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LONG-TERM CHROMOSPHERIC ACTIVITY IN SOUTHERN M DWARFS: Gl 229 A AND Gl 752 A

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ABSTRACT

Several late-type stars present activity cycles similar to that of the Sun. However, these cycles have been mostly studied in F to K stars. Due to their small intrinsic brightness, M dwarfs are not usually the targets of long-term observational studies of stellar activity, and their long-term variability is generally not known. In this work, we study the long-term activity of two M dwarf stars: Gl 229 A (M1/2) and Gl 752 A (M2.5). We employ medium-resolution echelle spectra obtained at the 2.15 m telescope at the Argentinian observatory CASLEO between 2000 and 2010, and photometric observations obtained from the ASAS database. We analyze Ca II K line-core fluxes and the mean V magnitude with the Lomb–Scargle periodogram, and we obtain possible activity cycles of ~4 yr for Gl 229 A and ~7 yr for Gl 752 A.

Key words: stars: activity – stars: late-type – techniques: photometric – techniques: spectroscopic

Online-only material: color figures

1. INTRODUCTION

Over the last few years, new interest in M dwarfs has emerged. One reason is that their low masses make them ideal targets around which to search for terrestrial planets in the habitable zone (e.g., Charbonneau et al. 2009). However, these stars can be very active and their activity signatures can hinder the detection of orbiting planets (e.g., Bonfils et al. 2007). Furthermore, levels of UV radiation, which are strongly related to stellar activity, can also limit the habitability (Buccino et al. 2006, 2007).

The usually accepted model to describe the generation and intensification of magnetic fields in late F- to early M-type stars is the $\alpha\Omega$ dynamo, first invoked to explain solar activity (Parker 1955). It is this model, in which large-scale magnetic field generation results from the interaction of differential rotation in the tachocline and convective turbulence, that predicts a strong correlation between activity and rotation. Magnetic activity therefore decays with time as the star spins down due to braking by magnetized winds. However, recent results show that this decay happens in the first two Gyr of a star's life, compared with lifetimes of late-type stars which are at least twice as large (Pace & Pasquini 2004).

Since stars with spectral type later than M3 are believed to be fully convective, they should not be able to sustain a solar-like $\alpha\Omega$ dynamo. Furthermore, most dM stars are usually slow rotators. In a recent survey of 123 M dwarfs, Browning et al. (2010) found that only seven of them are rotating more rapidly than their detection threshold of $v \sin i \approx 2.5$ km s^{-1}. However, there is plenty of observational evidence that late-type slow rotators like dMe stars are very active and have strong magnetic fields (Johns-Krull & Valenti 1996), with filling factors larger than for earlier stars (Mochnacki & Zirin 1980; Hawley & Pettersen 1991; Mauas & Falchi 1994, 1996; Mauas et al. 1997). In fact, there is evidence that stellar spin-down and active lifetimes change near the mass where full convection sets in (Delfosse et al. 1998; Barnes 2003; Reiners & Basri 2008; West et al. 2008).

Chabrier & Küker (2006) proposed that for fully convective dM stars, large-scale magnetic fields could be produced by a pure α^2 dynamo, where activity would not decay with time since it does not involve rotation. Browning (2008) developed a three-dimensional dynamo model for M dwarfs, and found that fully convective stars can generate kG-strength magnetic fields without the aid of a shearing tachocline.

To date, activity cycles have been detected in several late-type stars (e.g., Baliunas et al. 1995; Buccino & Mauas 2008). However, these works mainly concentrate on F to K stars, since due to the long exposure times needed to observe them, the red and faint M dwarfs are usually not the target of long-term observational studies of stellar activity. As a contribution to this subject, we have developed an observing program at the Argentinian observatory Complejo Astronomico El Leoncito (CASLEO) dedicated to periodically obtaining medium-resolution echelle spectra of southern late-type stars, including those stars which are fully convective. Our program has been operating since 1999. From our data, we found evidence of cyclic activity for the dMe 5.5 star Prox Centauri, with $P = 442 \pm 45$ days (Cincunegui et al. 2007a), and for the dMe 3.5 spectroscopic binary Gl 375, with $P = 763 \pm 40$ days (Díaz et al. 2007b).

In this work we study the long-term activity of the dM stars Gl 229 A and Gl 752 A. In Section 2 we describe the spectroscopic observations obtained and the photometric data used to analyze these stars. In Sections 3 and 4, we report our results. In Section 5 we analyze the role of Hα as an activity indicator in these stars.

2. OBSERVATIONS

Since 1999, we have systematically observed more than 140 main-sequence stars from F5.5 to M5.5 with the echelle spectrograph on the 2.15 m telescope of the CASLEO Observatory located in the Argentinean Andes. To date, we have more than 4000 spectra, ranging from 3890 to 6690 Å with $R = \lambda/\Delta\lambda \approx 26{,}400$, which constitute an ideal data set to study long-term activity. These spectra are flux-calibrated according to the

