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Chromospheric Long Term Activity of Very Cool Stars

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Abstract. We study the long-term chromospheric activity of dM stars, using in particular the results of an observational program we started in 1999, to systematically obtain mid-resolution spectra of late-type stars. First, we discuss which are good activity indicators for these stars. We investigated the relation between the activity measurements in the calcium and hydrogen lines, and found that the usual correlation observed reflects differences between stars, and it is not always preserved for simultaneous observations of a particular star. Later we investigate the variations in individual stars, and we report cyclic activity in four dM stars, including Prox-Cen.

1. Introduction

In the last years, dM stars became high priority targets for exoplanet searches. On one hand, these are the most common stars in the sky, representing 80% of all stars in the galaxy. On the other, it is easier to find smaller planets around smaller stars, both from radial velocity searches or with transits. Furthermore, lower mass stars appear more likely to host lower mass planets, and therefore these are the optimal targets to find terrestrial planets. Since M stars are cooler, planets are also more likely to orbit within the "liquid water habitable zone", and it is therefore around these stars where it is easier to find the next "holy grail" of planetary searches: an inhabitable, earth-like planet.

However, a large part of these stars is very active, and activity can be a problem for two reasons. First, it interferes with the search programs, since it can mimic both radial velocity variations and transits. Second, it can affect habitability, since the energy released by the host star can vary in different timescales (Buccino et al. 2006, 2007).

On the other hand, the study of long-term activity in dM stars is also interesting in itself, in particular for stellar dynamo studies, since fully convective stars do not support $\alpha\Omega$ dynamos.

In 1999 we started a program, the HKα project, to systematically obtain spectra of late-type stars, to study in particular chromospheric activity. Our observations are made at the 2.15 m telescope of the Complejo Astronómico El Leoncito (CASLEO), which is located at 2552 m above sea level, in San Juan, Argentina. We obtain high-resolution echelle spectra with a REOSC spectrograph. The maximum wavelength range of our observations is from 3860 to 6690 Å, and the spectral resolution ranges from 0.141 to 0.249 Å per pixel ($R = \lambda/\delta\lambda \approx 26400$). Details on the reduction and calibration procedures can be found in Cincunegui & Mauas (2004).

The stars were chosen to cover the spectral range from F to M, with different activity levels. Since we were particularly interested in the transition to completely convective stars, we included a larger number of M stars in our sample. Altough most

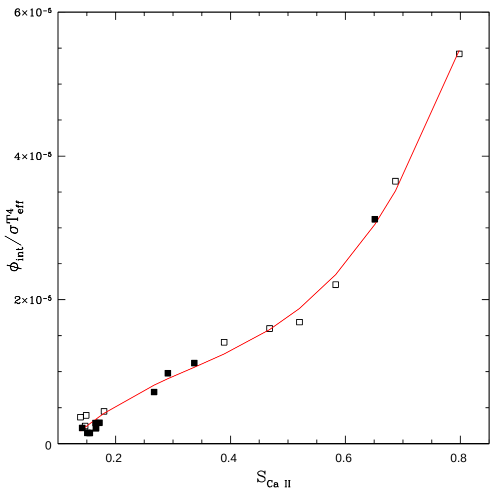

Figure 1. Normalized $\phi_{\rm int}$ versus the S index. The empty squares represent the K star models from Vieytes et al. (2009) and the full squares indicate the G star models from Vieytes et al. (2005).

of the stars are single dwarfs, we have several binaries and a few subgiants. At present, we have about 5500 spectra of 150 stars. In this review we present some results of the HKα project, focusing mainly in dM stars.

2. Activity indexes

Most activity studies are based on observations of the H and K lines of Ca II, which in the Sun is known to vary more strongly that continuum emission. It is also known that their flux correlates well with magnetic fields (e.g. Morgenthaler et al 2010). Recently, we found that it also correlates well with the chromospheric radiative losses for G and K stars, as it is shown in Fig. 1 (Vieytes et al. 2005, 2009).

