MODELING THE RV AND BVS OF ACTIVE STARS

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Abstract. We present a method of modeling the radial velocity (RV) measurements which can be useful in searching for planets hosted by chromospherically active stars. We assume that the observed RV signal is induced by the reflex motion of a star as well as by distortions of spectral line profiles, measured by the Bisector Velocity Span (BVS). The RVs are fitted with a common planetary model including RV correction term depending linearly on the BVS, which accounts for the stellar activity. The coefficient of correlation is an additional free parameter of the RV model. That approach differs from correcting the RVs before or after fitting the “pure” planetary model. We test the method on simulated data derived for single-planet systems. The results are compared with the outcomes of algorithms found in the literature.

1 Introduction

The current spectral Doppler technique makes it possible to measure routinely the radial velocity (RV) of stars with a precision better than 10 ms\(^{-1}\). It is well known that the RV variability may be caused not only by the reflex motion of a star accompanied by smaller bodies, but also by internal activity of stellar atmosphere (e.g., non-radial pulsations, inhomogeneous convection, and/or rotating surface spots). While the reflex motion of the star leads to the Doppler shift of spectral lines, the atmospheric activity may cause distortions of spectral lines profiles (SLP), which displace their measured minima. Fortunately, a determination of the true origin of the RV variability is possible through the analysis of line profiles or the cross-correlation function (CCF). The basic tool for such analysis is the line bisector (LB) technique (Gray 1983, 2005). The most simple and useful measure of the slope of LB is the Bisector Velocity Span (BVS) defined as the difference between the LB velocity measured at some upper and lower flux levels of the SLP.

It is well known (Desort et al. 2007 and references therein), that distortions of SLP caused by stellar activity may produce quasi-periodic RV signals mimicking planetary companions. The BVS analysis are then very helpful to reject or confirm the planetary

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nature of the RV variability. The first case, when the BVS measurements were used to withdraw a hypothesis of a low-mass planet, was HD 166435 (Queloz et al. 2001). In the next years, other stars with low-level RV variations stemming from stellar activity were discovered, for instance, HD 78647 (Setiawan et al. 2004), and HD 219542B (Desidera et al. 2004). In the first two instances, the authors relied on a correlation between the RV and the BVS data, indicating that periodicity of the RV signal has the stellar-activity origin. (Further in this paper we will demonstrate that, in general, such a correlation does not provide sufficient information to reject the planetary hypothesis).

Recently, Bonfils et al. 2007 report a discovery of a “super-Earth” planet orbiting GJ 674 with a 4.69-day period. Besides the strong signal of that planetary candidate, the RV data reveal also secondary, 34.85-day periodicity. The discovery team performed 2-planet Keplerian fits and, using photometric measurements, attributed the second period to the rotational modulation of the RV caused by a stellar spot.

In this work, we propose an alternative method of resolving non-unique sources of the RV variability. It relies on simultaneous analysis of both sets of observables, RV and BVS, within an uniform fit model. In Section 2, we introduce the generalized model of RV. In Section 3, we simulate RV data for our experiments. Section 4 is devoted to RV models and the results, which are finally discussed in Conclusions.

2 Modeling the RV and BVS data

The stellar RV variability caused by the presence of additional bodies may be modeled as a superposition of Keplerian, astrocentric orbits (Smart 1949):

\[ V_r(t) = \sum_{i=1}^{N} K_i \left[ \cos(\Omega_i + \nu_i) + e_i \cos \Omega_i \right] + \sum_{o=1}^{O} V_o, \]  

where \( N \) is the number of planets, \( K_i \) is the semi-amplitude of the \( V_r \) contribution by the \( i \)-th planet, \( \Omega_i \) is for the longitude of pericenter, \( e_i \) is for the eccentricity, \( \nu_i \) denotes the true anomaly (which depends implicitly on the orbital period \( P_i \) and the time of pericenter passage \( \tau_i \)), \( V_o \) are the RV offsets and \( O \) is their number. We search for such parameters \( (K_i, P_i, e_i, \Omega_i, \tau_i, V_o) \), which may explain the RV variability in the sense of the least squares.