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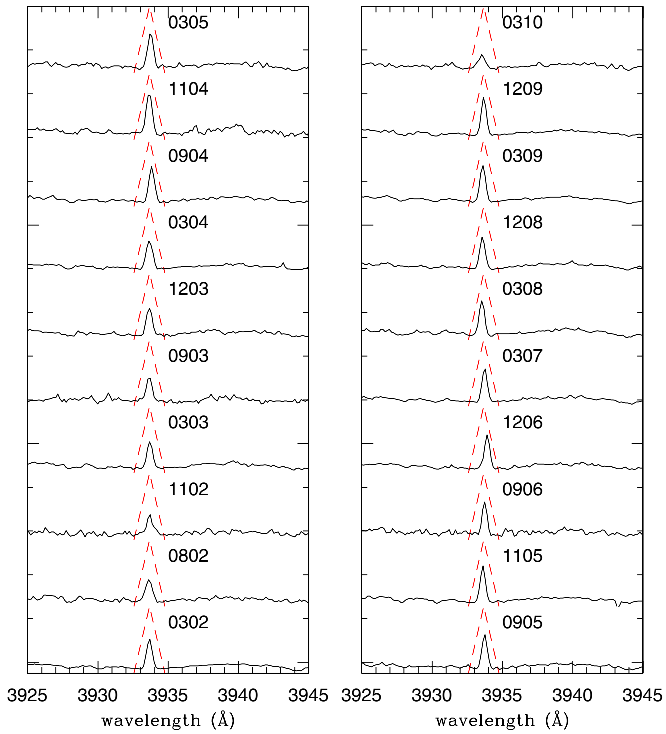

Figure 1. Gl 229 A. Ca II K line in the CASLEO spectra. The triangular profile used to integrate the fluxes is also indicated by dashed lines.

(A color version of this figure is available in the online journal.)

method outlined in Cincunegui & Mauas (2004), and allow us to simultaneously study different spectral features, from the Ca II lines to Hα (e.g., Díaz et al. 2007a).

The usual indicator of chromospheric activity in dF to dK stars is the well-known Mount Wilson S index, essentially the ratio of the flux in the core of the Ca II H and K lines to the nearby continuum (Vaughan et al. 1978). Cincunegui et al. (2007b) defined a Ca II index from the CASLEO spectra, which was calibrated to the Mount Wilson index. Since CASLEO spectra are flux-calibrated, Cincunegui et al. also derived a conversion factor which translates the known S index to flux in the Ca II cores. However, due to the low intrinsic luminosity of M dwarfs, the low signal-to-noise in the Ca II H line in several CASLEO spectra, and the fact that this line can be contaminated by the Hϵ line, the S index is not suitable for studying the chromospheric activity on the faint stars in this study. In this paper we use as a proxy of stellar activity the Ca II K line-core flux, integrated with a triangular profile of 1.09 Å FWHM, to mimic the response of the Mount Wilson instrument.

We complement our data with photometry from the All Sky Automated Survey (ASAS). This project is dedicated to constant photometric monitoring of the whole available sky, including approximately 10^7 stars brighter than 14 mag (Pojmanski 2002). Currently, ASAS consists of two observing stations, one in Las Campanas Observatory, Chile (since 1997) and the other on Haleakala, Maui (since 2006). Each site is equipped with two wide-field 200/2.8 instruments, observing simultaneously in the V and I bands.[5] In this work we used the mean V magnitude of each observing season to analyze the long-term activity of the stars.

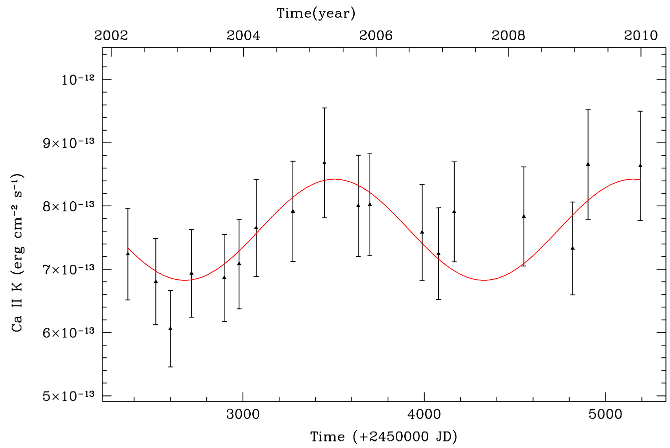

Figure 2. Gl 229 A. Ca II K fluxes derived from the CASLEO spectra in Figure 1. The errors are assumed to be 10% for the calibrated fluxes (Cincunegui & Mauas 2004). The solid line is the least-squares fit to the mean annual values after establishing a harmonic curve of period 1649 days obtained in Figure 4(b) with a correlation coefficient $R = 0.61$.

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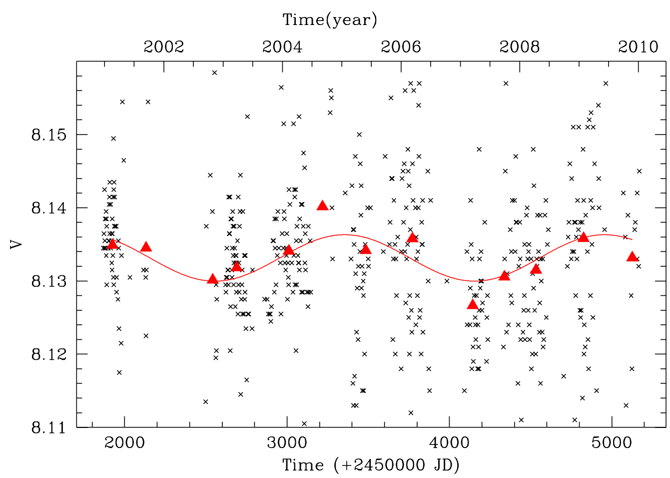

Figure 3. Gl 229 A. V magnitude measured by ASAS. The solid line is the least-squares fit to the mean values (▲) after establishing a harmonic curve of period 1600 days obtained in Figure 4(b) with a correlation coefficient $R = 0.83$.