To date, the most common indicator of chromospheric activity is the well-known S index, essentially the ratio of the flux in the core of the Ca II H and K lines to the continuum nearby (Vaughan et al. 1978). This index has been defined at the Mount Wilson Observatory, were an extensive database of stellar activity has been built over the last four decades. However, the Ca II lines are not the best suited to study dM stars, which are intrinsically faint and red. In fact, there is only one star of that spectral type in the Mt. Wilson program. For this reason, the S index is poorly characterized for these stars, and it would be interesting to find another spectral feature more suitable for the cooler end of the HR diagram.

In fact, since we observe simultaneously the different spectral features, unlike most surveys of this kind, our data provides an excellent opportunity to study the correlation between different spectral features and activity indexes. As a first step, we integrated the H and K profiles to obtain the S index for our spectra, and calibrated against the Mt. Wilson index using several inactive stars in common (Cincunegui et al. 2007b).

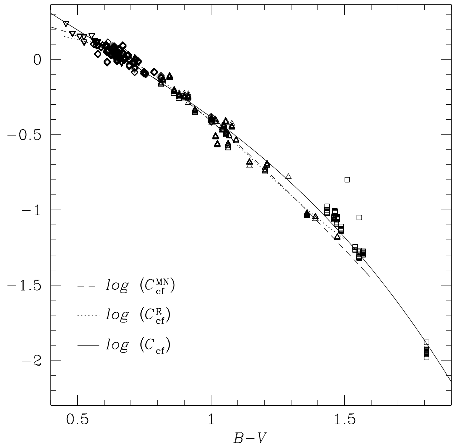

Figure 2. Conversion factor between Mount Wilson S index and F_{HK}. The dashed line corresponds to Noyes et al. (1984), the dotted line to Rutten (1984), and the full line to our derived factor (from Cincunegui et al. 2007b).

The S index can be converted to the average surface flux in the Ca II lines through the relation:

$$F_{HK} = F_{bol} 1.34\, 10^{-4}\, S\, C_{cf} \,, \tag{1}$$

where $C_{cf}\,(B-V)$ is a conversion factor that depends on color. Two different expressions are widely used for this factor (Noyes et al. 1984; Rutten 1984). The deductions used in both works to derive C_{cf} involve complex calibration procedures.

Since we have simultaneous measurements of the S index and the core fluxes, we can calculate directly the correction factor as a function of the index and the flux, which is shown in Fig. 2 together with the other two expressions (for details and a whole discussion, see Cincunegui et al. 2007b).

It is usually accepted that there is a tight relation between the chromospheric fluxes emitted in Hα and in the H and K Ca II lines, and that these two features can be used to study chromospheric activity. However, most works where this relation has been observed found it by using averaged fluxes for the calcium and hydrogen lines, which were not obtained simultaneously, and were even collected from different sources.

However, the situation is different when the individual stars are studied separately. In Fig. 3 we plot the individual simultaneous measurements of each flux for several stars of different spectral types and different levels of activity, divided into color bins as stated. We also show the linear fits for each star. It can be seen that the behavior is different in each case: in some stars both fluxes are well correlated, although the slopes of the fits are not the same. In other stars the H-α flux seems to be almost independent of the level of activity measured in the Ca II lines, and there are even stars where the fluxes are anti-correlated.

Walkowicz & Hawley (2009) obtained simultaneous spectra of Ca II and Hα for several M3 dwarfs, and found that the most active stars, with Hα in emission, show a strong positive correlation between instantaneous measurements of Ca II K and Hα. They also found that the relationship between Hα and Ca II K "remains ambiguous" for weak and intermediate activity stars. However, the question still remains, since "these lines may not be positively correlated in time-resolved measurements".

