RV modulations showed in Fig. 1. The fundamental frequency, P_{rot}, and its first harmonics are detected.

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 RV measurements subtracted from their fit of the planetary companion are variable 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} (∼12d) and its two-first 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 two-first harmonics and one Keplerian that gives the planetary parameters. These are in agreement with Bonfils

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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.

We use the 37 last days of HARPS data in order that the distribution of spots on the stellar surface does not change too much. We fit simultaneously three sinusoids for the active jitter with periods fixed at the rotational period and its two-first 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 5.10^{-4}. We then fit simultaneously 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% and on the transit phase of CoRoT-7b is less than 0.2% of the planetary period. 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±0.02d found for CoRoT-7c is in agreement with the value of 3.698±0.003d from Q09. For comparison, the same study is done on another data set. The main difference of our method is the simultaneous fit of the active jitter and the planetary parameters, instead of Q09 that fitted the active jitter before the search of the planets. We estimate approximately that a systematic noise due to active jitter of $1.5\,\mathrm{ms}^{-1}$ must be added quadratically to the error bars. We then find for the masses 5.7±2.5 M_{Earth} for CoRoT-7b agreeing with the value of Q09 and 13.2±4.1 M_{Earth}, slightly higher than the published value, for CoRoT-7c. Our method is robust but these differences illustrate the difficulty to measure the amplitudes accurately in presence of activity.

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 on ι Hor (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 $\approx 80\,\mathrm{cms}^{-1}$.

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. The residuals are equal to $\sigma = 1.03\mathrm{ms}^{-1}$ reaching almost the instrumental accuracy. We do not detect in the ιHor data a short-period companion. Nevertheless, we would like to know if we have subtracted the RV shift due to a companion subtracting the effect of activity. We ran simulations and added RV due to fake planets to the ιHor data. We consider only the case of circular orbits. We fit the active jitter with three sinusoids with period fixed at the rotational period and its two-first harmonics and look afterwards at the Lomb-Scargle periodogram of the residuals. If a peak at the planetary period is detected, we fit simultaneously a Keplerian with null-eccentricity to obtain the planetary parameters. We excluded the presence of planet with a minimum mass between 6 and 10 M_{Earth} with periods respectively between 0.7 and 2.4 days.

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