When we deal with significant stellar activity, and the BVS measurements are available, we can modify the RV model by adding a correction term, accounting for distortions of the SLP which contribute to the RV variability, \( V'_r(t) = V_r(t) + \Delta V(t) \). In the first approximation, \( \Delta V(t) \) may be expressed through the BVS time series (\( \{BVS\} \) from hereafter), \( \Delta V(t_j) = \alpha \{BVS\}_j, (j = 1, \ldots, N_m) \), where \( N_m \) is the number of observations and \( \alpha \) is a free parameter of the model. In fact, \( \alpha \) depends not only on stellar activity but also on the spectral resolution (Desort et al. 2007), and a particular choice of the upper and lower segments of the LB. Now, following the principle of the least squares, we define the \( (\chi^2_r)^{1/2} \) function of the fit model as follows:

\[ (\chi^2_r)^{1/2} = \left( \frac{1}{N_m - N_p - 1} \sum_{j=1}^{N_m} \frac{[\{RV\}_j - \alpha \{BVS\}_j - V_r(t_j)]^2}{\sigma_{RV,j}^2 + \alpha^2 \sigma_{BVS,j}^2} \right)^{1/2}, \]  

where \( \{RV\}_j \) and \( \{BVS\}_j \) are the RV and BVS measurements, respectively, \( \sigma_{RV,j} \) and \( \sigma_{BVS,j} \) are their uncertainties.
RV and BVS analysis

3 Simulated observations of the RV and BVS

To give an example, and to demonstrate features of our method, we test model Eq. 2.2 on synthetic RV and BVS observations. We consider a star exhibiting periodic activity that mimics planetary RV signal, and we assume that it also hosts a planet. To construct the synthetic data set, we fix the elements of Keplerian orbit, and we simulate the planetary RV signal, \{RV\}^{(pl)}, Eq. 2.1. We also simulate the \{BVS\} data. The synthetic signal, \{RV\} = \{RV\}^{(pl)} + \alpha \{BVS\}. Next, we add Gaussian errors independently to both sets of observables and also non-periodic noise (jitter) which is added to the \{RV\} and \{BVS\} in the same phase. Parameters of the synthetic signals are given in caption to Fig. 1.

For a reference, we assume that a single-planet system has the same orbital and stellar-activity periods. Our choice of stellar parameters follows the first discovery of a star that mimics the planetary signature of RV, i.e., HD 166435 (Queloz et al. 2001). The synthetic curves of the RV and BVS, as well as simulated measurements (the red points) in random epochs, are illustrated in Fig. 1. The first two panels are for the \{RV\} and \{BVS\} time series. The third panel is for a correlation between these observables. Grey, thick line illustrates the linear regression of the stellar-activity contribution to the RV (\{RV\}^{(st)}) on \{BVS\}. Black, thick line marks the linear correlation between the \{RV\} and \{BVS\} sets.

4 Tests of fitting algorithms and the results

The results of analysis of the synthetic data are illustrated in Fig. 2. Panels in this figure are for color-coded maps of \(\chi^2/2\) in planes of selected fit parameters. Contours mark the standard confidence intervals of (1\(\sigma\), 2\(\sigma\), 3\(\sigma\)), respectively. The filled, crossed circles
Fig. 2. Maps of $\chi^2/2$ for the test case. Simulated data are presented in Fig. 1. The left column: the $(P_b, e_b)$-plane; the right column: the $(P_b, K_b)$-plane. Each row is for a different fit algorithm tested in this paper (see the text for details). Filled, crossed circles mark the orbital parameters of the nominal system (given in caption to Fig. 1).

mark positions of the nominal solution in the $(P_b, e_b)-$ and $(P_b, K_b)-$planes (the left- and the right-hand columns, respectively). To compute the $(\chi^2)^{1/2}-$maps, we proceed as follows. We fix a particular point $(x, y)$ in the selected parameter plane, and we search for remaining best-fit elements of the RV model. To search for the best-fit solution, we apply the Monte-Carlo method to choose initial conditions for the fast Levenberg-Marquard algorithm (see, e.g., Goździewski et al. 2008). Such fits are repeated for all points $(x, y)$ of a discrete grid in the given plane of model parameters.

