INSTITUT DE FRANCE
Académie des sciences

Comptes Rendus

Physique

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Impact of stellar variability on exoplanet detectability and characterisation

https://doi.org/10.5802/crphys.140

Part of Special Issue: Exoplanets
Guest editors: Anne-Marie Lagrange (LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France.) and Daniel Rouan (LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France.)

Les Comptes Rendus. Physique *sont membres du*
Centre Mersenne pour l'édition scientifique ouverte
www.centre-mersenne.org
e-ISSN : 1878-1535

Comptes Rendus
Physique

`https://doi.org/10.5802/crphys.140`

Exoplanets / *Exoplanètes*

Impact of stellar variability on exoplanet detectability and characterisation

Impact de la variabilité stellaire sur la détectabilité et la caractérisation des exoplanètes

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Abstract. Stellar variability has become a major issue to detect low mass planets using the radial velocity technique. I present the approaches followed to characterise the amplitude and the properties of stellar variability in radial velocity. More specifically, the approach consisting in using our knowledge of the Sun to understand better the different processes which are occuring at different scales proved to be very useful. This has been done in different ways, based on observations and models. This is crucial because it is then possible to compare disk-integrated radial velocities with actual structures on the solar surface, such as spots and plages, and with photospheric flows at different spatial scales. Many physical processes indeed affect the radial velocity measurements: they are mostly due to magnetic features (spots and plages), flows (oscillations, granulation, supergranulation, meridional flows), and to the interactions between magnetic fields and flows (inhibition of the convective blueshift in plages). I present in more detail a selection of studies aiming at characterising the impact of stellar variability, in particular the relationship between activity indicators and radial velocities, and then focusing on mass characterisation and detection performance. Finally, I briefly review the impact of stellar variability on photometric transits and astrometry, which are also affected, but to a lesser extent.

Résumé. La variabilité stellaire est devenue un problème majeur pour détecter les planètes de faible masse en utilisant la méthode des vitesses radiales. Je présente les approches suivies pour caractériser l'amplitude et les propriétés de la variabilité stellaire en vitesse radiale. Plus précisément, l'approche consistant à utiliser notre connaissance du Soleil pour mieux comprendre les différents processus qui se produisent à différentes échelles s'est avérée très utile. Cela a été fait de différentes manières, sur la base d'observations et de modèles. Ceci est crucial car il est alors possible de comparer les vitesses radiales intégrées au disque avec les structures réelles de la surface solaire, telles que les taches et les plages, et avec les flux photosphériques à différentes échelles spatiales. De nombreux processus physiques affectent en effet les mesures de vitesse radiale : ils sont principalement dus aux caractéristiques magnétiques (taches et plages), aux écoulements (oscillations, granulation, supergranulation, circulation méridienne), et aux interactions entre les champs magnétiques et les écoulements (inhibition du blueshift convectif dans les plages). Je présente plus en détail une sélection d'études visant à caractériser l'impact de la variabilité stellaire, en particulier la relation entre les indicateurs d'activité et les vitesses radiales, puis je me concentre sur la caractérisation des masses et les performances de détection. Enfin, je passe brièvement en revue l'impact de la variabilité stellaire sur les transits photométriques et l'astrométrie, qui sont également affectés, mais dans une moindre mesure.

Keywords. Exoplanets, Stellar variability, Radial velocity, Photometric transits, Astrometry.

Mots-clés. Exoplanètes, Variabilité stellaire, Vitesses radiales, Transits photométriques, Astrométrie.

Note. Follows up on a conference-debate of the French Academy of Sciences entitled “Exoplanets: the new challenges” held on 18 May 2021, visible via https://www.academie-sciences.fr/fr/Colloques-conferences-et-debats/exoplanetes.html.

Note. Fait suite à une conférence-débat de l’Académie des sciences intitulée « Exoplanètes : les nouveaux défis » tenue le 18 mai 2021, visible via https://www.academie-sciences.fr/fr/Colloques-conferences-et-debats/exoplanetes.html.

