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ASTRONOMY AND ASTROPHYSICS

The CORALIE survey for Southern extra-solar planets*

IV. Intrinsic stellar limitations to planet searches with radial-velocity techniques

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Abstract. Activity related phenomena can induce radial-velocity variations, which can be very important when dealing with extra-solar planet search programmes requiring high-precision radial-velocity measurements.

In this paper we present a new chromospheric activity index, $S_{\rm COR}$, based on the Ca II H line central reemission, and constructed using CORALIE spectra. After one year of measurements, values of $S_{\rm COR}$ are available for a sub-sample of stars of the Geneva extra-solar planet search programme. After transforming the $S_{\rm COR}$ values into the Mount-Wilson "S" scale we obtained values of the Ca II H and K flux corrected from photospheric emission ($R'_{\rm HK}$) for the stars. The first results are presented, and in particular we focus on the study of the relation between the observed radial-velocity scatter and the chromospheric activity index $R'_{\rm HK}$, for F, G and K dwarfs.

Key words: techniques: radial velocities – stars: planetary systems – stars: activity – stars: starspots

1. Introduction

High precision (some $\rm m\,s^{-1}$) radial-velocity measurements give astronomers the possibility of detecting giant planets around other stars. To date, more than 30 extra-solar giant planets were discovered, and many others are expected to be found in the next few years (see e.g. Marcy et al. 2000 or Marcy & Butler 1998 for a review on the subject, and Queloz et al. 2000a, Udry et al. 2000, Santos et al. 2000a, Mazeh et al. 2000, Vogt et al. 2000, Naef et al. 2000, and Marcy et al. 2000 for the most recent announcements).

These techniques however, are not sensible only to the motion of a star around the center of mass of a star/planet system. Intrinsic variations, such as non-radial pulsation (Brown et al. 1998), inhomogeneous convection or spots (Saar & Donahue 1997) are expected to induce radial velocity variations, which can prevent us from finding planets (if the perturbation is larger than the orbital radial-velocity variation) or give us false candidates (if they produce a periodic signal over a few rotational periods).

The physics of the photospheric perturbations that produce the intrinsic radial-velocity variations is not easy to model (at least in detail). In one hand, the amplitude of the perturbations should depend, for example, on the size of the spots and on the velocities of the convection inhomogeneities (Saar & Donahue 1997), or on the rotational velocity of the star (e.g. Mayor et al. 1998). These are functions of the spectral type and age: a younger star is expected to have a higher rotation rate; the magnetic fields produced will then be more or less strong, depending on the depth of the convective zone, i.e. on the spectral type (e.g. Noyes et al. 1984). On the other hand, the presence of active regions is deeply associated with photospheric features (like spots or convective inhomogeneities, e.g. Schrijver et al. 1989) that can be responsible for intrinsic radial-velocity "jitter". This fact may permit us to study in a simple but indirect way the photospheric phenomena responsible for intrinsic radial-velocity "jitter", by measuring a chromospheric-activity index, such as the Mount-Wilson "S" index (Vaughan et al. 1978)[1].

In June 1998 we started a long term extra-solar planet search programme at ESO (La Silla) using the CORALIE echelle high-resolution ($\lambda/\Delta\lambda \sim 50.000$) spectrograph installed at the 1.2-m Euler Swiss telescope. This programme makes use of a large (about 1650) volume-limited sample of stars in the southern sky (Udry et al. 2000).

The precision obtained with CORALIE is of the order of $7\ \rm m\,s^{-1}$ (e.g. Queloz et al. 2000b). At this level, and given the nature of the sample (we have all kinds of dwarfs with spectral types from F8 to M0) it is very important to know the limits imposed by chromospheric activity, so that we can disentangle activity-related phenomena from real planetary candidates, and possibly exclude bad candidates for this survey and for future even more sensible programmes (Pepe et al. 2000).

In order to monitor the chromospheric activity of the stars in our survey, we use CORALIE spectra to compute a new chromo-

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* Based on observations collected at the La Silla Observatory, ESO (Chile), with the echelle spectrograph CORALIE at the 1.2-m Euler Swiss telescope

[1] It should be pointed out that a given activity level (as expressed by "S") may not by itself produce a radial-velocity variation; it may reflect, however, the presence of photospheric features that can produce a "jitter" (e.g. a rotating spot or an anisotropic distribution of magnetic activity).

spheric activity index, $S_{\rm COR}$, based on the flux in the center of the Ca II H line. In Sect. 2 we present the $S_{\rm COR}$ index, describing the technique and some tests. We then calibrate our activity index values to the Mount-Wilson "S" system (hereafter $S_{\rm MW}$). In Sect. 3 we present our sample of stars with $S_{\rm COR}$ values, and in Sect. 4 we discuss our results for F, G and K dwarfs. In particular we focus on the study of the relation between the radial-velocity "jitter" and the chromospheric activity as expressed by the fractional Ca II H and K flux corrected for photospheric flux ($R'_{\rm HK}$, as defined by Noyes et al. 1984).

2. The technique

The CORALIE spectra, with a bandpass from about 3900 Å to 6800 Å, include the two Ca II H and K resonant lines centered at 3968.49 Å and 3933.68 Å, respectively. In Fig. 1 we can see two high S/N CORALIE spectra of the Ca II H line central region. The upper spectrum corresponds to the chromospherically active star HD 22049 (K2V), and the lower one to the rather low activity star HD 115617 (G8V).