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3. GL 229 A-HD 42581

Gl 229 A is a moderately active dM1 flare star (Byrne et al. 1985) with a brown dwarf companion (Nakajima et al. 1995). We observed Gl 229 A for 20 nights between 2002 and 2010. In Figure 1 we plot each spectrum, with a label which indicates the month and year of the observation (e.g., 0302 means that the observation was obtained in 2002 March). We excluded the spectrum obtained in 2004 November due to its low signal-to-noise near the Ca II lines and the one observed in 2010 March because it was obtained on a cloudy night.

In Figure 2 we plot the Ca II K fluxes measured on the CASLEO spectra versus time, assuming an error of 10% for the calibrated fluxes (Cincunegui & Mauas 2004). In this figure we observe that the maximum of activity is reached in 2004, where the level of activity is 43% larger than at the minimum.

In Figure 3 we plot the V magnitude obtained from the ASAS catalog. The ASAS data for this system cover the period between 2001 and 2010. We discarded all observations that were not qualified as either A or B in the ASAS database (i.e., we retained

[5] The public data are available at http://www.astrouw.edu.pl/asas/.

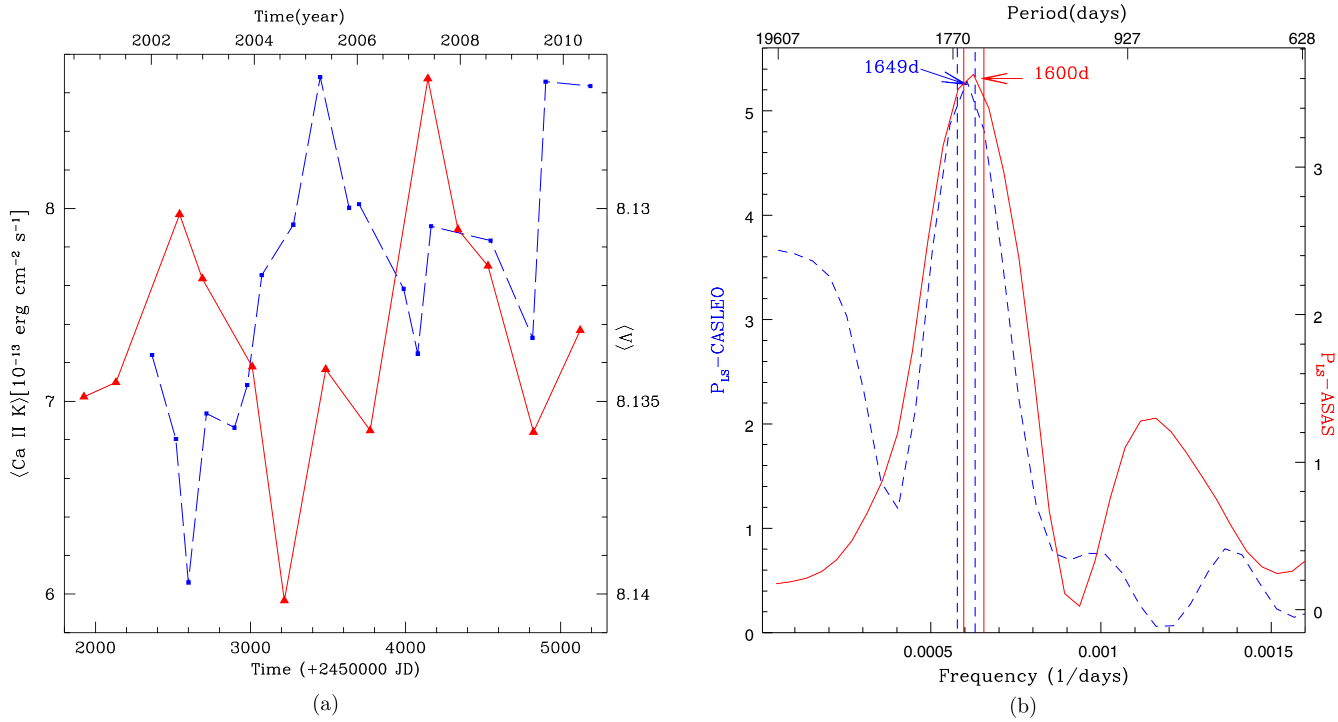

Figure 4. Gl 229 A. (a) The mean annual Ca II K fluxes derived from Figure 2 (blue, dashed) and the mean V magnitude of each observing season obtained from the data plotted in Figure 3 (red, solid). To avoid crowding the graph, we have not included the error bars, which are 10% for the Ca II fluxes and $< 0.1\%$ for the mean V magnitudes. (b) The Lomb–Scargle periodogram of the mean annual Ca II fluxes (blue, dashed) and the mean annual V magnitude (red, solid). The solid and dashed vertical lines represent the error interval of each period.

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only the best-quality data), as well as 16 outlier observations. The final data set consisted of 469 points, with typical errors of around 30 mmag. The mean magnitude variation for the whole period was only $\sim$0.17% around $\langle V \rangle = 8.133 \pm 0.003$, while the short-scale variations in the V magnitude had a $\sim$1% amplitude. To explore if these variations were governed by spots and active regions on the stellar surface, we checked for evidence of rotational modulation in the ASAS data, studying the data set in each observing season with the Lomb–Scargle periodogram (Scargle 1982; Horne & Baliunas 1986). However, in agreement with Byrne et al. (1985), we did not find evidence of rotational modulation in the ASAS data sets.

