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Modelling the photosphere of active stars

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Abstract

Stellar activity in late-type main sequence stars induces photometric modulations and apparent radial velocity variations that may hamper the detection of Earth-like planets and the measurement of their size, mass and atmospheric properties. The effect of stellar activity in the photosphere is seen in the form of spots and faculae, whose relationship with stellar parameters such as mass and age is still not well understood. Significant improvement in our knowledge of activity effects on starlight will be crucial to make the most of present and future planet search instruments (HARPS-N, CARMENES, ESPRESSO) and space missions (EChO). In this work we present a methodology to simulate spectra from the spotted photosphere of a rotating star. We use NextGen2 atmosphere models to generate synthetic spectra for the stellar surface, spots and faculae. The spectrum of the entire visible face of the star is obtained by summing the contribution of a grid of small surface elements and by considering their individual Doppler shifts and limb darkening coefficients obtained from Kurucz models. Using such simulator time series spectra can be obtained covering the rotation period the star or longer. By convolving these with the known passband for a specific instrument, this can be used to study the chromatic effects of spots and faculae on photometric modulation and radial velocity jitter. A methodology is also presented to obtain spot-model maps of stars using a similar approach. This allows, from the high precision photometry currently available from space missions like Kepler or CoRoT, to obtain accurate information on the presence of spots and their long-term behavior. Our results will allow us to investigate the effects of activity patterns on the measurable stellar flux and hence define the best strategies to optimize exoplanet search and measurement experiments.

1 Introduction

Exoplanet research has experienced an exponential growth over the past decade and is now entering an even more exciting era that should lead to the discovery and characterization of habitable planets, with the eventual aim of finding signs of biological activity. We are already able to start to characterise the atmospheres of hot giant exoplanet atmospheres through transit spectroscopy, measuring temperature as well as the presence of a range of molecular compounds. The identification of the first atoms, such as sodium and potassium [1, 2, 3], and molecular constituents, such as water, methane, carbon dioxide, and carbon monoxide [4, 5, 6], have represented significant milestones in the understanding of the physical and chemical properties of the atmospheres of exoplanets. As challenging as this may seem today, we will have to do much better to apply the same techniques to terrestrial exoplanets. For a hot Jupiter-type planet (i.e., a gas giant orbiting at less than 0.1 AU from its parent star), the typical molecular features in its atmosphere require the ability to measure light contrast in the order of a few parts in 10^4, which has been shown to be feasible today with space-based facilities [7]. To apply the same in Earth-like planets, the need will be to measure transits and eclipses with a precision of about 10^{-5} in the near- and mid-IR, even in the case of the more favourable M-type stellar hosts [8]. It is clear that it will not be possible to undertake a successful study of the exoplanet without a detailed knowledge of the host star.

The detectability and characterization of Earth-like exoplanets is nowadays limited because of the noise introduced in the observations by stellar activity effects such as spots and faculae. The currently available high precission data from space-based missions like Kepler and CoRoT are resulting in a large number of discoveries, but at the same time are becoming more sensitive to signal perturbations caused by stellar effects, such as activity and oscillations. This is giving rise to great advances in the field of asteroseismology, but a better knowledge on activity & rotation behavior for low-mass stars is needed in order to interpret the photometric and radial velocity jitters. Special efforts must be applied on understanding the effects of this variability on multi-band observations covering the visible and near-IR spectrum. In this range, terrestrial exoplanets are due to be observed with future space facilities such as JWST and with dedicated missions to characterise the atmospheres of large samples of exoplanets under study at NASA (FINESSE) and ESA (EChO).

Characterizing the timescales and amplitudes of the variability caused by the different phenomenology related to stellar activity is critical if we want to optimize the performance of the mentioned exoplanetary missions. These timescales can go from minutes, if related to granulation [9] and p-mode oscilations [10], to years or centuries, corresponding to activity cycles [11]. The variability that mostly affects current exoplanet missions is the one caused by the evolution of active regions in combination with stellar rotation. Due to its timescale, being from days to weeks, it can mask or even mimic the signal caused by planets.

This stellar variability related to active regions may be studied both modelling the currenly available data from space-based missions and generating multi-band data of a simulated active rotating star. This 2-way strategy is presented in sections 2 and 3.