The technique described in this paper to compute our chromospheric activity index mimics the procedure used at Mount-Wilson (MW) for more than three decades (Vaughan et al. 1978). At MW, the flux in two ~1 Å wide spectral windows centered on the Ca II H and K lines is divided by the flux in two 20 Å wide comparison windows placed on each side of the H and K lines. In our case, to compute the chromospheric activity index $S_{\rm COR}$, we simply sum and divide the flux in a 1 Å wide window centered on the Ca II H line by the flux in a 15 Å comparison window centered at 3996.5 Å. We only make use of the H line, since the K component is in a spectral order with very low typical fluxes, introducing undesirable noise.

The index is computed as follows. CORALIE spectra are extracted online following a standard echelle spectra reduction procedure. The details can be found in Baranne et al. (1996). The spectra are then corrected for the Doppler shift using the previously computed radial velocities, and they are rebinned with steps of 0.01 Å (about twice as small as the original binning), using an algorithm that conserves the flux. This way, we have about 100 bins in the Ca II H line central band.

The technique employed with the CORALIE spectrograph to determine high-precision radial velocities implies the use of a Thorium-Argon (hereafter ThAr) calibration lamp, whose spectra are simultaneously recorded in the "sky" orders (see Baranne et al. 1996 for a description of a similar instrument). The resulting inter-order space is very small, and the task of subtracting the background light becomes difficult. In addition, the ThAr lamp produces scattered light all over the CCD, that will add to the usual background light.

In order to account for this "pollution" we have to follow a different approach. We first "eliminate" the lines in the ThAr spectra using an appropriate routine which "cuts" all the fluxes higher than the "local" mean. This proved to be essential to the next step, where we adjust a cubic smoothing spline to the remaining ThAr spectrum (which is at this moment the sum of the background light and the "continuum" spectrum of the ThAr

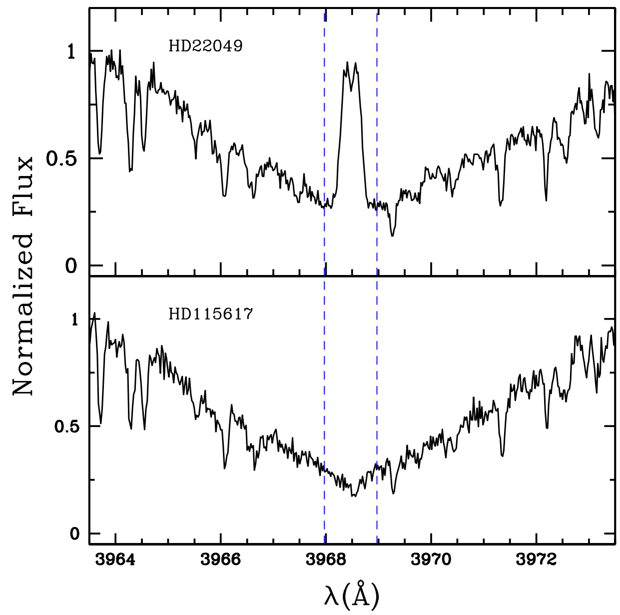

Fig. 1. Two CORALIE spectra of the central region of the Ca II H line. The upper spectrum corresponds to an active star, while the lower spectrum to a low activity star. The dashed lines represent the emission region of the spectra used to compute the activity index.

lamp). For this we used the E02BBF and E02BEF NAG fortran routines[2]. Finally, we subtract from each stellar spectral order of interest the spline adjusted to the corresponding ThAr order. In this procedure we suppose that the continuum spectrum of the ThAr lamp is very low and so we can ignore it. As we will see below, the results prove this is a good approximation.

After this subtraction, we compute our "S" index from the remaining spectrum by adding the counts in each of the spectral windows of interest (as described above).

Given the large amount of data available (in average, more than 30 stellar spectra are obtained every night), it was essential to have a completely automatic procedure. This implied the development of some automatic mechanisms to control eventual hazards in the spectra. In our routines we have thus some flags that give us information whenever cosmic rays are found in the continuum comparison window. Cosmis rays on the central H line region are also automatically detected whenever there are unusually high flux values (exceeding 5 σ), and a corresponding flag is raised. In such cases the spectra can be analysed and if confirmed, the $S_{\rm COR}$ value is not used.

Unfortunately, the CORALIE spectra are not always as good as those shown in Fig. 1. The blue orders where these lines are located have usually low fluxes. On the other hand, the technique used to obtain high-precision radial velocities does not require very high S/N ratios in the blue. We thus took the conservative decision of only using $S_{\rm COR}$ values for those measurements having more than about 4000 counts in the central region of the Ca II H line (this would correspond to 1800 counts for a non-

[2] NAG is a registered mark of The Numerical Algorithms Group Limited

Table 1. Stars used to calibrate the $S_{\rm COR}$ values into the Mount-Wilson "S" scale.

