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Disentangling planetary orbits from stellar activity in radial-velocity surveys

R. D. Haywood[1], A. Collier Cameron[1], D. Queloz[2], S.C.C. Barros[3], M. Deleuil[3], R. Fares[1], M. Gillon[4], A. Hatzes[5], A.F. Lanza[6], C. Lovis[2], C. Moutou[3], F. Pepe[2], D. Pollacco[7], A. Santerne[3,8], D. Ségransan[2] and Y. Unruh[9]

[1]*School of Physics and Astronomy, University of St. Andrews, St Andrews KY16 9SS, UK*
e-mail: rdh4@st-andrews.ac.uk
[2]*Observatoire de Genève, 51 Ch. des Maillettes, 1290 Sauverny, Switzerland*
[3]*Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 13388, Marseille, France*
[4]*Institut d'Astrophysique et de Géophysique, Universite de Liège, Allée du 6 août 17, Bat. B5C, 4000 Liège, Belgium*
[5]*Thüringer Landessternwarte, D-07778 Tautenburg, Germany*
[6]*INAF-Osservatorio Astrofisico di Catania, via S. Sofia, 78 - 95123 Catania, Italy*
[7]*Department of Physics, University of Warwick, Coventry CV4 7AL, UK*
[8]*Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal*
[9]*Astrophysics Group, Blackett Laboratory, Imperial College London, London SW7 2AZ, UK*

Abstract: The majority of extra-solar planets have been discovered (or confirmed after follow-up) through radial-velocity (RV) surveys. Using ground-based spectrographs such as High Accuracy Radial Velocity Planetary Search (HARPS) 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 dark spots on the stellar surface produces RV 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. To do so, we use the star's lightcurve to model the RV variations produced by spots. Here we present this method and show the results of its application to CoRoT-7.

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Introduction

Extra-solar planets can be detected by monitoring a star's radial velocity (RV) – the speed with which a star moves away or towards us along our line-of-sight from Earth. A planet orbiting a star exerts a gravitational pull on its host, which can lead to detectable RV variations as the star and planet orbit their common centre of mass. These variations can be detected by measuring the Doppler shift of the light emitted by the star, using a spectrograph.

With extremely stable spectrographs such as High Accuracy Radial Velocity Planetary Search (HARPS)(Mayor *et al*. 2003) and HARPS-North (Pepe 2010), it is now possible to detect signals corresponding to low-mass planets such as super-Earths and even Earth-mass planets such as the recently discovered alpha Centauri Bb (Dumusque *et al*. 2012). However, RV signals induced by these low-mass planets are entangled with the noise arising from the star's magnetic activity, and this had led to much controversy in planetary systems such as alpha Centauri B (Hatzes 2013) and CoRoT-7 (Leger *et al*. 2009; Queloz *et al*. 2009; Hatzes *et al*. 2010, 2011; Lanza *et al*. 2010; Pont *et al*. 2010 and others).

The magnetic activity of a star leads to the emergence of various features on the stellar surface (the photosphere). In stars like the Sun, the photosphere sits on top of a convection zone in which hot fluid cells are carried upwards due to buoyancy. When they reach the surface, they cool and eventually the fluid sinks back between the large convection cells. The pattern formed on the photosphere is known as granulation.

Granulation is inhibited in regions of strong magnetic fields; in these areas hot fluid is prevented from rising to the surface, so the photosphere is cooler and therefore appears darker. These dark regions are known as starspots (or sunspots in the case of the Sun). Strong magnetic fields can also lead to small bright pores, known as faculae. They are found around starspots and also inhibit the convection process.

The presence of these features can lead to RV variations of several $m\,s^{-1}$ in Sun-like stars (Saar & Donahue 1997; Hatzes 2002; Meunier *et al*. 2010a, b). Considering that the RV induced by the motion of an Earth-mass planet orbiting at 1 AU from its parent star is of the order of $0.1\,m\,s^{-1}$ (Mordasini *et al*. 2009), it is essential to find ways to model activity-induced RV variations in order to be able to detect such planets with confidence.

Data

We study the case of CoRoT-7. This Sun-like star was first observed in 2009 and was found to host a transiting