To search for long-term chromospheric cycles, we analyzed both data sets with the Lomb–Scargle periodogram, and computed the false alarm probability (FAP) of the obtained periods with a Monte Carlo simulation, as is explained in Buccino & Mauas (2009). For the Ca II K fluxes plotted in Figure 2 we obtained a period $P_{\mathrm{CASLEO}} = 1649 \pm 81$ days with a very good FAP = 1.4%.

For the ASAS time series we obtained a peak at 1649 days with an FAP = 5×10^{-5}. This extremely low FAP is related to the large number of points of this series (see Equation (22) in Horne & Baliunas 1986). To reduce the number of points and to eliminate short-term variations, we binned the data by grouping together observations corresponding to the same observing season. We weighted each value with the error reported in the ASAS database, and computed the error of each mean V magnitude as the square root of the variance weighted mean (see Frodesen et al. 1979, Equation (9.12)). For this series we detected a similar period, $P_{\mathrm{ASAS}} = 1600 \pm 75$ days, with an FAP = 7.2%. To check whether the period we obtained depended on the binning, we also analyzed the mean annual V magnitude with the same algorithm and obtained a similar peak at $P_{\mathrm{ASAS}} = 1722 \pm 46$ days, although with a larger FAP = 70%.

To analyze the robustness of our results, we considered the series obtained by binning the data by observing season, and analyzed the periodograms of the series obtained by successively eliminating each data point. We obtained P_{CASLEO} between 1615 and 1799 days with FAPs <15% (75% of them were $P_{\mathrm{CASLEO}} = 1649$ days) and P_{ASAS} between 1493 and 1723 days with FAPs <45% (62% were $P_{\mathrm{ASAS}} = 1600$ days). The fact that the periods are similar in all cases supports the interpretation of a harmonic component with period $\sim$4 yr present in the ASAS series.

In Figure 4(a) we plot the Ca II fluxes and the weighted mean V magnitudes per observing season together. The Lomb–Scargle periodograms of both series are shown in Figure 4(b). Note that both periods coincide within the statistical errors.

Radick et al. (1998) studied long-term photometric and chromospheric emission variations in solar-type stars and found that young, active stars become fainter as their chromospheric emission increases, whereas older, less active stars, including the Sun, tend to become brighter as their chromospheric emission increases. Since during active periods the surface of the star is covered by dark spots and bright faculae, a simple interpretation of this behavior is that long-term variability of young stars is spot dominated, whereas for older stars it is faculae dominated. Recently, Hall et al. (2009) confirmed the anticorrelation between brightness and chromospheric emission for active stars, and found that direct correlations are not prevalent for the less active solar-age stars.

In particular, for Gl 229 A the maximum Ca II K line-core emission nearly coincides with the minimum mean V magnitude, as in the Sun. In Figure 4(a) we invert the V-magnitude scale and

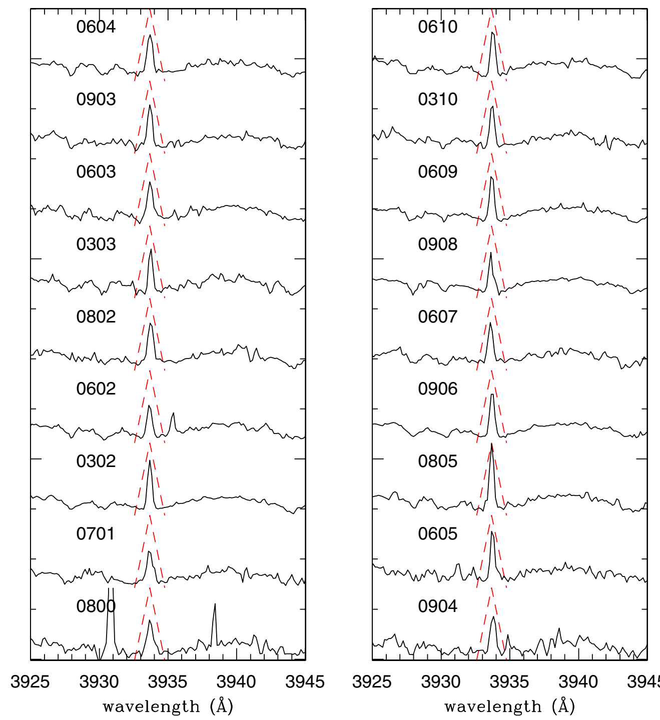

Figure 5. Gl 752 A. Ca II K line in the CASLEO spectra. The triangular profiles used to integrate the fluxes are also indicated by dashed lines.

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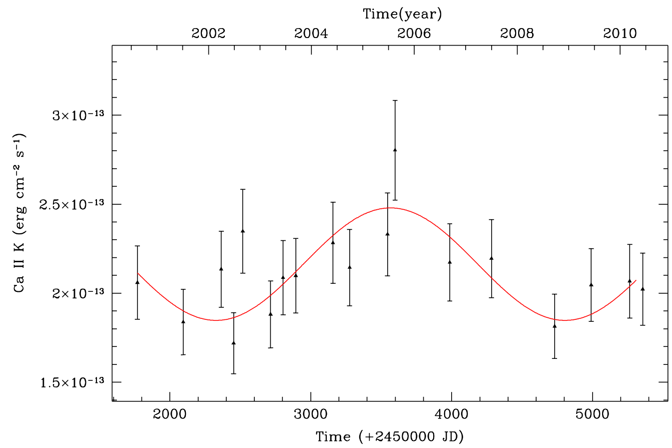

Figure 6. Gl 752 A. Ca II K fluxes derived from the CASLEO spectra in Figure 5. The errors are assumed to be 10% for the calibrated fluxes (Cincunegui & Mauas 2004). The solid line is the least-squares fit to the mean annual values after establishing a harmonic curve of period 2477 days obtained in Figure 8(b) with a correlation coefficient $R = 0.79$.