Star	$S_{\rm MW}$ †	$\sigma(S_{\rm MW})$ †	$S_{\rm COR}$	$\sigma(S_{\rm COR})$	N
HD 1835	0.364	0.024	0.369	0.058	4
HD 3443A	0.198	0.049	0.181	0.054	2
HD 3795	0.159	0.004	0.138	0.007	7
HD 10700	0.173	0.004	0.158	0.027	34
HD 17925	0.693	0.075	0.793	0.112	4
HD 22049	0.515	0.026	0.496	0.056	8
HD 23249	0.150	0.012	0.119	0.017	4
HD 26965	0.208	0.018	0.186	0.015	8
HD 30495	0.292	0.016	0.317	0.037	13
HD 45067	0.142	0.002	0.100	0.027	3
HD 61421	0.187	0.010	0.169	0.007	787
HD 76151	0.262	0.018	0.237	0.022	3
HD 81809	0.176	0.012	0.166	0.009	2
HD 115617	0.161	0.003	0.163	0.038	22
HD 149661	0.356	0.042	0.412	0.154	5
HD 152391	0.392	0.030	0.450	0.046	6
HD 155885	0.400	0.020	0.342	0.034	1
HD 158614	0.163	0.008	0.136	0.020	5

† From Duncan et al. (1991).

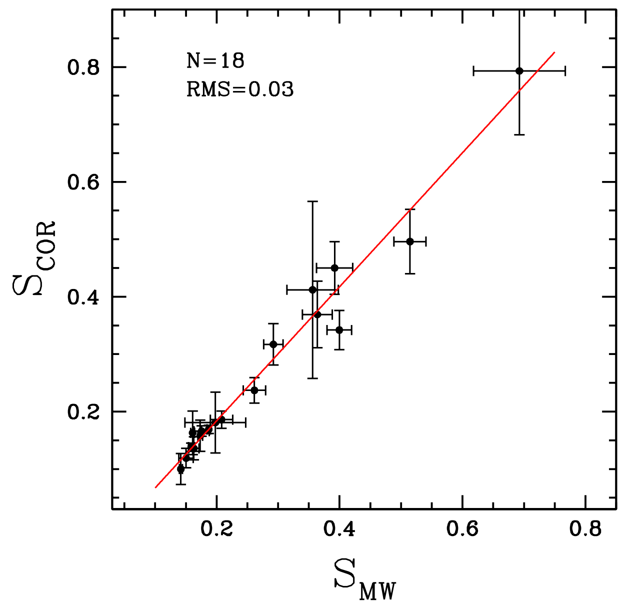

Fig. 2. Mean $S_{\rm COR}$ values compared with $S_{\rm MW}$ values for a set of 18 calibration stars. The solid line represents the best least-square linear fit. Horizontal error-bars represent the dispersion of $S_{\rm MW}$ values around the mean seasonal value (Duncan et al. 1991). Vertical error-bars represent the dispersion in our $S_{\rm COR}$ values over one year. The values are taken from Table 1.

rebinned spectrum). This limits our "survey", but is necessary since lower fluxes give high uncertainties in $S_{\rm COR}$.

Finally, the use of the Ca II H line alone instead of both H and K is not expected to cause any serious systematic errors. Cuntz et al. (1999) showed that for a set of K dwarfs the ratio of the fluxes for this two lines is almost constant. This ratio depends on the rotational period of the star, but the dependence is small, and we expect errors to be significantly lower than 10%. Moreover, the Cuntz et al. relation is only valid for K dwarfs. We thus do not make any corrections.

2.1. Calibration to the Mount-Wilson system

In order to convert our $S_{\rm COR}$ values to the Mount-Wilson scale, we use observations of some stars for which we have values of $S_{\rm MW}$. In Table 1 we present the list of calibration stars. In Columns 2 and 3 we list the values of $S_{\rm MW}$ and their dispersions, $\sigma(S_{\rm MW})$. The values were computed from Duncan et al. (1991), and correspond to the mean and rms of the $S_{\rm MW}$ values over all the seasons listed in his Table 1. In Columns 4 and 5 we present our $S_{\rm COR}$ values and corresponding dispersions. In the case of HD 155885 we only have 1 measurement (Column 6), and so we adopt a conservative error of 10%. The best least-square fit to the data holds (Fig. 2):

$$S_{\rm COR} = (1.1671 \pm 0.0506)\, S_{\rm MW} - (0.0495 \pm 0.0159) \quad (1)$$

This relation is valid for $S_{\rm COR}$ between 0.10 and 0.79 ($S_{\rm MW}$ between 0.14 and 0.69). The fit is quite remarkable ($\sigma_{\rm fit} = 0.030$) reflecting the precision of our $S_{\rm COR}$ values. Since both our $S_{\rm COR}$ and the $S_{\rm MW}$ values correspond to the mean over a long period of time (a few seasons for the case of the $S_{\rm MW}$ and about one year for our $S_{\rm COR}$ values), $\sigma_{\rm fit}$ reflects not only the uncertainties in our procedure but also intrinsic stellar variation.

From this calibration we can then compute values of the Ca II H and K flux corrected for the photospheric flux, $R'_{\rm HK}$ (Noyes et al. 1984), for our programme stars.

2.2. Our precision: two examples

To better illustrate the stability and precision of the $S_{\rm COR}$ index, we plot in Fig. 3 (upper panel) the values of $S_{\rm COR}$ as a function of time for the star HD 20794, a chromospherically-quiet G8 dwarf. The quality of these values is representative of our usual measurements.