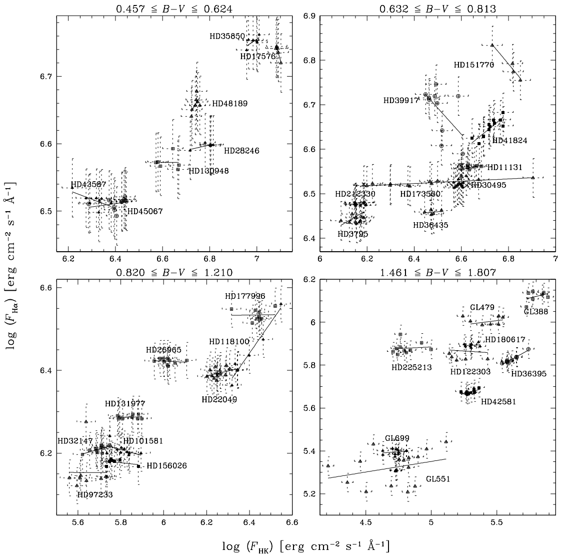

Figure 3. H-α vs. Ca II surface fluxes, for stars of different spectral types, divided into different color bins, as indicated (from Cincunegui et al. 2007b)

In Fig. 4 we show results for two active dM stars, with Hα in emission, taken from our observations. In the left panel we show the individual fluxes for Ad Leo, a dM3 star included in ths sample studied by Walkowicz & Hawley (2009). It can be seen that these fluxes are not correlated (R=0.38). At right, the fluxes for Prox Cen (dM5.5) show two branches. The less active one, measured in Ca II, is not correlated (R=0.52), while the most active one shows a correlation with R=0.78. The most active point was taken, indeed, during a flare, and it fits nicely in the most active branch. On the other hand, it can be seen that, excluding this flaring point, the range of the Hα flux is the same in both branches, with very different Ca II fluxes. If we consider all the observations for a set of 8 dM stars, we get the plot shown in Fig. 5. Here, the correlation is very good, with R=0.83. However, it can be seen that this is not true when looking at the individual observations for a given star in detail.

In fact, Gomes da Silva et al. (2011) found a similar result: studying a sample of 23 stars from the HARPS M-dwarf planet search program, they found a significant correlation between Hα and Ca II fluxes for 25% of the sample, and correlation coefficients between -0.8 and 1.

The relation between these fluxes was also studied, for the Sun, by Meunier & Delfosse (2009). They found that the correlation was much larger during solar maximum than during minimum, and the same happened to the slope. In Fig. 6 we show observations from our program for three solar analogs. It can be seen that Ha and Ca II show a low correlation for the whole series, but the correlation is strongly positive during the active phases (red circles), in agreement with the results by Meunier & Delfosse (2009). It should be noted that HR 6060 (about solar-age) and HD 1835 (about Hyades-age, an older Sun) present similar correlations, implying that this is a property which seems to remain over epochs in which other observables change dramatically.

In Díaz et al. (2007a) we studied the sodium D lines (D1: 5895.92 Å; D2: 5889.95 Å) in our stellar sample. We found a good correlation between the equivalent width

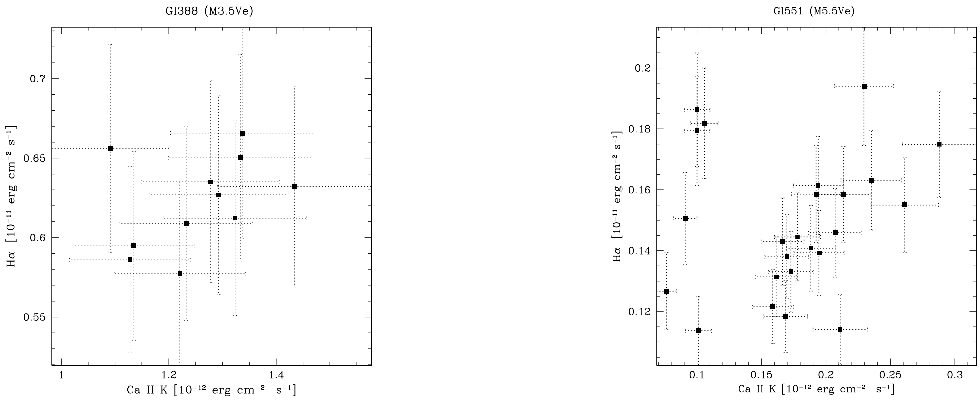

Figure 4. Individual Hα vs. Ca II surface fluxes, for Ad Leo (left) and Prox Cen (right).