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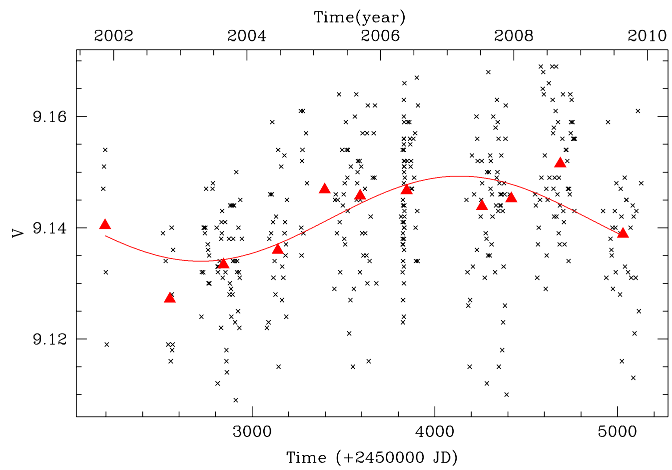

Figure 7. Gl 752 A. V magnitude measured by ASAS. The solid line is the least-squares fit to the mean annual values (▲) after establishing a harmonic curve of period 2845 days obtained in Figure 8(b) with a correlation coefficient $R = 0.77$.

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observe that if we shift the chromospheric activity indicators by approximately 500 days, there is a good correlation between both series with a Pearson correlation coefficient $R = 0.59$.

This time lag between photometric and magnetic variations has already been observed for stars of different spectral types, from β Com (G0V) to ϵ Eri (K2V), including the binary ξ Boo (see, e.g., Gray & Baliunas 1995; Gray et al. 1996a, 1996b). For the coolest star in their sample (ϵ Eri), the time lag of temperature variations is about 0.3 yr (∼110 days). Gray et al. (1996a) showed that, when different stars are compared, this time lag is anticorrelated with effective temperature (see their Figure 8). However, the Sun does not fit this relation (Gray & Livingston 1997). Recently, Díaz et al. (2007b) reported a 140 day (∼0.4 yr) time lag between chromospheric and photospheric activity in the Gl 375 system and Brown et al. (2008) obtained a two-year lag for the K2 III star Arcturus. The physical explanation for these time lags remains unknown (Gray 1998; Brown et al. 2008).

4. GL 752 A-HD 180617

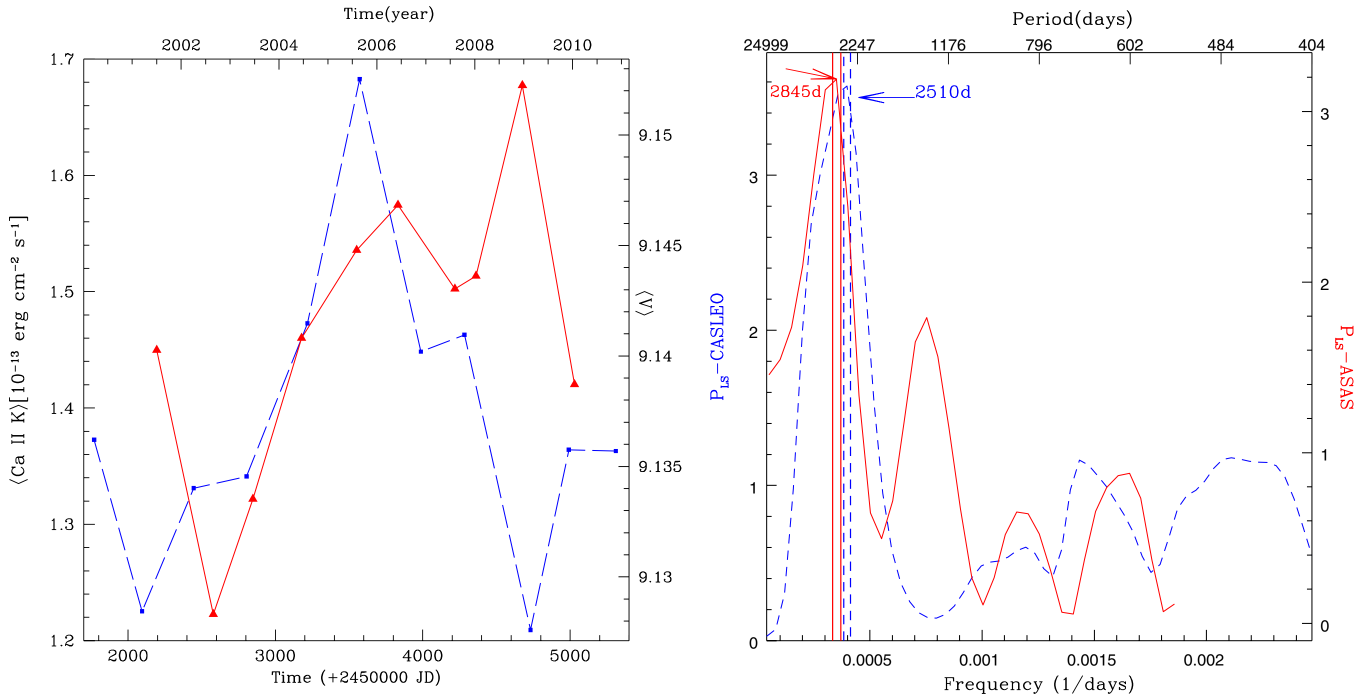
Gl 752 is a binary system comprising the BY Dra variable M2.5 star Gl 752 A and a fainter companion Gl 752 B (also known as VB10) of spectral class M8V. Pravdo & Shaklan (2009) reported that the astrometric variations detected in Gl 752 B could be evidence of the first giant planet around an ultra-cool star. However, Bean et al. (2010) discarded the possibility of a planetary companion around this star using radial velocity techniques.

