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# Studying the Sun's radial velocity jitter to improve low-mass exoplanet detections

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## Abstract

One of the most common methods used to discover extra-solar planets is to monitor a star's radial velocity (RV) in order to detect the reflex orbital motion caused by one or more planets orbiting the star. When looking for "small" planets (Neptune or Earth mass), the RV signals induced by these planets are entangled with the jitter arising from the star's magnetic activity. The Sun's activity is well known and it is possible to remove all RV components induced by all other bodies of the solar system. We have obtained its activity-driven RV variations over two solar rotations using HARPS by observing sunlight reflected off the bright asteroid Vesta. We aim to model the solar RV jitter in terms of the continuum lightcurve, the chromospheric Ca II H&K emission, and the line-profile distortions produced by spots drifting across the face of the Sun. By using the "ground truth" of solar observations in this way, we will identify photometric and spectroscopic proxies that will make it possible to model and remove the stellar activity RV contribution from exoplanet RV curves.

## 1. Introduction

The majority of extra-solar planets have been discovered (or confirmed after follow-up) through radial-velocity surveys. Using ground-based spectrographs such as HARPS (High Accuracy Radial Velocity Planetary Search) and HARPS-North, it is now possible to detect planets that are only a few times the mass of the Earth. However, the presence of magnetically active regions such as dark spots, faculae, plages, on the stellar surface produces radial-velocity signals that are very similar in amplitude to those caused by orbiting low-mass planets. Disentangling these signals has thus become the biggest challenge in the detection of Earth-mass planets using RV surveys. We are studying the RV of the Sun to determine the physical origin of activity-induced RV. This will allow us to infer proxies to mitigate activity-induced RVs. The methods derived will be applied to CoRoT-7 and low-mass Kepler planets.

## 2 Data

### 2.1 HARPS data

The HARPS spectrograph mounted on the 3.6 m at La Silla was used to collect 98 spectroscopic measurements of sunlight reflected off the asteroid Vesta, spread over a period of over two solar rotations. At the time of the observations in 2011, the Sun was just over three years into its 11-year activity cycle so it is expected to show relatively many sunspots and other activity-related markers. We obtained full spectra, from which the RV and the shape of the cross-correlation functions can be extracted.

### 2.2 Sun as-a-star RVs

Because we observed the Sun indirectly by measuring the RV of Vesta, several factors have to be taken account and removed in order to obtain Sun as-a-star RVs:

- To place the Sun back in its rest frame, the contribution of all bodies in the solar system have to be removed.

- We account for the relativistic Doppler shift incurred by the light travelling from the Sun to Vesta, and then from Vesta to the Earth. This effect has a non-negligible amplitude of about 1.5 m.s$^{-1}$.

- The asteroid Vesta rotates about its axis every 5.34 hours. Its surface brightness is inhomogeneous so this will induce a RV modulation of a few m.s$^{-1}$.

### 2.3 SDO data

High-resolution full-disk continuum and doppler images are available from the HMI instrument (Helioseismic and Magnetic Imager) onboard the Solar Dynamics Observatory. They were retrieved for the period spanning the HARPS observations of Vesta. Figure 2 shows two typical continuum and doppler images.

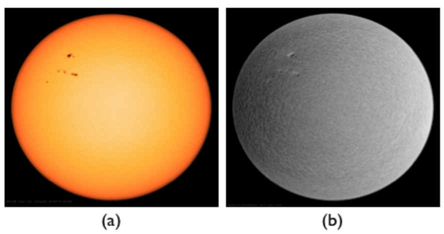


Figure 2: (a) HMI Intensitygram – (b) HMI Dopplergram. The sunspots that are visible on the intensity image produce a signature on the doppler image. This illustrates the fact that sunspots lead to anomalies in the stellar Doppler shift. (Images from the SDO online database)

## 3 Work

### 3.1 Sun's line profile distortions

The HARPS reduction pipeline generates a cross-correlation function (CCF) for each observation, whose shape gives information on the Sun's line-profile.