1. Introduction: the challenge

Since the discovery of the first exoplanet around a main sequence star [1], 51 Peg b, over 5000 exoplanets have been detected using a large panel of techniques. They show a very large diversity in exoplanet properties and system architectures, as well as planets that are very different from those of our own solar system, for example Hot Jupiters like 51 Peg b, or very compact systems such as TRAPPIST-1 [2]. Most of the techniques to detect exoplanets are indirect however, in the sense that they are based on the analysis of the light coming from the star only (and not from the planet). In the case of the radial velocity technique for example, on which I focus in this paper, the presence of a planet orbiting the star leads to a motion of the star around the barycenter of the system, and the line-of-sight velocity of the star can be monitored to ascertain the presence of the planet. However, because it is an indirect technique, it suffers from several caveats. First of all, instruments with an excellent long-term stability must be devised. This has been the case for example with HARPS, and later with ESPRESSO, together with a large panel of other instruments. This stability is however challenged by possible modifications of the instrument during the lifetime of the instrument, such as the fibre change on HARPS in 2015 [3], which also affect RV measurements. Furthermore, it has been recognised early-on [4] that stellar activity, by modifying the shape of the lines, would also perturb RVs. They therefore impact detectability, as the planetary signal can be hidden in the stellar “noise”, or, even worse, the activity signal can be mistaken for a planet. The latter case has happened several times over these last 27 years of discoveries. The detection issue is a real challenge for the detection of low-mass planets, because it has been shown [5–7], based on different approaches using the Sun as a reference, that the amplitude of the stellar signal could be very strong, up to two orders of magnitude larger than the Earth signal, despite the fact that the Sun is a moderately active star: this is a critical challenge for the coming years. The lower envelope of the mass of the detected planets based on the RV technique as a function of discovery date shows a steady decrease after 1995, due to the improvement in instrument stability and the availability of longer time series, but has been stagnating over the last 10 years. Furthermore, the low-mass planets which have been detected orbit around very low mass stars and not solar-type stars.

This is most likely due to stellar variability, which has become dominant compared to instrumental limitations. In this paper, I focus on the RV techniques, which are affected by many stellar processes, due to the presence of magnetic structures on the surface, to photospheric flows at different spatial and temporal scales, and to the interaction between magnetic fields and flows. Many groups have therefore addressed this issue, to characterise the amplitude and properties of the signal due to stellar variability, to elaborate innovative correcting techniques. The three first sections of this paper are therefore devoted to the impact of stellar variability on exoplanet detection. In Section 2, I describe the different approaches that have been implemented to tackle with stellar variability. A general overview of the different physical processes involved is given in Section 3, as well as their main properties. Finally, in Section 4, I present in more details several studies aiming at characterising the impact of stellar variability, in particular in terms of detection performance. This does not represent an exhaustive review of all studies on the subject however, as I focus more on certain approaches and do not describe in detail all techniques that have been implemented to correct for the stellar contribution. Then in Section 5, I briefly describe the impact of stellar variability on photometric transits and astrometry, which are also affected but to a lesser extent, because many processes affecting RVs are directly due to flows, with no impact on those two techniques. I conclude in Section 6.

2. Approaches

A large panel of approaches have been implemented to understand the impact of stellar variability on RV. Because there are many processes involved, it is important to predict and compare the expected amplitudes of these processes at different time scales. Their respective properties depend on spectral type for example, or on the average activity level of the star. Because various mitigating techniques, based on a large panel of independent activity indicators (i.e. observables which are not affected by the presence of the planet, such as chromospheric indexes, photometry, or spectral line properties), have been used, it is also crucial to understand how these different techniques and indicators are impacted and relate to each other in different conditions (i.e. planetary period, spectral type, activity level of the star). This should allow to quantify the impact of these processes on two types of studies. First, RVs are used to estimate the mass of planets which have been detected using photometric transits. Transits indeed provide the radius of the planet (relatively to the stellar radius), but not the mass. A good knowledge of this mass is however critical to derive the planet density and then compare with models: it can be obtained using the RV technique during follow-up observations (RVs provide the projected mass along the line-of-sight, but in case of a transit, the inclination is well constrained). The objective is to be able to reach good uncertainties on the mass to be able to obtain low uncertainties on the planet density and differentiate between internal structure models. Second, blind searches of planets in the framework of large RV surveys have been implemented for different types of stellar samples by many groups, and it is important to characterise the detection performance for different types of planets (terrestrial or giant, close to their star, in the habitable zone or at very long period), stars (solar-type stars or M dwarfs for example), and observational strategies. Blind tests can therefore be implemented to answer both questions (mass estimation in RV follow-ups and detection) and quantify the expected performance.

These questions have been addressed using very different data sets. First, large samples of stellar RV time series, associated to various activity indicators, have been studied to empirically establish correlation (or lack of correlation) between observed RVs and these indicators depending on the type of stars, see for example [8, 9]. Although most studies are usually based on small samples, often when a planetary candidate is detected justifying a detailed analysis of the stellar properties, it is indeed crucial to study large samples to cover a wide range of conditions.