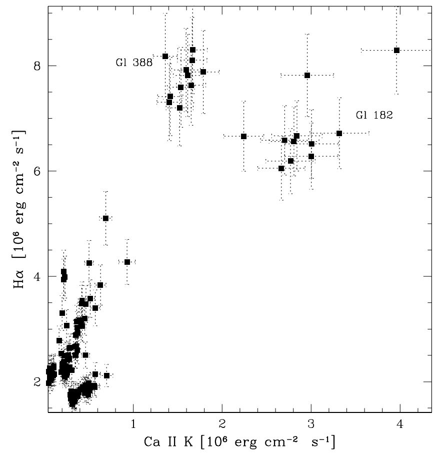

Figure 5. Individual Hα vs. Ca II surface fluxes, for 8 M stars from our sample.

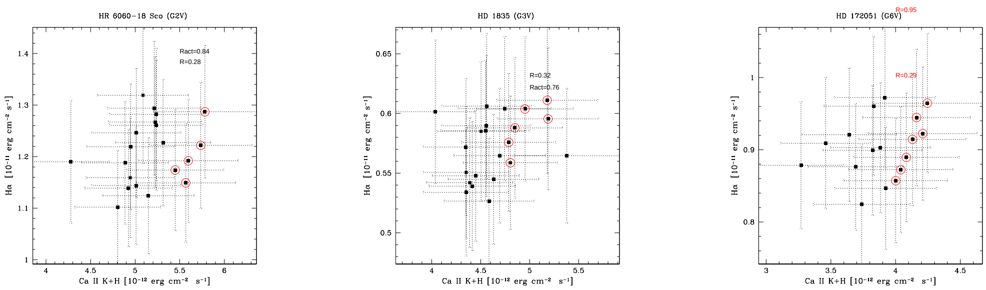

Figure 6. Individual Hα vs. Ca II surface fluxes, for three solar analogs. The red circles indicate the active phases.

of the D lines and the color index $(B - V)$ for all the range of observations. Since equivalent width is a characteristic of line profiles that do not require high resolution

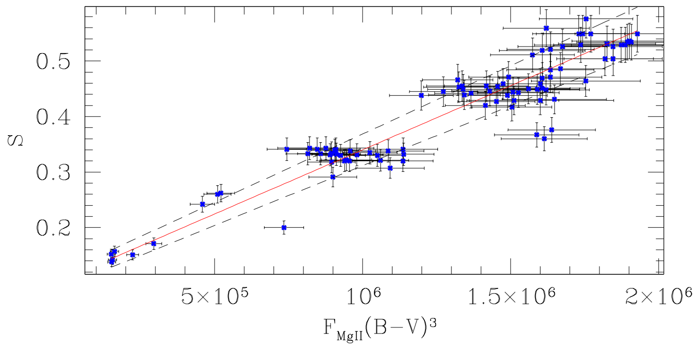

Figure 7. S vs. F_{MgII} . $(B-V)^3$ for our calibration stars. The least square fit (solid line) has a correlation coefficient of 0.95. The dotted lines indicate $\pm3\sigma$ from the fit (from Buccino & Mauas 2008).

spectra to be measured, this fact could become a useful tool for subsequent studies. Finally, we constructed a spectral index (R'_D) as the ratio between the flux in the D lines and the bolometric flux. Once corrected for the photospheric contribution, this index can be used as a chromospheric activity indicator in stars which show Hα in emission.

Gomes da Silva et al. (2011), using the HARPS spectra, with much better spectral resolution, were able to integrate the D line flux in narrower windows, and found a significant correlation with the Ca flux in 70% of the M stars. In this case, the correlation is always positive.