The spectra were taken over one night with exposure times going from 2 to 3 minutes. As we can see from the figure, the rms around the mean $S_{\rm COR}$ value is quite low, amounting to about 0.005. If we take all the 61 measurements of this star over one year we find a mean value of $S_{\rm COR}$=0.155±0.016 (where the error corresponds to the rms around the mean), corresponding in the MW system to $S_{\rm MW}$=0.175. Henry et al. (1996) found $S_{\rm MW}$ = 0.167 with 6 measurements. The difference might be related to errors in the $S_{\rm COR}$ vs. $S_{\rm MW}$ calibrations, both in this work and in the work of Henry et al., as well as to eventual activity level variations: the observations presented here were not carried out during the same season as the survey of Henry et al.

Since we have to use a rather "tricky" technique to subtract the background light over the CCD, one might eventually expect some systematic errors. In Fig. 3 (lower panel) we plot the $S_{\rm COR}$ values against the flux in the central region of the Ca II H line. As

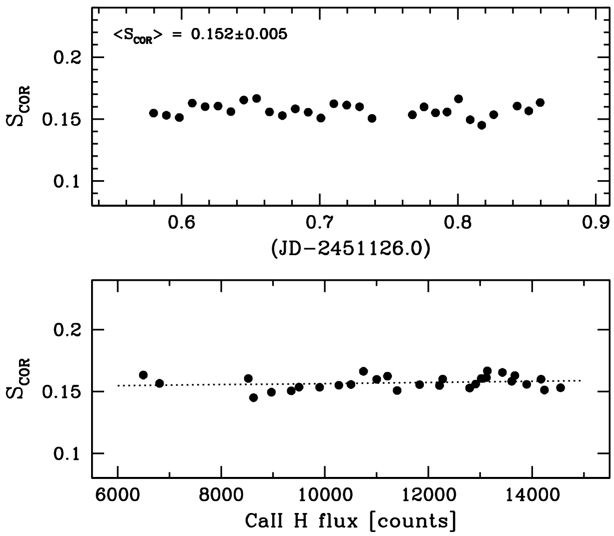

Fig. 3. *Upper panel*: values of $S_{\rm COR}$ obtained on the same night for HD 20794. Each point corresponds to one individual measurement; *lower panel*: the same $S_{\rm COR}$ values plotted against the flux in the center of the Ca II H line. The dotted line represents the best least-square linear fit.

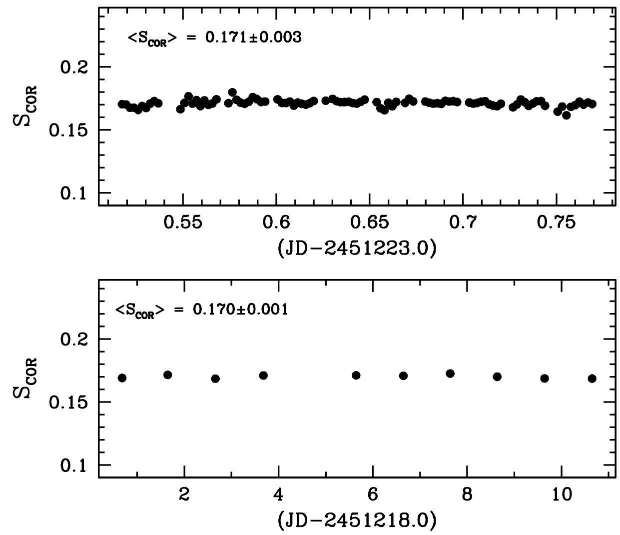

Fig. 4. *Upper panel*: values of $S_{\rm COR}$ obtained on the same night for Procyon. Each point corresponds to one individual measurement; *lower panel*: the mean of the $S_{\rm COR}$ values for 10 nights for this same star. Each point corresponds to the mean of all the measurements over one night, and is centered on the mean of the JD of that night. Error bars are smaller than the size of the points.

we can see from the plot, there is no systematic error in $S_{\rm COR}$ connected with the number of counts in the central H line region, at least in the range of observed fluxes. The fit shows a small, but not significant trend (dotted line); the Spearman correlation coefficient is 0.18, and a F-test shows that the probability against a trend is ∼50% (the error in the slope is higher than the slope itself).

In Fig. 4 we can see our results for the star Procyon (HD 61421) over one night (upper panel) and for a series of 10 almost consecutive nights (lower panel). Given the brightness of the star, the fluxes are much higher than for the case of HD 20794, and our precision is also much better. In this case we have a mean $S_{\rm COR}$ value of 0.170 with a rms of only 0.001 over all the 10 nights. This corresponds to $S_{\rm MW}$ = 0.188. A value of $S_{\rm MW}$ = 0.185 was found over two seasons by Duncan et al. (1991). Although this star is particularly bright and the obtained fluxes are particularly high, this example shows that the $S_{\rm COR}$ index is very stable, not only during one night but also from night to night.