Another approach has been based on our very good knowledge of solar activity, both observationally and theoretically, to directly explore the impact of stellar variability on RVs and activity indicators. The proximity of the Sun, allowing a very good spatial and temporal resolution, and guaranteeing observations of a large amount of photons over long periods of time, is extremely favorable to tackle with this problem. We note that the Sun is however not representative of all stars of any masses or any evolutionary stage for example, so that those approaches will present limitations if applied to other stars.

This latter approach has been followed using different methods, which are detailed here. The observation of the Sun is naturally a good way to obtain answers, either directly or indirectly. Historically, it has been difficult to observe the solar RVs on long timescales with the proper stability. Therefore, first works were based on a reconstruction of the solar integrated RV, from observed velocity maps [6, 10–12], usually focusing on the contribution of spots and plages, or reconstructions based on a model (see below). A similar reconstruction has been made from observed meridional circulation [13]. The solar light can also be observed indirectly, for example with asteroids, the Moon, or Jupiter satellites [14]. A crucial step has been achieved with the possibility to observe the Sun as a star using stable stellar spectrographs, first with HARPS-N [15–18]. The advantage of such observations is that they take all physical processes into account, including possible unidentified ones or processes which are not yet well characterised. Furthermore, even if all processes are therefore mixed and cannot be studied separately, it is possible to compare the observations with the features that are actually present on the solar surface. It also has the advantage that it is possible to study a time series for which we are sure there is no unknown planet signal.

Another crucial approach is based on forward modelling of the RV due to stellar variability, starting with the Sun and then extrapolating to other stars. The solar variability is due to complex activity (spots and plages) pattern which can be modelled realistically by generating random structures with well-constrained properties [19–22]. Another important source of variability comes from surface flows at various spatial and temporal scales, and in particular oscillations, granulation and supergranulation. Granulation in particular has been modelled based on HD or MHD simulation of the solar surface to produce RV time series [23, 24], from laws derived from HD simulations [25], or from solar observations [26,27]. The advantage of such simulations is that it is then possible to extrapolate them to stars other than the Sun, including various configurations (inclinations different from edge-on) and activity levels. As for direct solar observations, this also allows to study time series with no exoplanet contamination. In addition, longer time-series can be analysed, although they do not necessarily include all processes. This proved to be very efficient to test the performance of different methods by exploring systematically a large parameter space, both describing the planet or the star. It also allows to study the different processes separately to better understand their behaviour.

Finally, another possibility is to join the two approaches, by reconstructing the solar integrated RV from observed solar features such as spots or plages, based on a model [7, 28, 29]. This allows to establish a link between observations and models and to test those models.

In parallel, many groups have developed different techniques to be able to account for the stellar contribution to RVs in order to improve the detectability of exoplanets. I give here a brief and non-exhaustive overview. They are based on several types of approaches:

- Use of the information in the RV time series alone, such as the fit of sinusoids around the rotation period and harmonics and pre-whitening [30–32], spot modelling if the temporal sampling is sufficient [33–35], averaging of the signal [36], and periodogram standardisation [37].
- Use of activity indicators computed from the same spectra than the RVs, for example correlation with the bisector span [38], line depth [39], or chromospheric emission [40–42], gaussian processes based on those indicators [43–46], PCA analysis [47], Doppler imaging techniques [48], CCF shape [49], or magnitude-squared coherence comparison [50].
- More complex computation of RVs, for example of subsets of spectral lines to produce independent RV time series [51], use of selected lines with different sensitivity to magnetic field [52–54], PCA analysis of the spectra [55], and wavelength dependence of the signal [56].
- Use of external activity indicators, mostly photometry, as in the ff' method proposed by [57].

A large number of methods has been compared, to quantify detection performance [44, 58] or residuals after correction without injecting planets [59]. In addition, efforts have been devoted to improve the determination of the false alarm level [37, 60–63].