The Gl 752 system is particularly interesting for the study of dynamo processes as it is composed of two coeval stars with different internal structures. The primary star has a radiative core, where a solar-type dynamo could operate, and the secondary component is a fully convective star. With this aim, Linsky et al. (1995) analyzed several UV lines from *Hubble Space Telescope* spectra of Gl 752 A and B. They detected a flare-like event in the M8 component, which is indirect evidence of a dynamo operating in this fully convective star.

We observed Gl 752 A at CASLEO during 18 nights between the years 2000 and 2010. In Figure 5 we plot the spectra obtained, where the labels are as in Figure 1 with the month and year of the observation. The line-integration windows are also marked with a dashed line.

In Figure 6 we plot the Ca II K fluxes measured on the CASLEO spectra versus time. Following Cincunegui & Mauas (2004) we assumed a 10% error in the calibrated fluxes. For our time interval, the yearly mean of the K-line flux varies by 35%, and the maximum is reached in 2005.

Finally, in Figure 7 we plot the V magnitude available from the ASAS catalog. We selected the best-quality data and discarded seven outlier points, resulting in a total of 398 points. From these data, we obtain a mean magnitude $\langle V \rangle = 9.140 \pm 0.006$ between 2001 and 2010, with a long-term variation of only 0.25% between minimum and maximum. However, short time



(a) (b)

Figure 8. Gl 752 A. (a) The yearly mean Ca II fluxes derived from Figure 6 (blue, dashed) and the weighted mean V magnitude of each observing season obtained from the data plotted in Figure 7 (red, solid). To avoid crowding the graph, we have not included the error bars, which are $<$ 10% for the Ca II fluxes and $<$0.2% for the mean V magnitudes. (b) The Lomb–Scargle 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.

(A color version of this figure is available in the online journal.)

variations (around one month) of the V magnitude are more evident, and are between 0.3% and 1.5%. As for Gl 229 A, we checked whether these variations were modulated by stellar rotation. In particular, from the projected rotational velocity published in Glebocki & Stawikowski (2000), Cincunegui et al. (2007b) estimated a rotational period $P_{\rm rot} = 16.8$ days for this star. However, we did not find any significant periodicity either in the seasonal data sets or in the whole ASAS series.

To search for long-term chromospheric cycles, we analyzed the Ca II K fluxes with the Lomb–Scargle periodogram and detected a period $P_{\rm CASLEO} = 2510 \pm 95$ days with a Monte Carlo FAP = 25%. This relatively large FAP is due to the large variations that can be seen in the data in 2002 and 2005. In both cases, these variations, obtained between observations taken a few months apart, cannot be caused by cyclic activity. If we smooth out these variations by averaging these points, we obtain a similar period with a more significant FAP of ∼5%.

For the mean V magnitude per observing season, the period found was $P_{\rm ASAS} = 2845 \pm 145$ days with an FAP of 22%. In Figure 8(b) both periodograms are plotted together, and it can be seen that the periods coincide within 2σ errors. The periodogram derived from the ASAS data sets exhibits a second peak near 1400 days, which is probably a subharmonic component of the time series. For completeness, we also studied the periodogram obtained for the whole data set, without binning, and obtained a significant peak at 2944 days, again with an extremely low FAP of 6×10^{-9}. For the series obtained with the annual means, we detected a significant peak at 2833 days with an FAP of 50%. Again, all periods coincide.

To study the robustness of the periods detected in Figure 8(b), we repeated the test outlined in Section 3 for both series plotted in Figure 8(a). For the series obtained from the CASLEO

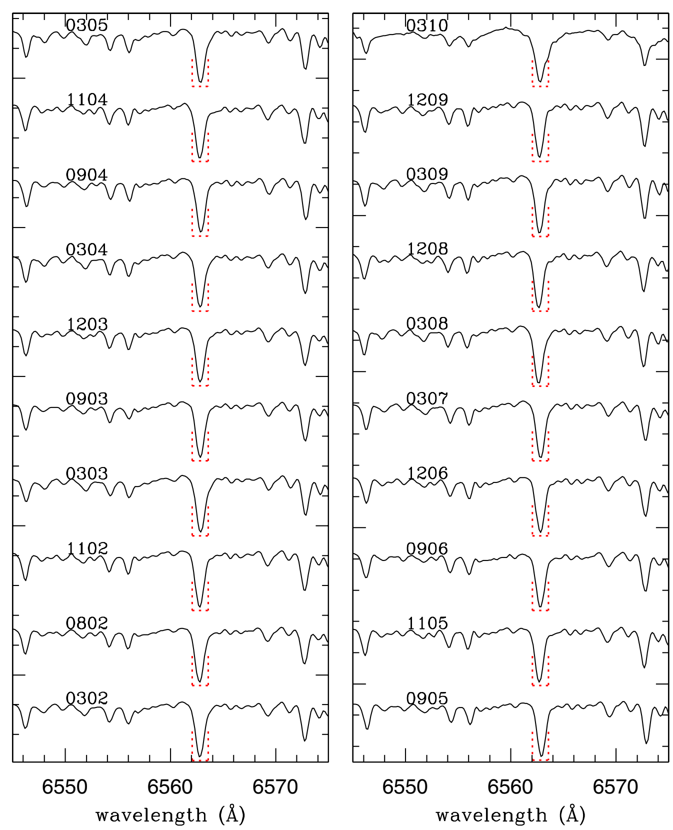


Figure 9. Hα line in the CASLEO spectra of Gl 229 A. The square integration windows are also indicated by dashed lines.