2 Data simulations

We present a package of tools that can be used in order to generate simulated spectral time series data of a spotted rotating star. This can be useful both to:

- Evaluate photometric jitter caused by spots at vs. wavelength. Then, modulation caused by spots in light curves can be correlated for different spectral ranges or filters.
- Evaluate radial velocity jitter caused by activity. Radial velocity measurements precission can be then optimized by selecting the spectral ranges which are less affected by the "noise" produced by active regions.

Therefore, this can be especially important to study the most efficient approach to characterize certain activity effects from observations, and also for the design of exoplanet space missions or astronomic instrumentation and their observing strategies.

In our methodolody to obtain simulated data, a grid of NextGen2 (Phoenix) models are used in order to generate the spectrum (1 nm$< \lambda < 5$ μm) for a stellar photosphere and the cool spots. The imput parameters are $T_{\rm eff}$ (2000 K $< T_{\rm eff} <$ 10000 K), the metallicity (-2.3 $< [M/H] <$ +0.3), the surface gravity (-0.5 $< \log g <$ +5.5), the temperature contrast of the spots ($\Delta T_{\rm S}$, [12]), the rotation period ($P_{\rm rot}$) and the stellar axis inclination (i). A spot map is also defined by introducing the positions and sizes of the cool spots.

The stellar surface is subdivided in a grid of $1^\circ \times 1^\circ$ pixels and the individual spectrum of each pixel is computed considering its local conditions and convolved with a limb darkening function obtained from Kurucz models with the same input parameters. The spectrum is also Doppler shifted according to its local radial velocity. Finally, the spectrum of the whole photosphere is built from summing the contribution of all the visible pixels.

This step is repeated a specific number of times while the projected visibility of the spot map changes according to the stellar rotation. The code is also able to produce light curves by convolving the resulting spectra with a filter bandpass or spectrograph resolution element (Fig. 1), then allowing us to study the resulting modulation produced by different spot distributions. In the current version of the code, no evolution for the active regions is considered. Differential rotation is also expected to be introduced in the near future.

Preliminary results are showing that photometric jitter in late-type stars produced by the presence of spots is much more significant at $\lambda <$ 1000 nm, while the general shape of the modulation is conserved (Fig. 2). For instance, the amplitude of the variability for a specroscopic resolution element ($R \sim 300$) at $\lambda = 700$ is ~ 2.7 times higher than at 5μm (see Fig. 3). On the other, the signal from an Earth-like planet around this type of star will be most easily detected in the near- or mid-IR. Therefore, variability amplitude scales as shown by our simulations can provide the method to remove activity jitter from mid-IR data by using simultaneous observations in the optical or near-IR.

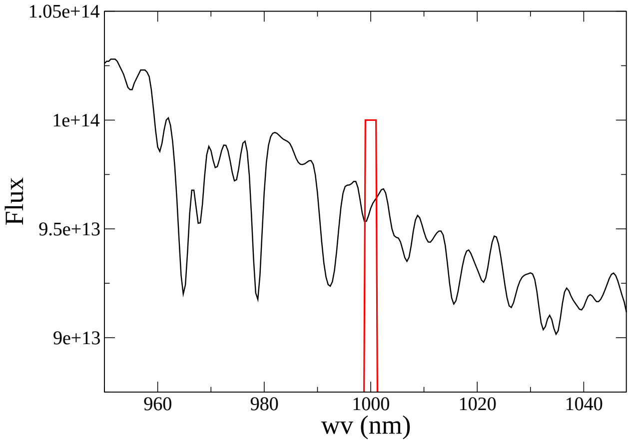

Figure 1: Simulated spectrum for a M0V spotted rotating star, degraded to $R = 300$ (black). Example filter passband used to compute a light curve (red) as obtained with a $R = 300$ spectrograph.

3 Modelling of light curves

Since the discovery of photometric variations due to cool spots, several techniches have been introduced to deduce starspot properties and study activity−rotation relations. The reconstruction of the surface brightness distribution from the rotational modulation of the stellar flux is an ill-posed problem, because the variation of the flux vs. rotational phase contains only information on the distribution of the brightness inhomogeneities vs. longitude. So some a priori information needs to be included in the analysis. Nevertheless, spot modelling of light curves is the main source for our knowledge on active region evolution on stars.

We are currently using the methodology presented by [13] in order to analyse the Kepler light curves from a sample of M-dwarfs. In order to obtain an acceptable fit of the light curve and a stable map of the spot covering factor of the stellar surface, a maximum entropy (hereafter ME) technique is used. This has been proven to successfully reproduce active region distributions and area variations in the case of the Sun [13].