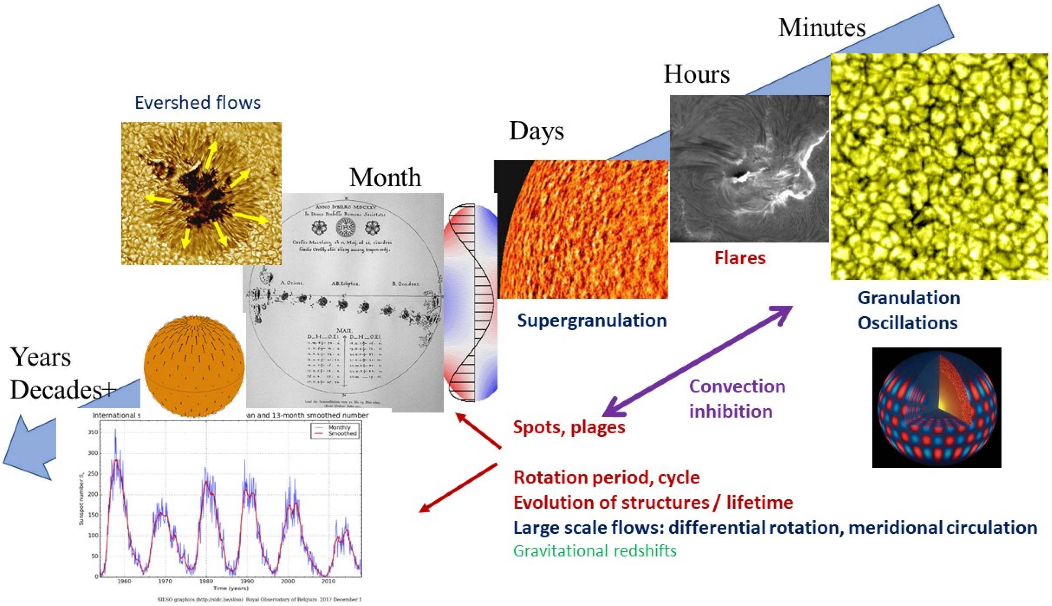

Figure 1. Overview of the different processes at play, due to magnetic regions (red), flows (blue), interaction between the two (purple), and gravitational redshift (green). Typical time scales indicated here correspond to the Sun. Granulation image: Pic du Midi Observatory; Flare: Hα image, Big Bear Solar Observatory; Supergranulation: Dopplergram MDI/SOHO; oscillations: example of a mode from the GONG project, NSO; differential rotation: NASA/Marshall Solar Physics; spot drawings: Scheiner, 1625; Evershed flows: photosphere image from Vacuum Tower Telescope, NSO/NOAO; meridional circulation flows: Figure 1 from [66] (© AAS. Reproduced with permission); spot number versus time from SIDC. Figure reproduced from [64].

3. Physical processes impacting radial velocity measurements

In this section, I describe the different processes which have been identified to impact RV measurements. They deform the lines and/or shift them, so that they perturb the estimation of the RVs, which is usually made assuming a symmetrical shape of the lines. Figure 1 presents a summary of the different categories of processes, organised by typical temporal scale [64]. Some are directly due to the presence of magnetic structures, mostly because of their contrast. The flows in the photosphere also directly affect the RVs, at different time scales. Magnetic fields interact with flows and therefore also produce additional contributions. These processes are described in more detail below. Finally, the gravitational redshift also affects radial velocities, for example if there is a radius variability, but the effect is expected to be small for main sequence stars [65].

3.1. *Magnetic activity: impact of spots and plages*

A first important contribution comes from the temperature contrast of (dark) spots and (bright) plages, both related to strong magnetic fields in the photosphere. As the star rotates, this deficit or excess in flux affects different positions in the spectral lines over time, because of the rotational broadening. This leads to an RV variability over time, since lines are distorted and the average position of the lines as measured by a symmetrical profile is biased in one direction or the other (the impact is null when on the central meridian). Simple simulations with one spot were performed corresponding to various configurations (such as rotation rate, inclination, latitude) [34, 67, 68], as well as simulations based on complex activity patterns [5, 7]. The presence of spots and plages also impacts the bissector span of the cross-correlation function of the spectrum, as well as its width, which provides an additional diagnosis.

Since spots and plages exhibit a strong magnetic field, from a few 100 G to a few kG on the Sun, many lines are affected by the Zeeman effect, which could also distort lines and therefore bias the RV measurements. Their impact has been studied by [69], who concluded that it was expected to be weaker than the contrast contribution in the visible. However, with current (CARMENES, SPIRou) and future (NIRPS) instruments in the infrared domain, this effect may have to be taken into account in the near future, while the contrast effect is expected to play a weaker role in this wavelength range.

3.2. *Surface flows at different scales*

The photosphere of stars is submitted to flows at various spatial and temporal scales, which are also affecting RV measurements: oscillations, granulation, supergranulation, and meridional circulation. Oscillations are affecting the whole surface and correspond to many modes at different frequencies. In the case of the Sun for example, the typical frequencies are around 5 min. This contribution is relatively easy to average out because it is composed of periodic components [36, 70]. It should be noted that in addition to these modes, which are well studied in asteroseismology, specific modes can lead to contribution at longer timescales, for example sectoral modes at a fraction of the rotation period, with an amplitude of a few 10 cm/s [71].