A time series of the CCFs is shown in figure 3a. The average of the CCFs is computed (figure 3b) and then subtracted from each individual CCF in order to obtain the residuals in the line-profile, plotted as a time series in figure 3c. The time series of residuals effectively constitutes a temporal map of the surface of the Sun. The white trails drifting across the centre of the plot represent groups of sunspots drifting across the face of the Sun.

### 3.2 Modeling line-profile distortions using SDO data

We use the SDO/HMI data to synthesize Sun as-a-star CCFs. Information on the scale of the line-profile can be obtained by measuring the brightness of each pixel in the continuum images. The amount by which the line is doppler-shifted is given by the greyscale of each pixel in the dopplergrams.

### 3.3 Activity indices derived from HARPS spectra

The $S$ and $R'_{HK}$ indices will be computed from the HARPS observations. Ca II H&K emission is associated with regions of faculae and plages so these indices will give an idea of the location of these features on the solar surface. This will allow us to deduce what part, if any, these features have in producing activity-induced RV variations.

## 4. Summary and Conclusions

The search for low-mass planets is now primarily limited by the stars themselves: most stars are magnetically active, and this can be witnessed on their surface by the presence of markers such as starspots, faculae, plages, etc. These activity features produce an RV perturbation, often referred to as stellar jitter. The present work is focussed on gaining a better understanding of the exact source of this jitter and on finding ways to mitigate its effects in the context of RV planet searches. In this perspective, the Sun's apparent RV and line-profile distortions were recently obtained using HARPS observations of sunlight reflected off the bright asteroid Vesta. Combining these results with knowledge gained from SDO/HMI data will allow us to determine the respective contributions of spots and faculae to RV jitter, as well as to identify proxies for stellar activity-induced RV variations.

## Acknowledgements

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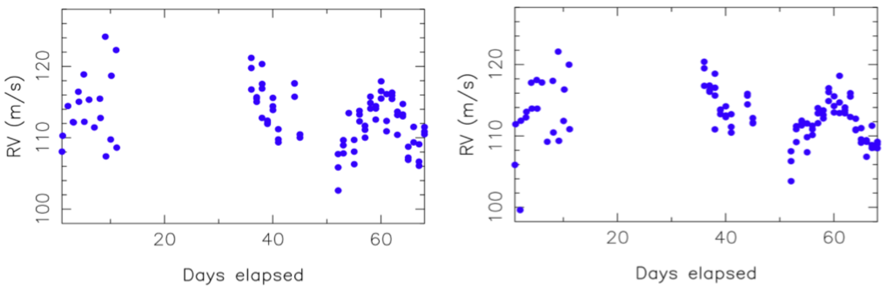


Figure 1: RV of the Sun in its rest frame, based on HARPS RV data corrected for relativistic Doppler effects, and: (a) before removing the RV contribution of Vesta's axial rotation – (b) after removal. The RV variations show less scatter after accounting for Vesta's axial rotation.

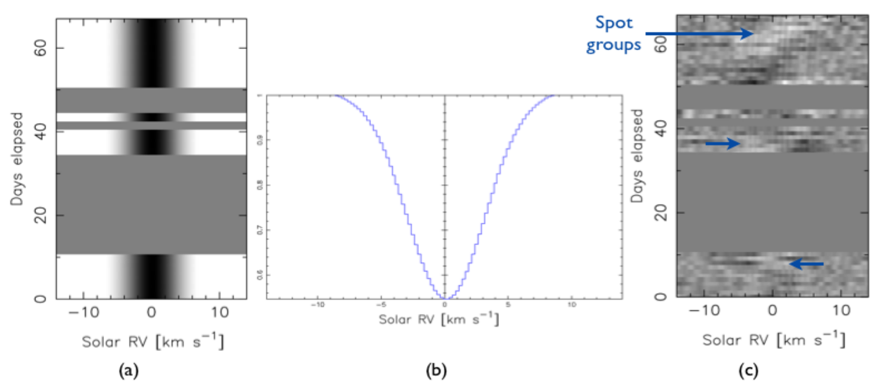


Figure 3: Diagram showing the steps taken in order to obtain the residuals of the Sun's line-profile. (a) Time series of CCFs over the span of the measurements – (b) Average of all CCFs – (c) Time series of residuals. Uniform grey areas indicate the absence of observations on given nights.