A first fit with a 3-spot model [14] is used in order to estimate the facular-to-spotted area ratio (Q) and the maximum time interval where the spots remain unperturbed δT_{f}. Then, the stellar surface subdivided in 200 surface elements and reconstructed by fitting the filling factor through ME regularization, minimizing a linear combination of χ^2 and the entropy functional S; i.e.,

$$Z = \chi^2(\vec{f}) - \lambda S(\vec{f}), \tag{1}$$

where $\vec{f}$ is the vector of the filling factors of the surface elements, $\lambda > 0$ a Lagrangian multiplier determining the trade-off between light curve fitting and regularization; the expression for S is given in [15].

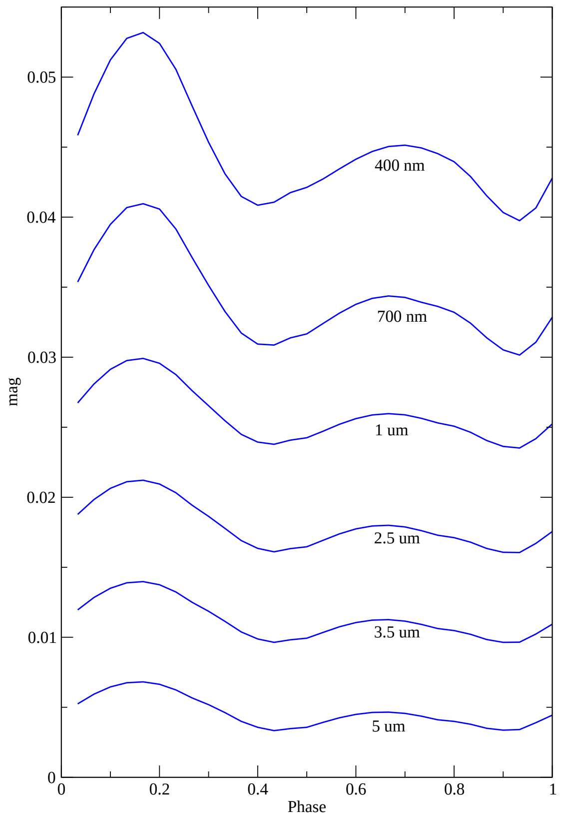

Figure 2: Simulated multi-wavelength light curves for an M0V spotted rotating star with a 4 spots configuration (total filling factor $\sim 0.5\%$) and $R = 300$ passband filters.

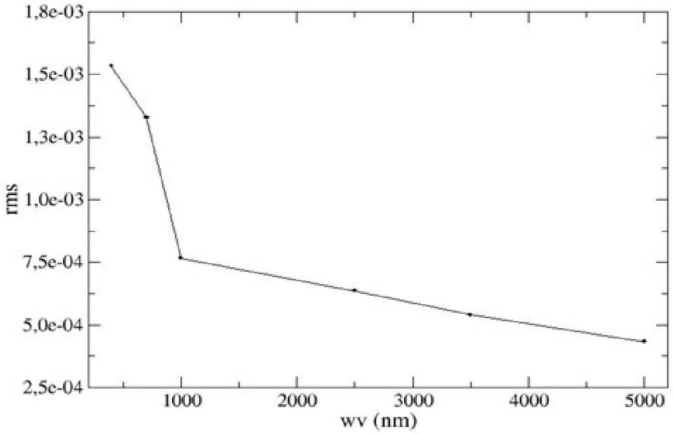

Figure 3: RMS of the fluxes simulated in Fig. 2, showing the decrease in the amplitude of the modulation when observing in the near-IR.