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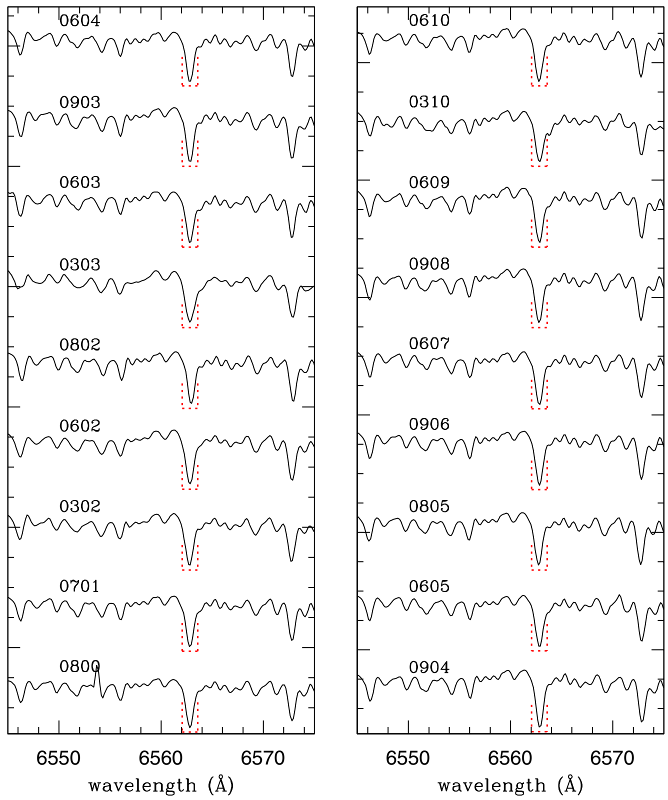

Figure 10. Hα line in the CASLEO spectra of Gl 752 A. The square integration windows are also indicated by dashed lines.

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observations we detected P_{CASLEO} between 2477 and 2505 days with FAPs < 55%, where nine of the eleven periods detected were 2477 days. From the ASAS data set, we obtained eight series with P_{ASAS} between 2845 and 2990 days with FAPs < 55%, two series with P_{ASAS} between 3300 and 3495 days with FAPs of ∼55% and one with $P_{\mathrm{ASAS}} = 1398$ days. We remark that in this last periodogram there is a secondary maximum near 2985 days with an FAP of ∼50%. This test shows that although we shortened the series by discarding their extremes the seven-year period is still detected.

In contrast to Gl 229 A, in Figure 8(a) we observe that Gl 752 A becomes fainter when the Ca II emission increases, implying that, for this star, spots dominate the emission.

On the other hand, in Figure 8(a) the Ca II K-line series precedes the mean *V*-magnitude data set. The chromospheric activity increased between 2001.2 and 2005.6, while the corresponding photospheric activity increment was between 2002.7 and 2006.5, as expressed by the Ca II fluxes and the *V* magnitude, respectively. If we shift the chromospheric series by 360 days, both data sets coincide within the normalization constant with a Pearson correlation coefficient $R = 0.78$.

5. Hα AS AN ACTIVITY INDICATOR

Another activity indicator usually employed in the study of dM stars is the flux in Hα. The flux in this line is generally considered to correlate well with that in the Ca II H and K lines and has the advantage of being located in a redder wavelength range than the Ca II lines, where M dwarfs are brighter. However, it has been reported by Cincunegui et al. (2007b) that the correlation between Ca II and Hα is not always valid. They found that, while some stars exhibit correlations between Hα and the Ca II lines, the slopes change from star to star. Furthermore, in several cases both fluxes were not correlated, as in the binary system Gl 375 (Díaz et al. 2007b), and other stars even exhibited anticorrelations. Recently, Walkowicz & Hawley (2009) analyzed the relation between simultaneous measurements of Ca II K and Hα fluxes in a sample of nearby M3 dwarfs and found that the relationship between both tracers remains ambiguous for weak and intermediate activity stars.