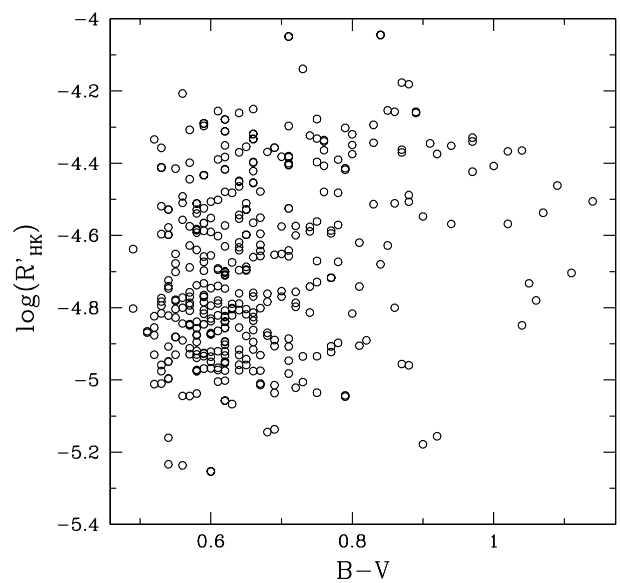

Fig. 5. Values of $R'_{\rm HK}$ derived from $S_{\rm COR}$ values for our sample of stars as a function of the colour $B-V$.

3. Our sample of stars with $S_{\rm COR}$ values

After about one-and-a-half years of measurements (from August 1998 to March 2000) we have about 400 stars (from the more than 1000 stars observed for radial velocities) with at least one derived $S_{\rm COR}$ value. This sample is represented in Fig. 5, where we plot the values of $\log R'_{\rm HK}$ as a function of the colour index $B-V$. The individual data will be published in a future paper.

Our original sample of stars (part of the CORALIE extra-solar planet survey) was chosen to be volume-limited (Udry et al. 2000), containing this way no sampling biases. This kind of choice will give us the possibility of studying the characteristics of extra-solar planetary systems and their occurrence in a statistical and unbiased way.

From the "activity" point of view, the determination of the chromospheric activities for the stars in such a sample can be particularly interesting: when completed, this survey will be the first large volume-limited survey for chromospheric activity in dwarfs. Unfortunately, the sub-sample of stars with presently derived $S_{\rm COR}$ values is not unbiased like the original sample. First, K dwarfs are intrinsically fainter than F or G dwarfs, and hence are more difficult for measuring activity (higher integration times are needed). Since K dwarfs have deeper lines, our radial-velocity technique is more accurate for these stars, and a lower flux is required to obtain high-precision radial velocity measurements than for a F or G dwarf. These facts make K dwarfs rather difficult targets for computing activity values with our spectra.

On the other hand, since active stars have more flux in the center of the Ca II H line (compared to lower activity objects), we can easier find "acceptable" values (with high fluxes) of $S_{\rm COR}$ for active dwarfs than for their inactive counterparts. This way, we expect a bias favoring high-activity F dwarfs in our preliminary data (while we don't have $S_{\rm COR}$ values for all the CORALIE sample) and comparatively a small number of K dwarfs with low activity values.

These biases can be seen in the plot of Fig. 5 as the underpopulated region with $B-V>0.9$ and $\log R'_{\rm HK}<-4.7$. Also, comparing to the similar diagram of Henry et al. (1996), we have a higher number of active dwarfs ($\log R'_{\rm HK}\geq-4.75$) compared with non-active dwarfs ($\log R'_{\rm HK}<-4.75$). This biases will be corrected as more measurements will be collected, and the sample covered. The distribution of stars in this diagram follows, however, a pattern very similar to the one found by Henry et al. The data gathered until now already permit us to do some interesting studies.

4. Activity, rotation, and radial-velocity "jitter"

The basic motivation for computing our $S_{\rm COR}$ index is to monitor the activity of the stars in the planet-search programme. This can be done essentially in two ways. First, we can try to verify if there is any rotational modulation of the Ca II flux. Such a detection would give us the rotational period of the star, and hence any radial-velocity variation with the same periodicity would be highly suspicious (although it would not exclude a planetary explanation). Unfortunately, the obtained precision and the bad time sampling of the data don't permit us to "directly" derive the rotational periods for our stars from rotational modulation of the Ca II flux (e.g. Vaughan et al. 1981). An estimate of the rotational periods can therefore only be made using the mean "S" index (Noyes et al. 1984). On the other hand, the fact that we have activity values for such a large sample of stars gives us the possibility of studying the relation between the radial-velocity scatter and the chromospheric activity as expressed by the index $R'_{\rm HK}$.

In Fig. 6 we plot three log-log diagrams of the reduced radial velocity scatter, σ'(Vr), against the chromospheric activity expressed by $10^5\,R'_{\rm HK}$, for 15 F, 98 G and 18 K dwarfs for which we have $S_{\rm COR}$ values. The σ'(Vr) values were computed by subtracting quadratically, for each star, the rms of the mean of the individual photon-noise statistical errors, $\langle\epsilon_i({\rm Vr})\rangle$, from the rms around the mean radial velocity, σ(Vr). The values of the instrumental long-term errors are not known and thus were not taken into account. This way, σ'(Vr) includes unknown systematic instrumental errors as well as dispersion due to activity-related phenomena.