Granulation is a small-scale convective pattern, which manifests itself by 1000 km cells with a strong intensity contrast and strong flows (~1 km/s). They have a very stochastic behaviour, and the average velocity over many granules is not exactly zero, leading to a significant jitter, most likely around 0.4 m/s for the Sun, from observations [72] and MHD simulations [24] and amplitude estimations by [23, 73] (see also the review by [74]). With a typical lifetime of granules of the order of 5–10 min, the power spectrum is increasing from high frequencies to lower frequencies, and then reaches a plateau after a turnover frequency which depends on the lifetime of the structures [75]. Simulations based on the properties of granules derived from MHD simulations confirmed this behaviour, although with a larger amplitude of 0.8 m/s, and the difficulties to average it by more than a factor ~2 [25].

At a larger scale, supergranulation is constituted of larger cells (30 Mm) with no measurable intensity contrast [76], typical horizontal flows of a few 100 m/s, and a longer lifetime (typically 24–48 h) [77, 78]. Ref. [75] proposed a law similar to that of granulation for the power spectrum, with a turnover corresponding to larger time scales. Ref. [25] showed the importance of this contribution, with a median estimate of the jitter of 0.7 m/s and a lower limit of 0.28 m/s. Their impact on radial velocities has been quantified in [26, 27].

Finally, meridional circulation is a global-scale flow, related to the conservation of angular momentum and the presence of differential rotation. On the Sun, photospheric meridional flows are poleward. When integrated on the whole disk, the corresponding contribution to RVs is changing if the flows are variable [66]. Based on a long time series of solar meridional circulation measurements [79], it was shown that the variability due to these large scale flows could be crucial [13]. The sign changes for medium inclinations, and the variability for stars seen pole-on compared to edge-on are anticorrelated. However, depending on rotation and inclination, the amplitude can be as large as 1.7 m/s for the edge-on configurations (and a few m/s for the pole-on configurations), varying on cycle timescales and possibly with small phase difference between them.

3.3. *Interaction between surface flows and magnetic activity*

Due to the presence of small-scale convection (granulation), the surface of stars appears to be shifted due to the correlation between intensity and flows (compared to a star with no convection): for a solar-type star, upflows correspond to the largest fraction of the surface (granules) and are brighter than average, while downflows correspond to a smaller fraction of the surface (intergranules) and are darker than average: therefore, on average, there is a convective blueshift, compared to a star with no convection. The correlation between intensity and velocity depends on the height where the line is forming, therefore leading to an amplitude of the effect depending on line depth, and on line distortion [80]. Because of the presence of strong magnetic fields in plages however, this convective blueshift can be partially inhibited (leading to smaller granules and weaker flows): as the plage filling factor is changing with time (corresponding to different activity levels during the cycle, in addition to a modulation by rotation), the amplitude of the inhibition varies, leading to a variation of the measured RV [4]. This effect has been shown to be the dominating contribution in the solar case, with peak-to-peak over the solar cycle up to 8 m/s [6, 7].

Other flows related to magnetic activity could also impact RVs. This is the case of strong flares for example. Their impact is expected to be small for solar-type stars, but outliers corresponding to flares are observed for very active M dwarfs. Also associated to spots, radial flows for example like the Evershed effect are observed for the Sun: if they are irregular and not symmetric, they could also distort the RV signal [12].

3.4. *Global view*

In this last section, we present results obtained when directly observing the Sun as as a star. There is traditionally a lack of long-term stable RV measurements for the Sun, because solar instruments are either focusing on spatial resolution or small field-of-view observations, or on short timescales processes such as oscillations. Earlier works therefore found a diversity of ranges, from a large variability of 30 m/s (long-term) and 20 m/s (short-term) in the K 7699 Å [81] and at 2.3 μm [82], to a small variability below 4 m/s based on deep lines [83]. More recently, based on GOLF data allowing only short-term analysis, [24] found a variability due to granulation of the order of 0.4 m/s.

It is only recently that it was possible to observe the Sun as a star with a long-term stability as good as stellar observations with HARPS-N [15, 16]. The last reduction of those high-cadence observations [18], with an improved data analysis, provides an extremely useful reference 3-y time-series, since it includes all solar processes, is planet-free, and can be compared to actual features on the solar surface for a better understanding of the processes. These observations correspond to the end of cycle 24 however: it therefore does not include the passage by cycle maximum, and corresponds to a low activity period. Yet, there is a strong long-term trend in the data corresponding to the cycle variation, as well as power in the period range corresponding to rotation and differential rotation as expected, and some power around 200 d which may also be due to solar variability. The day-to-day variability is around 1 m/s, which includes a very low amount of noise (given that the daily observations cover up to 6 h, leading to a very low SNR on the RV daily values), a small contribution from the difference in position of active regions from one day to the next, a small residual from granulation, and probably mostly supergranulation.