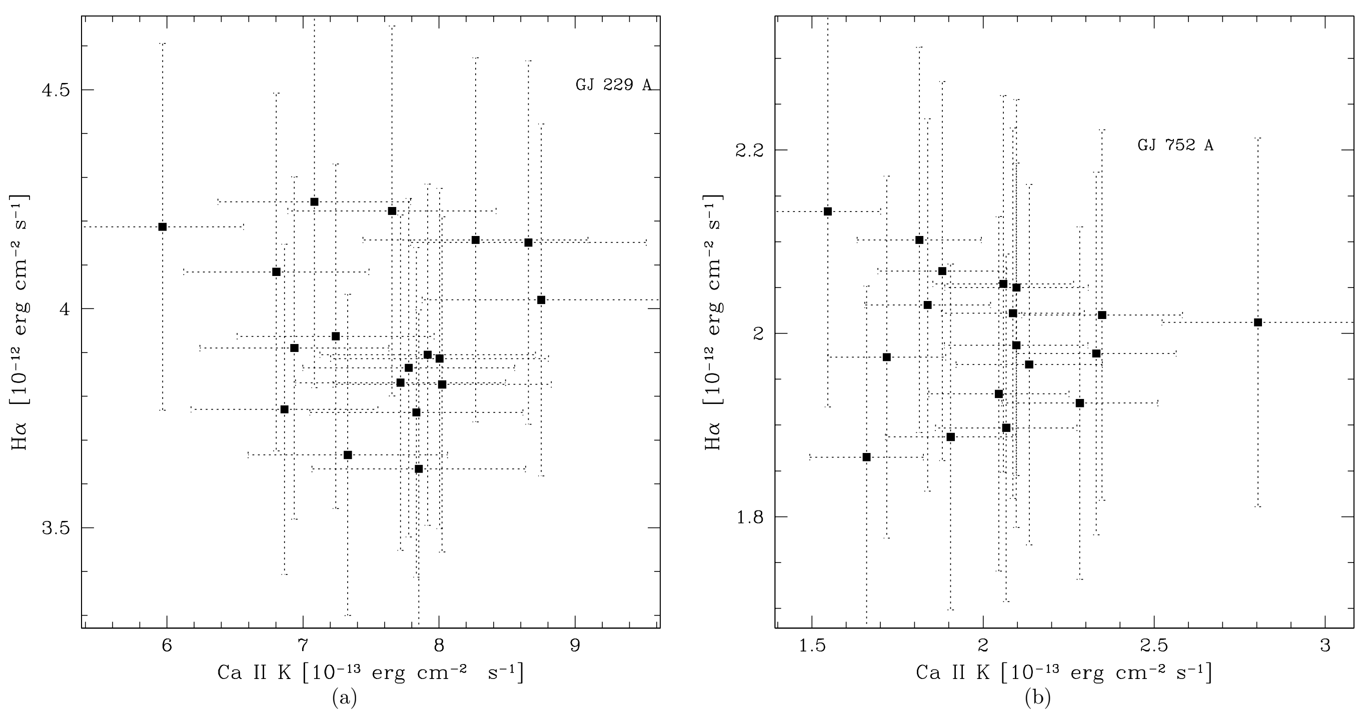

Figure 11. Hα vs. Ca II. We plot the Hα line-core flux integrated in a 1.5 Å square passband centered in the line vs. the Ca II K flux obtained with a triangular profile of 1.09Å FWHM for the stars Gl 229 A (a) and Gl 752 A (b). The Pearson correlation coefficients between the fluxes are $R = -0.09$ and $R = -0.11$, respectively.

On the other hand, Meunier & Delfosse (2009) studied the contribution of plages and filaments in the Hα–Ca II relation in the Sun for different timescales in an attempt to explain the results by Cincunegui et al. (2007b).

In this work, we checked whether an Hα–Ca II correlation exists for Gl 229 A and Gl 752 A. To do so, we computed the flux in the Hα line as the average surface flux in a 1.5 Å square passband centered at 6562.8 Å for all the spectra plotted in Figures 9 and 10. For both stars the Hα line is in absorption, which indicates that Gl 229 A and Gl 752 A are not strongly active, since most active M dwarfs have Hα in emission. In Figures 11(a) and (b), we plot the line-core fluxes in Hα versus those in the Ca II K line. It can be seen that, within the errors, none of these stars exhibits any sign of correlation between the line fluxes, as expressed by the Pearson correlation coefficients $R = -0.09$ for Gl 229 A and $R = -0.11$ for Gl 752 A. Therefore, the Hα line cannot be used as an activity indicator for these stars.

6. CONCLUSIONS

In this work we studied the long-term activity of two M dwarf stars: Gl 229 A and Gl 752 A. To do so, we analyzed the Ca II K line-core fluxes measured on our spectra obtained at the CASLEO Observatory since 2000, and ASAS photometric data. Using the Lomb–Scargle periodogram, we obtained a possible activity cycle of ∼4 yr for Gl 229 A and ∼7 yr for Gl 752 A, respectively. We note that, for both stars, similar periods are found in the photometry and in the Ca II fluxes, which constitute two completely independent data sets, a fact which strongly reinforces the significance of the results. As our program continues, we hope to confirm both periods in future work.

These periods are in agreement with evidence of periodic activity in M dwarfs which was previously reported for the dM stars Proxima Centauri (Cincunegui et al. 2007a) and the Gl 375 system (Díaz et al. 2007b).

Another interesting result of this work is that the chromospheric activity seems to precede the photometric data by ∼1 yr. This time lag was also reported for the dMe system Gl 375 (Díaz et al. 2007b). Although the physical explanation for this phenomenon remains unknown, one possible interpretation for the offset between the photometric and chromospheric variations is that the chromosphere becomes heated before spots are formed. The time lag detected in the Gl 229 A and Gl 752 A data sets provides further evidence of this phenomenon in late-type stars.

On the other hand, since the chromospheric emission in Gl 752 A is larger when the system is fainter, we conclude that the emission of this star should be dominated by dark spots rather than bright active regions. In contrast, in the case of Gl 229 A, the data indicate that the active regions dominate the emission. These results are consistent with the chromospheric–photospheric relations observed in solar-type stars in the literature (Radick et al. 1998; Lockwood et al. 2007; Hall et al. 2009).

We also analyzed simultaneous measurements of Ca II K and Hα fluxes obtained from our CASLEO spectra, and found no evident correlation between the indices, in agreement with previous results by Cincunegui et al. (2007b). Also, Walkowicz & Hawley (2009) found some correlation for the most active stars, but it breaks down for weakly active stars like those we study in this paper.

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