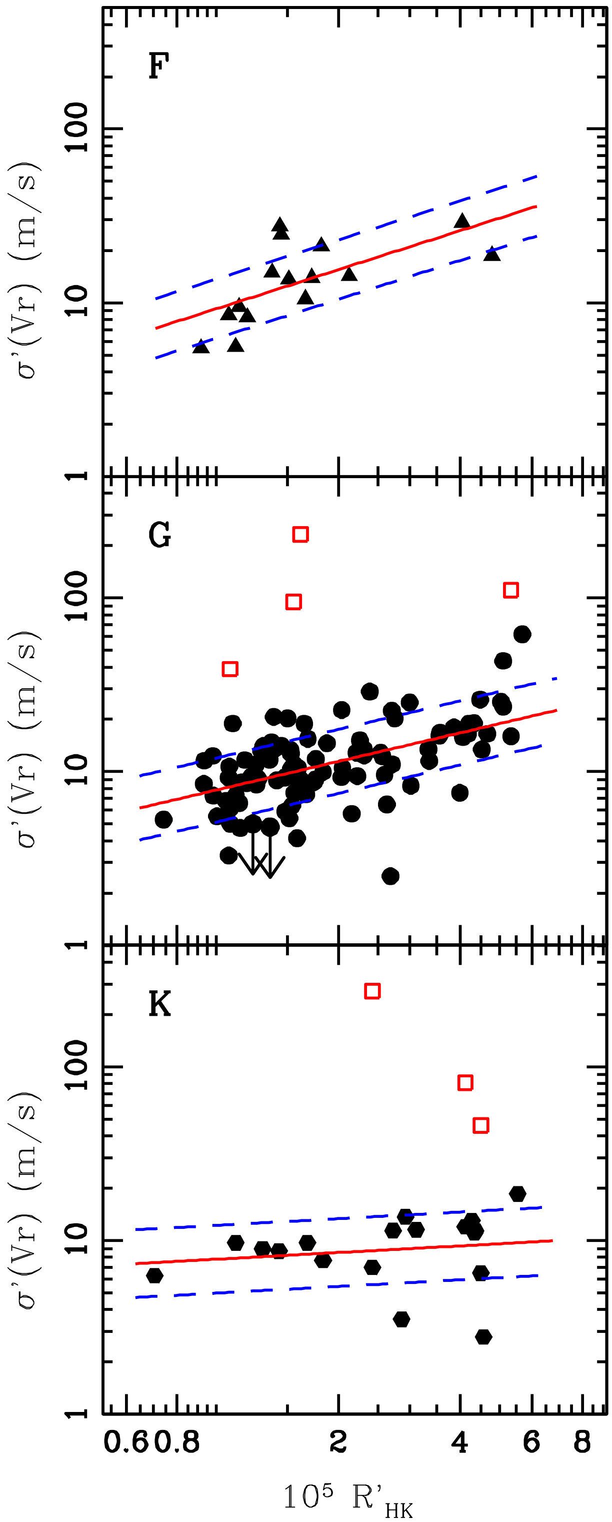

Fig. 6. Plots of the reduced radial-velocity rms, σ'(Vr), as a function of $R'_{\rm HK}$ for F dwarfs (filled triangles), G dwarfs (filled circles) and K dwarfs (filled hexagons) of the CORALIE sample. Down arrows represent stars for which σ'(Vr) is lower than $\langle\epsilon_i({\rm Vr})\rangle$. The solid lines represent the best least-squares linear fit to the points, while the rms of the fit is represented by the dashed lines. Open squares represent stars with known planetary systems when the σ'(Vr) was computed without subtracting the orbital solution.

Values of σ'(Vr) were computed only for stars with at least 7 CORALIE high-precision radial-velocity measurements. In general, the dispersion of the photon-noise errors around the mean is low, but all points with ϵ_i(Vr) larger than 2 $\langle\epsilon_i(\mathrm{Vr})\rangle$ were eliminated (measures with errors much higher than usual). In order not to underestimate the activity-related scatter, in the cases where we have multiple radial-velocity observations per night, only one (the more precise) was considered. Stars for which linear radial-velocity drifts were found were also excluded from the fits, but some of these may have escaped. For stars with planets, the values of σ'(Vr) were computed in the same way after subtraction of the orbital solutions.

First of all, the number of F dwarfs in Fig. 6 is much lower than that of G dwarfs, although they are intrinsically brighter, and thus easier targets for activity determinations. This is in fact another observational bias that occurs because F stars in our sample have usually higher values of $v \sin i$ with respect to G dwarfs, and thus they have lower priority in the planet-search programme (the expected radial-velocity "jitter" is higher, e.g. Mayor et al. 1998). This way, often we don't have enough radial-velocity measurements for these stars to put them in the diagram of Fig. 6.

We can easily see from the plots that there is a clear relation between σ'(Vr) and activity (expressed by R'_{HK}) for F, G and K dwarfs, confirming the results of Saar et al. (1998). The linear fits hold:

$$\sigma'_{\mathrm{F}}(Vr) \;=\; 9.2\,R_5^{0.75} \tag{2}$$
$$\sigma'_{\mathrm{G}}(Vr) \;=\; 7.9\,R_5^{0.55} \tag{3}$$
$$\sigma'_{\mathrm{K}}(Vr) \;=\; 7.8\,R_5^{0.13} \tag{4}$$

where $R_5 \equiv 10^5\,R'_{\mathrm{HK}}$. The fits have a rms of σ_{fit}=0.17 dex (F dwarfs), σ_{fit}=0.18 dex (G dwarfs), and σ_{fit}=0.19 dex (K dwarfs).[3]

These relations clearly show that a trend does exist between σ'(Vr) and R_5 (at least for F and G dwarfs), but also that the slopes of the R_5 vs. σ'(Vr) relation increase as we go from K to F dwarfs. The zero points for the three relations also decrease slightly with increasing $B-V$. These two facts together have an important consequence: they impose different limits on the expected activity induced radial-velocity noise for solar type stars of different spectral types. For example, for an active F dwarf with an activity index $\log R'_{\mathrm{HK}}$= −4.3 ($10^5\,R'_{\mathrm{HK}}$ = 5.0) we expect a value of σ'(Vr) between 21 and 45 $\mathrm{m\,s^{-1}}$ (within 1σ). On the other hand, for a K dwarf with the same activity level, we expect a significantly lower radial-velocity "jitter", between 7 and 14 $\mathrm{m\,s^{-1}}$.