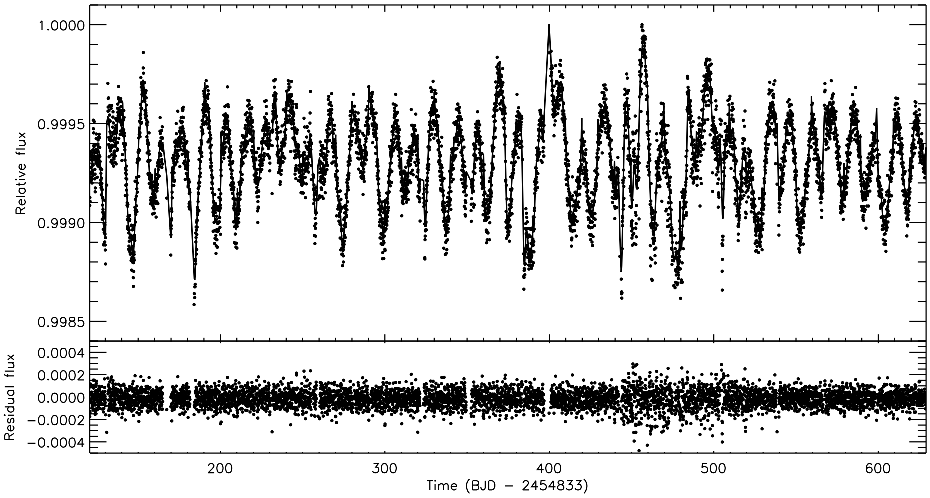

Figure 4: *Upper panel:* The out-of-transit light curve of LHS 6343 (dots) and its ME-regularized best fit for a facular-to-spotted area ratio $Q = 8.0$ (solid line) during the time interval between BJD 2454953.569 and BJD 2455462.163. The flux is normalized to the maximum observed flux along the time series. *Lower panel:* The corresponding residuals.

The modelling has proven to work succesfully even with the limited signal-to-noise (SNR$\sim$30) observations from LHS 6343 A, an M4V star with a brown dwarf transiting companion [16, 17]. The modelling of the out-of-transit light curve reveals several active longitudes rotating with a slightly longer period than the orbital period of the brown dwarf, and we found evidence of a persistent active region on the M dwarf preceding the sub-companion point by $\sim 100^\circ$ and lasting for at least ~ 500 days. This can be relevant for understanding how magnetic interaction works in low-mass binary stars.

4 Future work and conclusion

In order to furtherly extend our capabilities on exoplanet athmospheres characterization and Earth-like planets detectability around low-mass stars, we need to improve our knowledge on the host stars. Especially, the contribution of some activity patterns to observations presents similar amplitude and time scales than the signal caused by planets. Activity jitters at hours-to-days scales can be simulated by using currently available stellar models. These data simulations represent a very useful tool to better understand activity effects on observations and also for the design of astronomical instrumentation optimized for specific observing strategies. Moreover, the modelling of available high precission observations of a wide sample of low-mass stars is essential to obtain evidence of the activity patterns that produce the observed variability power spectrums of stars.

The presented spot modelling technique is to be applied in a wide sample of M-dwarfs in the near future. The results will represent an important feedback as input parameters to generate multiple simulated data. In the generation of this data, important activity effects at

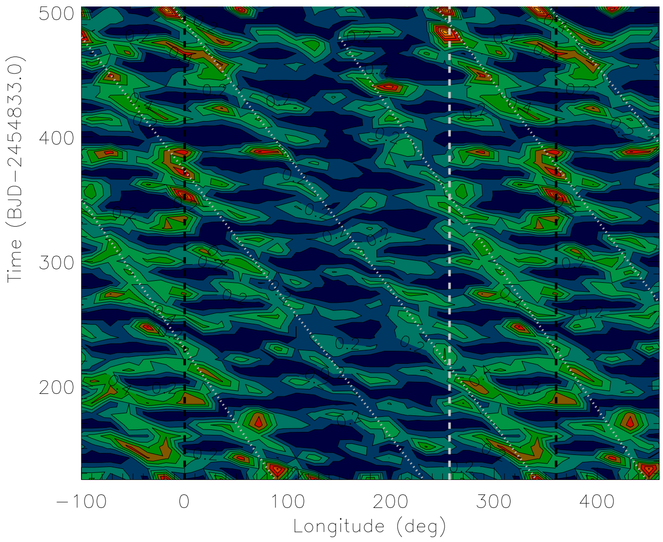

Figure 5: Map of the spot filling factor resulting from the ME modelling of the Kepler light curve of LHS 6343 A. Time is plotted versus longitude of the active regions. The two dashed black lines mark longitudes 0° and 360° beyond which the distributions are repeated to easily follow spot migration. The dashed white line marks the longitude of the sub-companion point, which is fixed in this reference frame at $\sim 257°$. The dotted white lines trace the migration of the main active regions.

the day-scale, such as differential rottation or active region evolution, are being implemented in our code in order to obtain more realistic observations that would be useful in a wider range of astrophysical and instrumental applications.

Acknowledgments

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