4. A few applications

In this section, we describe some dedicated studies which have been implemented on synthetic time series or on a large sample of stars, to better characterise the impact of stellar variability on radial velocities. They can be used to better understand the behaviour of the activity indexes in relationship with RVs (two first sections), and allow to perform blind tests to quantify the performance (two following sections).

4.1. *Understanding the limitations of the linear relationship with activity indicators*

For some stars, the presence of a correlation between the RV time series and the $\log R'_{HK}$ activity indicator has been widely used to either check if the presence the presence of a peak in the periodogram of the time series could be due to activity, or to correct the RV time series based on a linear correlation. We focus here on the latter use of this activity indicator. The correlation arises from the fact the convective blueshift, producing a signal at both the rotational timescales and on longer timescales (cycle), is strongly correlated with the filling factor of plages, as is the $\log R'_{HK}$. If this process is dominating, the correlation is therefore strong. However, the other processes are degrading the correlation, and leads to some limitations [84]. Furthermore, even when considering only this process, the relationship is not linear, as shown in [22] based on a large panel of simulations of realistic RV and $\log R'_{HK}$ for solar-type stars of different activity levels [20]. This is due to the combination of two effects. The first one is that the activity pattern is not always in the same latitude range over the cycle, i.e. on long timescales: Therefore, as the average position of the plages on the disk varies with time, it corresponds to different average center-to-limb distances over time. The second effect is that both processes (inhibition of the convective blueshift and chromospheric emission) suffer from different projection effects. There is therefore a departure from the linear correlation, which should be taken into account [85], with a non-linear dependence of the RV on $\log R'_{HK}$ as well as a dependence on cycle phase.

4.2. *How do activity indicators relate to various contributions to RV?*

A large sample of stars observed with HARPS has been used to study the relationship between the $\log R'_{HK}$ activity indicator and four other indicators derived from the cross-correlation function (CCF), i.e. the CCF bissector span, the CCF full width at half maximum (FWHM), the CCF contrast and the CCF area [9]. These 5 indicators were also compared to the RV variability on long timescales, as a function of spectral type. They found that long-term RV variations are correlated with $\log R'_{HK}$, CCF bissector span and FHWM for F and G stars, with the notable exception of the Sun which shows almost no correlation between RV and CCF FWHM, as do a few F stars. In addition, the CCF contrasts and areas tend to be anticorrelated with RVs. On the other hand, K stars exhibit a larger dispersion in correlations. This dependence on spectral type could be due to F and G stars being more plage-dominated while K stars could be more spot-dominated [17]. The large presence of a strong correlation between $\log R'_{HK}$ and RVs was also observed by [8], with also a trend as a function of effective temperature, which can be explained by the decrease of the convective blueshift from F to K stars [51, 86, 87]. The presence of a few K stars with an anticorrelation between $\log R'_{HK}$ and RVs [8, 9] has been interpreted as the possible presence of a convective redshift. This is however not corroborated by independent studies of the convective shift on a very large sample of stars of similar spectral type, and importantly including these stars [51, 86, 87], who found only positive convective blueshifts down to 4100 K. The solution to this puzzle must lies somewhere else. A possibility for such observations could be the presence of meridional circulation [13].