A very large set of observations available for this kind of studies is the one given by the IUE observations, spanning from 1978 to 1995. In particular, since the Mg II h and k lines have a formation similar to the Ca II lines, they should provide a very good activity indicator. In Buccino & Mauas (2008) we studied the correlation between the Mg II flux and the S index (see also Buccino & Mauas 2009). To calibrate, we used 117 quasi simultaneous observations of 21 stars with 0.41 B-V 1.0, and found that

$$S = b\ .\ F_{MgII}\ .\ (B-V)^{\alpha} + a \qquad (2)$$

where $\alpha = 3.0 \pm 0.2, b = (2.31 \pm 0.05).10^{-7}, a = 0.109 \pm 0.004$ and R=0.94. The fit is shown in Fig. 7. As an application of this calibration, we have measured the Mg II line-core flux on 1623 IUE high resolution spectra of 259 main sequence stars of spectral types F to K, and then converted to the Mount Wilson index, and studied cyclic behaviour in several of them (Buccino & Mauas 2008).

3. Activity cycles in dM stars

One of the main goals of our program was to extend the studies of stellar cycles to M-stars, at and beyond the limit for full convectivity. The first star we studied was Proxima Centaury, a dMe 5.5 star with strong and frequent flaring activity (Cincunegui et al. 2007a). Since for this star the Hα flux is well correlated with Ca II, we used it as an activity indicator, since it has better S/N ratio. We used 56 individual spectra, taken over 20 different nights in 15 observation periods spred over more than 6 years

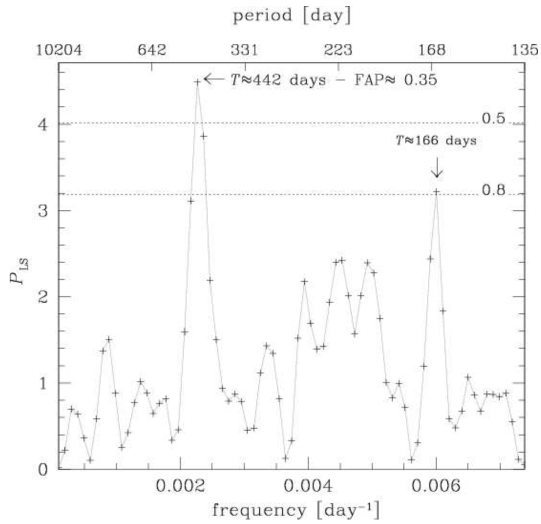

Figure 8. Lomb-Scargle periodogram of our observation of Prox Cen. The False Alarm Probability levels of 50 and 80% are shown. (from Cincunegui et al. 2007a).

For this star we excluded the spectra taken during flares, computed the nightly average of the Hα flux, and calculated the Lomb-Scargle periodogram, which is shown in Fig. 8. In the periodogram we found strong evidence of a cyclic activity with a period of ~442 days. Similar values for the period were found using three different techniques in the time domain (see Cincunegui et al. 2007a, for details). We were also able to determine that the activity variations outside of flares amount to 130% in S, three times larger than for the Sun.

Since this star should be fully convective, it cannot support an $\alpha\Omega$ dynamo, and a different mechanism should be found to explain this result. Recently, Chabrier & Küker (2006) showed that these objects can support large-scale magnetic fields by a pure α^2 dynamo process. Moreover, these fields can produce the high levels of activity observed in M stars (see, for example, Mauas & Falchi 1996). This α^2 dynamo does not predict a cyclic activity. However, our observations suggest that this cool star has a clear period.

We also studied the spectroscopic binary system Gl 375 (Díaz et al. 2007b). We first obtained precise measurements of the orbital period (P = 1.87844 days) and separation (a = 5.665 $R_\odot$), minimum masses and other orbital parameters. We separated the composite spectra into those corresponding to each component, which allows us to confirm that both components are of spectral type dMe 3.5.