Each row in Fig. 2 is for a different method of modeling the RVs. We start from the most simple (but generally wrong) method I that relies on fitting single-planet model (Eq. 2.1) to the $\{RV\}$ signal, without making any use of additional information “hidden” in the BVS. The results are illustrated in Fig. 2a,b. Clearly, the nominal solution lies...
beyond the 3σ level of the best fit solution. In particular, the fitted \( K \) is significantly larger than the reference value. Both signals, \( \{RV\}^{(pl)} \) and \( \alpha \{BVS\} \), have the same periods, and depending on their relative phase, the semi-amplitude of the resulting \( \{RV\} \) may be larger or smaller than that ones of the planetary signal. In the tested example, the \( \{RV\} \) signal has larger amplitude than the \( \{RV\}^{(pl)} \). Hence, we obtain too large mass of the planetary companion, however, the original orbital period is found correctly.

To improve method I, one may proceed as follows (method II). At first, we find the coefficient \( \alpha_{\text{obs}} \) of the linear correlation between the \( \{RV\} \) and \( \{BVS\} \) signals. Then we subtract a correction term, \( \alpha_{\text{obs}} \{BVS\} \), from the observed \( \{RV\} \) signal. We obtain, as we suppose, a pure planetary signal, so we can fit the single-planet model to corrected \( \{RV\} \) data. The results are presented in Fig. 2.c, d. Again, the derived best-fit solution is displaced from the true position (in particular, its semi-amplitude is badly determined).

To explain that improper outcome of the fit, we look at the right-hand panel of Fig. 1. The grey line is for the correlation between \( \{BVS\} \) and \( \{RV\} \) observables when the star would be alone. If the planet is present then the detected correlation (\( \alpha_{\text{obs}} \), black line) changes. The difference between \( \alpha \) and \( \alpha_{\text{obs}} \) depends on the semi-amplitudes of both signals as well as on their relative phase. Unfortunately, also uncertainties of the measurements (instrumental ones or stemming from the stellar jitter), as well as their irregular sampling may change the correlation coefficient. Then, if we use \( \alpha_{\text{obs}} \) to correct the RVs by the linear term of \( \alpha_{\text{obs}} \{BVS\} \), we may subtract too large or too small correction from the \( \{RV\} \) signal, and the best fit parameters of the orbital solution will be wrong. In contrary to method I, we obtain too small mass of the planet.

The next approach relies on fitting 2-planet Keplerian model to the \( \{RV\} \) data (method III, see Bonfils et al. 2007). We obtain two best-fit Keplerian orbits, moreover, we have to identify which orbit describes the true reflex motion of the star, and which one corresponds to a false orbit mimicked by stellar activity. We did a test of this method and the results are illustrated in Fig. 2.e, f. Still, we do not obtain correct results. The main difficulty in this approach emerges from a non-unique identification of the signals. For instance, a sum of two different (de-phased) RV signals with the same period may look very similar to a composition of two signals with the 2 : 1 commensurability of periods (see, e.g., Goździewski and Konacki 2006). In fact, the second orbital period found in the best fit solution, may be very different from its real value. Method III gives also too large mass of the planet.

Finally, we apply our method IV relying on simultaneous analysis of both sets of \( \{RV\} \)– and \( \{BVS\} \)–observables. We assume that \( \alpha \) is an additional, free parameter of the fit model. Actually, we found that this approach provides the best results, as compared to the outcomes of methods I–III. That is illustrated in Fig. 2.g, h. In this case, the agreement of the reference parameters with the orbital elements of the best-fit solution is basically perfect. Thanks to the self-consistent fitting process, we also find the true correlation coefficient \( \alpha \) of the stellar contribution to the RV, \( \{RV\}^{(st)} \), and the BVS.

### 5 Conclusions

Recently, the line bisectors are routinely derived from the same spectra used to measure the RVs (e.g., the I_2-cell technique, Martínez Fiorenzano et al. 2005). They are much
more useful to understand the origin of the RV variations than alternative, even more indirect observables. The BVS data may help to detect stellar-induced periodicity in the RV signals or to correct the RVs by accounting for the linear correlation between the RV and BVS data. In this work, we also show that these data make it possible to find correct orbital parameters through fitting the planetary model to the RV and BVS data simultaneously. Our method seems to work well, even if there is a close commensurability between periods of both signals. In such a case, other algorithms tested here, provide the best-fit orbital elements which are significantly different from the true, reference solution.

We note that the proposed method omits one more indicator of a distortion of the SLP, the Bisector Curvature (BC). The BCs measure the second order derivative of the LB. It still may be possible to improve the algorithm by using the BCs to correct $\Delta V(t)$. We are going to investigate such an improved method with more sophisticated and realistic simulations of the measurements.

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