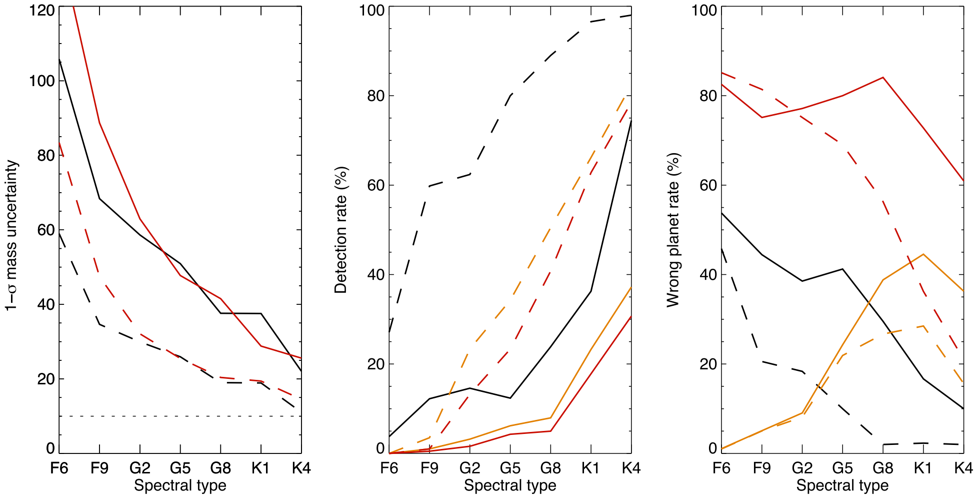

Figure 2. Mass uncertainties in RV follow-up (left panel), detection rate (middle panel) and wrong planet rate (right panel) in blind searches versus spectral type, for 1 M_{Earth} (solid line) and 2 M_{Earth} (dashed line) in the habitable zone, for a a realistic amplitude of oscillation, granulation and supergranulation alone, adpated from [27] (in black, sampling of 1266 nights over 10 years), and for a signal dominated by magnetic activity, adapted from [85], for a sampling of 1000 nights over 10 years (in red: planet search in the whole period range; in orange: planet search at long period only).

4.3. *Impact on performance in terms of mass estimation*

Exoplanet detected using the transit technique must be characterised further using RVs. The transits indeed provide the period of the planet, as well as its radius relatively to the stellar radius. However, the mass cannot be estimated from the transits, which is crucial to derive the density of the planet and therefore to compare with internal structure models. The mass can be derived from the amplitude of the RV planetary signal however. The objective of PLATO mission is to detect Earth-like planet on the habitable zone around solar type stars using photometric transits. To determine the mass of those planets, with an objective of 10% in precision, RV follow-ups will be implemented to characterise the planetary candidates. Stellar activity will however strongly degrade the achievable precision [85, 88]. A few results are illustrated in the left panel in Figure 2. Simulations made for RV follow-ups of typically 1000 observations over ten years shows that for G2 stars, the expected precision is of the order of 50–60% for a 1 M_{Earth}, i.e. significantly above the objective of 10%, when using a detection method based on a non-linear relationship between RVs and $\log R'_{HK}$. This precision significantly improves for larger masses (typically 15% for a 4 M_{Earth} planet) and towards K stars (typically 20% for a 1 M_{Earth} in the habitable zone around a K4 star). Mitigation of stellar activity must therefore be significantly improved over the next 4–5 years to reach the objective of 10% for G2 stars, typically down to RV rms of the residual around 0.3–0.35 m/s (for this temporal sampling).

4.4. *Impact on performance in terms of detection rates and false positive*

The first blind test was organised by [44], with several synthetic time series and controlled injected planets analysed by several teams in [52]. Several correction techniques were tested: Those based on gaussian processes performed the best in this blind test. A criteria was defined, showing that for $K_{pla}\sqrt{N_{obs}}/rms$ (where K_{pla} is the amplitude of the planetary signal, and rms the root-mean-square of the time series after a given correction) higher than ~7.5, the results were globally good, while below this threshold, they were in general corresponding to a poor performance. A smaller blind test performed on a more limited sample of six time series by [58] focused on comparing Bayesian approaches and their robustness with respect to each other, but was based on gaussian noise to model the stellar contribution.

Blind tests have also been implemented on a very large panel of realistic synthetic time series, covering the F6-K4 spectra type range, and for stars of different activity levels. From these planet-free time series, it is possible to test different sampling, to add noise of different amplitudes, or other stellar variability contributions, and to inject a planet which can be retrieved in a blind test. The objective is to determine the detection rate of such planets, and to see whether wrong planets are detected and the level of false positives. To be able to consider a very large number of realisations, we adopted the following simple protocol [26,27,85]: After injection of a planet (or no injection for some realisations), the time series is corrected for stellar variability using a synthetic time series of $\log R'_{HK}$ (when magnetic activity is present), the periodogram of the residual is computed as well as a false alarm probability (fap) level of 1% based on a bootstrap approach. The highest peak in the periodogram is identified, and if higher than the fap, it is considered to be a detection. This detection can be compared to the injected planet, and in particular its period, and for the detections close to the true period (considered to be good detection), the distribution of the fitted mass can be determined. Granulation and supergranulation significantly affect the performance of exoplanet detectability, especially with the upper bound in supergranulation amplitude, leading in this case to poor detection rates and a high level of false positives [26, 27]. The impact is however dominated by the presence of active regions (middle and right panels in Figure 2), which leads to very poor detections rates for G2 stars (almost no detection for a 1 M_{Earth} in the habitable zone of a G2 star) and very high levels of wrong planets, which are found mostly at low periods, but they are found at long periods at a level far above 1% [85, 88].