[3] The errors in the slopes and zero points of the linear fits of $\log \sigma'_{\mathrm{F}}(Vr)$ vs. $\log R_5$ show that the results are quite significant for the F and G star relations (the slopes are 0.75±0.27 and 0.55±0.08, respectively, while the zero points are 0.97±0.07 and 0.89±0.03). For K dwarfs the zero point is 0.88±0.19, and slope has not a significant value (0.13±0.20), representative of the poor dependence of $\sigma'_{\mathrm{K}}(Vr)$ with R_5 for these stars. On the other hand, the dispersion of the fits (expected if we consider that e.g. we did not "subtract" the $\sin i$ effect – see discussion) is well illustrated by the obtained Spearman correlation coefficients of 0.8, 0.6 and 0.3 for the F, G, and K plots, respectively.

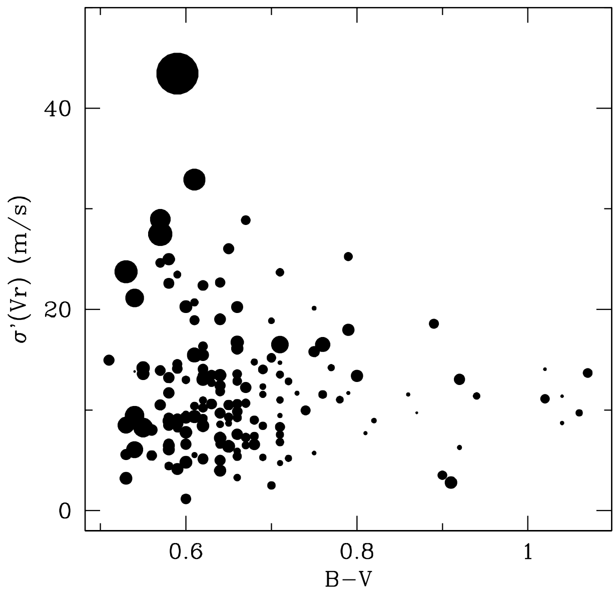

Fig. 7. Plot of the radial-velocity scatter as a function of spectral type for our programme stars. The size of the dots is proportional to the $v \sin i$ of the star. Given the ambiguity in the $\sin i$, the size of the symbols should be seen as a lower value for the rotational velocity of the stars.

This fact can also be seen in Fig. 7, where we plot the values of σ'(Vr) against the $B-V$ of our programme stars. From the plot we can see that for the upper envelope of the F and early G dwarfs σ'(Vr) is in general considerably higher than for late G or K dwarfs. This fact is most probably a real effect and not a sampling bias, since the whole activity range is relatively well covered for all spectral types.

The plot of Fig. 7 also suggests that to higher $v \sin i$ stars (larger symbols) corresponds generally a higher σ'(Vr) for the same T_{eff}. The values of $v \sin i$ go from ∼0 to 15.4 $\mathrm{km\,s^{-1}}$, and were obtained from the width of the CORAVEL cross-correlation dip (Benz & Mayor 1984). A higher $v \sin i$ is indeed expected to induce more radial-velocity "jitter" for the same activity level and spectral type, since it will introduce more important line asymmetries (Mayor et al. 1998; Saar et al. 1998). But some dispersion in this relation is expected, because for a given mass the activity level is physically related with the rotational period (Noyes et al. 1984; Patten & Simon 1996) and not with $v \sin i$, the projected component of the rotational velocity.

It is interesting to verify that the F and early G dwarfs in the plot of Fig. 7 have in general higher values of $v \sin i$ with respect to the late G and K dwarfs. This may indicate that "bluer" dwarfs need higher rotational velocities to produce the same chromospheric activity level (we remember that our samples of F and G dwarfs have a similar distribution of R'_{HK} values). Such a fact is also expected, because the depth of the convective layer increases as we go from F to K dwarfs, also increasing the convection overturn time and the dynamo effect (Noyes et al. 1984).

The higher radial-velocity scatter of the F stars is thus likely to be explained by two separate mechanisms acting simultaneously. On the one hand, it might be related with the higher "intrinsic" $v\,\sin i$ for a given activity level. On the other hand, for solar-type stars, the convective velocities decrease with increasing $B-V$, making convective inhomogeneities less important (Gray 1984; Saar & Donahue 1997). Since convection movements introduce an extra velocity field (Saar & Donahue 1997), to stars of different spectral types but of the same activity level and $v\,\sin i$ will correspond different radial-velocity perturbations, being larger for F dwarfs (Saar et al. 1998).