To study the variability of Gl 375, besides using the spectra obtained at CASLEO, we also employed photometric observations provided by the All Sky Automated Survey (ASAS Pojmanski 2002). We calculated the Lomb-Scargle periodogram for these data, and obtained a distinct peak corresponding to a period of P_{phot} = 1.876667 days, a period resembling very closely the measured orbital period. We believe this harmonic variability is produced by spots and active regions in the stellar surface carried along with rotation. This would imply that the rotational and orbital periods are synchronized, as is expected for such a close binary.

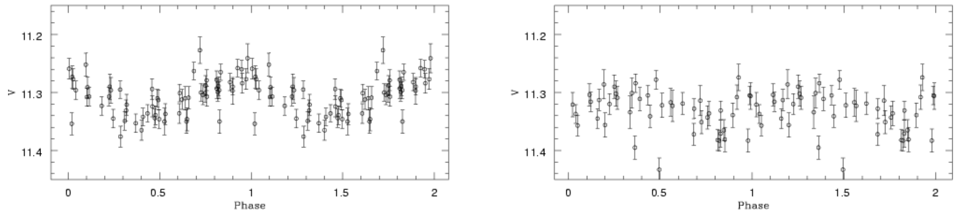

Figure 9. ASAS photometry phased to the orbital period for two different epochs. Left: 2002.5-2003.5 Right: 2006. (from Díaz et al. 2007b).

To verify if this is indeed the case, we phased the data to the obtained period, for two different seasons (Fig. 9). The sinusoidal shape of the variation is evident, although the amplitude of the modulation is different in both cases, probably an indication of different area covered by starspots or active regions, and therefore different activity levels, in each epoch. Therefore, the amplitude of this modulation can be used as an activity proxy, and indicates that the system exhibits a roughly periodic behavior of 2.2 years (or 800 days). The same period was found in the mean magnitude of the system and in the flux of the Ca II K line, although the Ca flux variations occur 140 days ahead of the photometric ones, a behavior that has been previously observed in other stars (Gray et al. 1996). The agreement between the behavior of the three observables is remarkable because of the different nature of the observations and the different instruments and sites where they were obtained.

Another interesting result of this work is that the activity of Gl 375 A and Gl 375 B, as measured in the flux of the Ca II K lines, are in phase, as can be seen in Fig. 10. There is an excellent correlation between the levels of chromospheric emission of both components, implying a magnetic connection between them. Due to its vicinity and relative brightness, this system presents an interesting opportunity to further study this type of interaction.

We also studied the long-term activity of two other M dwarf stars: Gl 229 A and Gl 752 A (Buccino et al. 2011). For these stars, we used the Ca II K line-core fluxes, since they are not correlated with the Hα flux (R=0.09 and R=0.11), and the ASAS photometric data. In Fig. 11 we show the Ca II K fluxes obtained from our observations, the ASAS photometry and its season means, and the Lomb-Scargle periodograms, for both data sets, for Gl 229 A (at left) and Gl 752 A (at right). In this case, we obtained possible activity cycles of ~4 and ~7 yrs for Gl 229 A and Gl 752 A, respectively.

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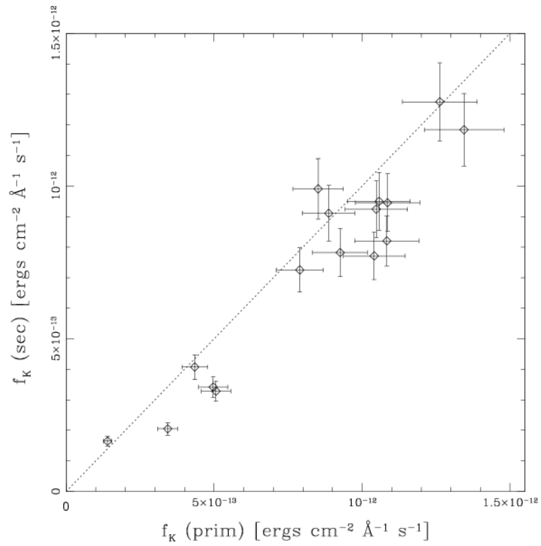

Figure 10. Comparison of the fluxes in the Ca II K line for both components. The error bars correspond to a 10% error in the line fluxes, and the dotted line is the identity relation. (from Díaz et al. 2007b).