5. Impact of stellar variability on photometric transits and astrometry?

Photometric transits and astrometry are much less affected by stellar variability, because less processes are involved: the spot and plage contrast is the main contribution to the variability in this case as well as granulation. Furthermore, the transits occur only at specific times, and usually at timescales very different from the stellar timescales. It is therefore easier to separate the two signals compared to RVs. Concerning astrometry, the relative amplitude between the planetary signal and the stellar contribution is also more favorable than for RVs.

Stellar activity has not been so far a strong limitation to detect photometric transits. However, stellar variability affects the photometric transit properties, mostly the transit depth, due to the presence of spots and plages, as well as granulation. In addition, it also affects the estimation of stellar parameters (for example limb darkening), which in turn also impact the transit modelling [89]. Spots and plages affect the transit depth in two ways. First, they can be non-occulted by the planet, and different approaches to model the light curve has been proposed, e.g. [90, 91]. On the other hand, they can be occulted by the transit, distorting the profile of the transit [90, 92, 93], with some degeneracy between spots and plages. The impact on the planet radius reaches a few percents. The presence of granulation also affects the transit depth [94] with a strong effect for Earth-like planets around solar type stars, which can be as high as 10% [95]. This type of impact is critical for PLATO [96] and for future observations with JWST [97] and more generally to all transit spectroscopy studies (e.g. [98, 99]). In addition, spots and plages affect transmission spectroscopy because they are wavelength-dependent. They can create trends in the spectra or molecular spectral signal, such as water for example. The knowledge of the host star activity level and property (size, contrast) is therefore critical to interpret those transmission spectra [89].

The impact of stellar variability on high precision astrometry measurement has been considered early-on with very simple models. More complex synthetic time series have then be reconstructed for the Sun seen edge-on [28, 29], showing that for stars like the Sun or slightly more active, stellar variability was small, with a jitter of typically 0.05–0.07 µarcsec in both directions for a Sun at 10 pc. Such simulations have then been extended to more configurations (inclination, activity level), and for a large array of spectral types (F6-K4). A first series of blind tests have been made systematically for this very large set of simulations, for a star at 10 pc [100]. The temporal sampling of the synthetic time series was the one proposed for the THEIA mission [101, 102], with 50 observations covering 3.5 years and a typical uncertainty on individual measurements of 0.2 µarcsec. The detection rates are excellent, above 50% for such Earth-like planet in the habitable zone, if technological challenges can be overcome to reach such a high-precision astrometry. Dedicated blind tests have also been done for the most promising targets in the solar neighbourhood, again for the THEIA mission [103]: The detection limits were recomputed using these realistic time series and confirmed the low impact of stellar activity. The closest stars in the THEIA target list, α Cen A and B, are more strongly affected due to their proximity, but their detection limits remains very small (below 1 $\mathrm{M}_{\mathrm{Earth}}$ in the habitable zone), since the astrometric signal of planets orbiting those stars would be large as well. The subgiants in the target list of [101] are not very promising however, due to their habitable zone corresponding to larger periods, which cannot be well characterised by the proposed duration of the mission.

6. Conclusion

In conclusion, many processes affect radial velocity measurements at all time scales, ranging from minutes to years. Apart from the dominating contribution of the inhibition of the convective blueshift (in the solar case, two orders of magnitude larger than the Earth signal) and possibly meridional circulation, which have a large amplitude, most contributions are in the 0.3–1 m/s range, which makes them difficult to identify and correct. In addition, stellar variability associated to magnetic regions exhibit a complex and stochastic pattern (number of structures, sizes, latitudinal distribution, lifetime, stochastic variability over the cycle), and are associated to differential rotation, which also contributes to make the task of modelling their contribution difficult. The sum of different contributions can also be associated to strong degeneracies (in particular between spots and plages), leading to complex relationships with activity indicators. Finally, the time scales of each phenomena, although relatively well known, does not mean that they impact the search for exoplanet only at the corresponding periods, as shown for example for the small-scale granulation or supergranulation which may affect the signal at long periods as well. Among the different approaches implemented to tackle with this issue, the use of our knowledge of the Sun in different ways proved to be very fruitful. It also illustrates the strong challenge faced when searching for Earth analogues around solar-type stars: it is very likely that very long time series will be necessary, as well as complementary techniques to ensure the robustness of the detections.

Conflicts of interest

The author has no conflict of interest to declare.

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