The obtained relations between σ'(Vr) and $R'_{\rm HK}$ can be particularly useful when dealing with extra-solar planet search programmes: together with the knowledge of the projected rotational velocity ($v\,\sin i$) of the star, they can be used to distinguish, to a first approximation, activity-related scatter from orbital radial-velocity variations. For example, a periodic radial-velocity variation with a rms of 40 $\mathrm{m\,s^{-1}}$ for a K dwarf would be, even if the star is chromospherically very active, an indication that we are much probably dealing with a planetary system. Such a limit may however not be comfortable for an active G or F dwarf, for which much higher activity-related "jitter" is expected (especially when the $v\,\sin i$ is high).

To better illustrate this fact we can take the case of the two extra-solar planet parent stars HD 130322, (Udry et al. 2000) and HD 192263 (Santos et al. 2000a). Both are early K dwarfs that have high chromospheric activity levels (with $\log R'_{\rm HK}$ of -4.39 and -4.35, respectively). However, the orbital radial-velocity signal is much higher than the expected activity-related scatter. It is interesting to point out, however, that in both cases the radial-velocity rms around the orbital solution is relatively high (about 15 $\mathrm{m\,s^{-1}}$ for HD 130322 and 13 $\mathrm{m\,s^{-1}}$ for HD 192263), as expected according to the fits of Fig. 6.

The future addition of more data to the plots of Figs. 6 and 7 is probably necessary to better constrain and clarify the validity and precision of these relations. This is particularly noticeable in the cases of F and K dwarfs, for which we don't have many points yet. For G dwarfs, however, the present results are perfectly consistent with the ones presented in Santos et al. (2000b), even though the number of points has almost doubled.

In all cases (except F dwarfs) stars with known planetary systems are all considerably (more than 2 σ) above the fits when compared to "single" stars. On the other side, there are two objects (HD 55720 and HD 73322, late G and K dwarfs, respectively) that are positioned more than 2 σ below the fit. The reason for this deviation may have to do with a statistical bias caused by the relatively low number of points used to compute the values of σ'(Vr), or to a projection effect (star seen pole-on). However, we cannot exclude the presence of some physical process possibly responsible for the observed high values of chromospheric activity, but not able to produce changes in the observed radial-velocities. For example, observations of the Sun showed that the presence of chromospheric "plages"[4] is not necessarily connected to the existence of a spot group (Howard 1996). We can thus imagine that these two chromospherically active stars may lack the photospheric features capable of producing important radial-velocity variations.

Since the instrumental long-term errors have not been subtracted, the physical meaning of all these quantities has not, however, a straightforward interpretation. For example, the exponents of the relations are probably under-evaluated while the zero points are over-estimated. Thus, for a given chromospheric-activity level (expressed by $R'_{\rm HK}$), the value of the computed σ'(Vr) is probably higher than the "real" value. This can be further stressed if we imagine that our sample may still contain some stars with unknown planetary companions, inducing radial-velocity variations (still treated as "noise"). This lead us to conclude that the results must be considered as upper-limits for the expected σ'(Vr). Qualitatively, the fact that the instrumental errors have not been taken into account does not have any serious implications, and the main conclusions would remain the same.

As an observational test we have computed the value expected for the radial-velocity rms of the Sun, according to our relations. If we consider that the instrumental long-term errors in radial velocity amount to about 7 $\mathrm{m\,s^{-1}}$ (Queloz et al. 2000b), and taking a value of $\log R'_{\rm HK} = -4.94$ (Noyes et al. 1984), we obtain from Eq. 3, $\sigma'_{\odot}$(Vr) ~ 5 $\mathrm{m\,s^{-1}}$ (subtracting quadratically the errors). This is compatible with the results obtained by McMillan et al. (1993), that showed that the long term radial-velocity "jitter" of the Sun is lower than $\sim$4 $\mathrm{m\,s^{-1}}$. The small excess might be related to the existence of undetected planetary companions amid the stars in the plots.

5. Concluding remarks

We have computed a new chromospheric-activity index based on CORALIE high-resolution echelle spectra. After transforming our $S_{\rm COR}$ values into the Mount-Wilson "S" scale, this index gives us the possibility of checking the activity of the stars of the Geneva extra-solar planet search programme in the southern sky. After almost two years, we have values of $S_{\rm COR}$ for more than 400 stars in the CORALIE sample.

We applied our results to the study of the relation between activity and radial-velocity variation to show that a clear trend exists between radial-velocity "jitter" and the chromospheric activity index $R'_{\rm HK}$ for the F, G and K dwarfs in our sample. In general, higher activity dwarfs have higher radial velocity "jitter". This relation is nonetheless not the same for all spectral types, K dwarfs being more "stable" in velocity than G or F dwarfs: the radial-velocity scatter increases with decreasing $B-V$, confirming former results (e.g. Saar et al. 1998).

The obtained relations may be very useful when dealing with extra-solar planet searches using radial-velocity techniques. Depending on the observed radial-velocity rms, we can use the derived results together with the value of $v\,\sin i$ of the star to exclude (or not) activity related phenomena as the cause of the observed radial-velocity variation.

The current results are, however, not "precise" enough to permit us to consider the activity diagnostic as satisfactory and

[4] Regions in the chromosphere associated with magnetic activity. They appear as bright patches in Ca II H and K line photographs of the Sun.

able to clearly distinguish activity related phenomena from real planetary candidates. As more data will be gathered we expect to better clarify and precise the observed relations. In the meanwhile, we think that the use of other activity induced radial-velocity indicators, like the shape of line profiles as seen in the bisector analysis (e.g. Queloz et al., in preparation), may be essential.

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