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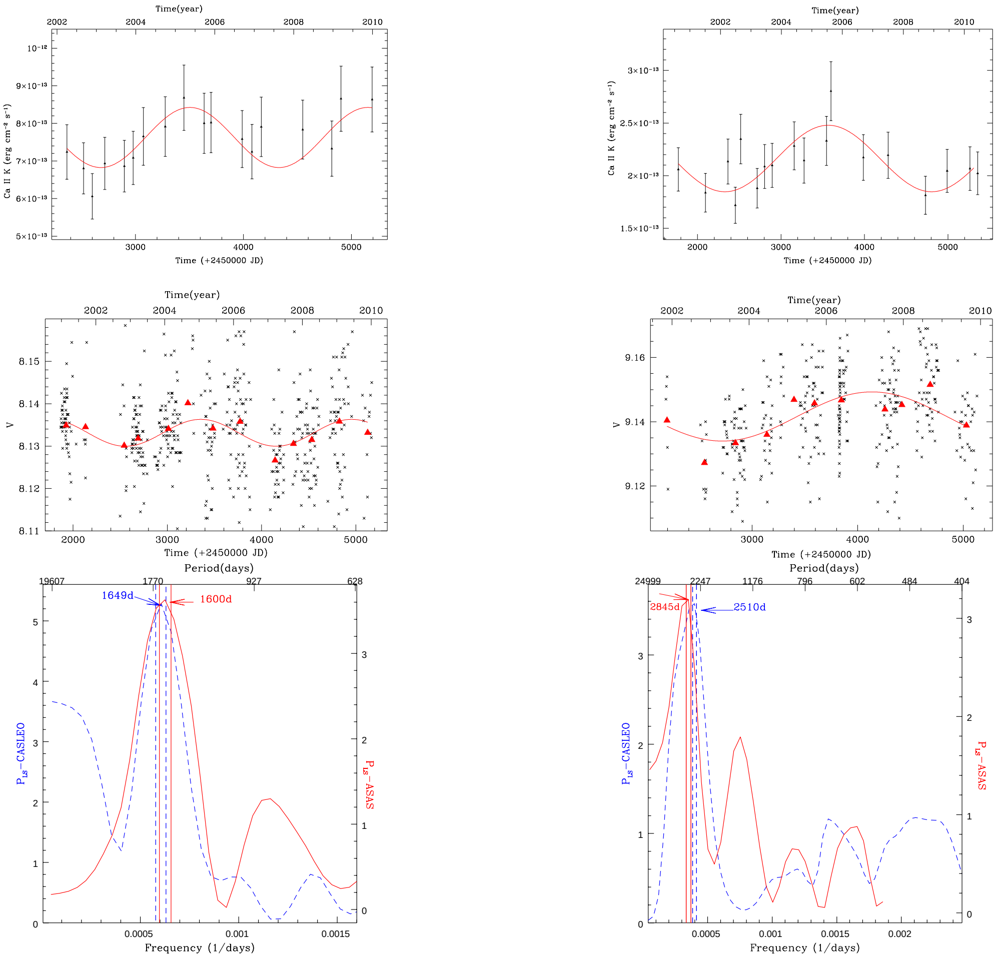

Figure 11. Chromospheric activity of Gl 229 A (left) and Gl 752 A (right). In the uppermost panels, the Ca II K fluxes derived from the CASLEO spectra, with 10% errorbars. In the middle panels, V magnitude measured by ASAS. The triangles indicate the mean annual values. In these four panels, the solid lines are the least-squares fit to the mean annual values after establishing a harmonic curve of the corresponding period. The bottom panels show the LombScargle periodogram of the mean Ca II fluxes (blue, dashed) and the mean V magnitude (red, solid). The solid and dashed vertical lines represent the error interval of each period (from Buccino et al. 2011).