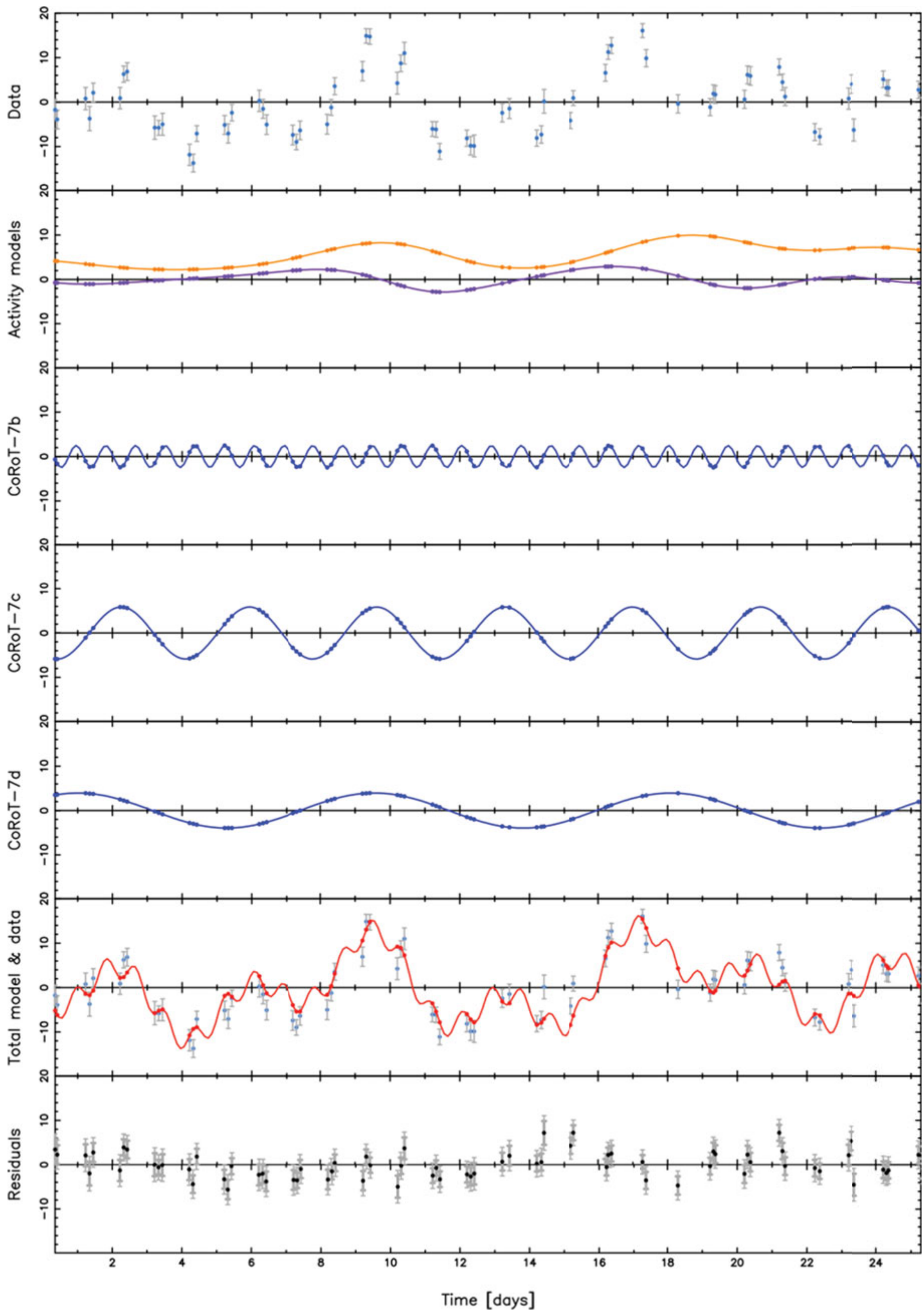

Fig. 1. Time series of the various parts of the total RV solution. All RVs are in m s^{-1}. Second panel: model for suppression of convective blueshift (orange/light shade) and for stellar rotation (purple/dark shade). Second to last panel: the total model (red) is the sum of activity and planet RVs. Subtracting it from the original data yields the residuals plotted in the bottom panel. The error bars on the residuals represent the original errors of the data (smaller bars), and the errors after the extra noise term have been added (larger bars) for comparison.

super-Earth with the smallest measured planetary radius at the time (Leger *et al*. 2009). This discovery was followed by an intensive RV campaign with HARPS to measure its mass and investigate on the possible presence of other planets (Queloz *et al*. 2009). Since then, several analyses were made but all yielded different results due to the star's strong magnetic activity.

In 2012, CoRoT-7 was re-observed with the CoRoT satellite and the HARPS spectrometer, at the same time. These simultaneous photometric and RV data allow us to perform a new analysis.

Method

The lightcurve of a star, after all planet transits have been removed, only contains information about the star's magnetic activity. It is modulated by the presence of starspots on the stellar disk.

We can use the information contained in the simultaneous lightcurve to model the RV variations produced by those spots. This is done according to a model developed by Aigrain *et al*. (2011).

The activity model is incorporated into a total RV model accounting for stellar activity and the orbit of several planets. The best model is found through an Monte Carlo Markov Chain (MCMC) analysis.

Results and conclusions

Figure 1 shows the RV data (top panel), the best fit models obtained for the two stellar activity basis functions (second panel), the Keplerian models found for each planet (three subsequent panels) and the total fit (second to last panel) with the residuals of the fit (last panel). The residuals appear to contain some correlated noise which is likely to be due to incomplete modelling of stellar induced RV variations. This is discussed in depth in Haywood *et al*. (submitted to MNRAS).

We confirm the presence of three planets in the system: CoRoT-7b, with a mass of 3.38 ± 0.86 Earth masses, and two sub-Neptune mass planets, CoRoT-7c (13.31 ± 1.27 Earth masses) and CoRoT-7d (11.92 ± 2.11 Earth masses), at orbital periods of 3.68 ± 0.03 and 8.54 ± 0.24 days, respectively. More details are given in Haywood *et al*. (submitted to MNRAS).

We find that the RV variations induced by stellar activity are dominant contributors to the total RV of the CoRoT-7 system. We conclude that modelling the activity-induced RV is essential in the search for super-Earths and Earth-mass planets around moderately active Sun-like stars.

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