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High-amplitude, long-term X-ray variability in the solar-type star HD 81809: the beginning of an X-ray activity cycle?

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Abstract. We present the initial results from our XMM-*Newton* program aimed at searching for X-ray activity cycles in solar-type stars. HD 81809 is a G2-type star (somewhat more evolved than the Sun, and with a less massive companion) with a pronounced 8.2 yr chromospheric cycle, as evident from from the Mt. Wilson program data. We present here the results from the initial 2.5 years of XMM-*Newton* observations, showing that large amplitude (a factor of $\simeq 10$) modulation is present in the X-ray luminosity, with a clearly defined maximum in mid 2002 and a steady decrease since then. The maximum of the chromospheric cycle took place in 2001; if the observed X-ray variability is the initial part of an X-ray cycle, this could imply a phase shift between chromospheric and coronal activity, although the current descent into chromospheric cycle minimum is well reflected into the star's X-ray luminosity. The observations presented here provide clear evidence for the presence of large amplitude X-ray variability coherent with the activity cycle in the chromosphere in a star other than the Sun.

Key words. Stars: X-rays

1. Introduction

The 11 year cycle is perhaps the oldest known manifestation of the Sun's magnetic activity, having first been noted by Schwabe in 1843 as a periodic modulation of the number of sunspots. Subsequently, most activity indicators have been observed to follow a similar cyclical variation, with the amplitude of the modulation dependent on the indicator used. On cool stars other than the Sun, the detection of cycles had to wait for the foresight of O. Wilson, who started a long-term monitoring of a Ca II H&K activity indicator (the "S index") in a significant number of stars, using the Mt. Wilson 100 inch telescope. An analysis of the vast amount of data from the Mt. Wilson program, now covering nearly 40 years of observations (Baliunas et al., 1995), shows that solar-like cycles are present in many stars, although some stars show no detected variability (perhaps being in a "Maunder-like" state) while others show significant non-periodic variability. In the Sun, the amplitude of the cyclical S index modulation is a factor of about 2, while the amplitude in X-rays is much stronger, i.e. a factor of 100 in the Yohkoh 0.73–2.5 keV band.

Yet evidence of cyclical variability in X-rays in stars other than the Sun has only become available very recently. In fact (with the recent exception of 61 Cyg), the X-ray observations of the few stars for which sufficient data exist suggest that their X-ray luminosity is relatively stable over long-term intervals, as discussed e.g. by Stern (1998). Observations of homogeneous samples of active stars, e.g. of the Hyades, show little variation in $L_{\rm X}$ across the $\simeq 10$-year separation between the *Einstein* and ROSAT PSPC surveys, with 90% of the stars showing less than a factor of 2 variability. In these stellar samples, however, the median activity level is much higher than the Sun's, by 2 or more dex: stars at this activity level typically do not show cycles in Ca II, instead varying irregularly, so that perhaps the lack of X-ray modulation is not surprising. This result was however confirmed by Liefke & Schmitt (2004) on a volume-limited sample of solar-type stars using ROSAT All-Sky Survey (RASS) and pointed observations. Weak statistical evidence for the presence of solar-like cycles in less active stars was derived by Hempelmann et al. (1996) using the RASS observations of the stars in the Mount Wilson program, looking at the deviations from a "mean" X-ray luminosity for each star as a function of the Ca II cycle phase.

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In their analysis of X-ray variability properties of solar mass stars Marino et al. (2002) found that, in relatively quiet stars, amplitude variations increase with time scales, and interpreted this as an indication of the presence of solar-like cycles in stars with X-ray activity of the same order of that of the Sun. The comparison between the Sun and nearby stars is consistent with a fraction of moderately active stars ($\overline{L}_{\rm X} < 10^{28}$ erg/sec) having X-ray variability similar to the Sun, while more active stars lack solar-like cyclic coronal activity (Micela & Marino, 2003).

More recently, Hempelmann et al. (2003) presented evidence of X-ray luminosity modulation in 61 Cyg A and B (K5V and K7V) over 4.5 years, well correlated with their S index, strongly suggestive of an activity cycle in X-rays. The observed modulation amplitude (using ROSAT HRI data, which prevented a study of the spectral evolution) is a factor of 2.5.

In this paper we present the results of the first 2.5 yr of the HD 81809 XMM-*Newton* monitoring program, showing for the first time in a star other than the Sun strong evidence for long-term coherent X-ray variability with an amplitude a factor of about 10, consistent with the cyclic amplitude modulation in the Sun.

2. Characteristics of HD 81809

To search for the presence of clearly visible cycles in the X-ray activity of solar type stars we have selected what appeared to be the best target from the Mt. Wilson sample, HD 81809, which has a very clearly defined cycle in Ca II, with a sufficiently short period (8.2 yr, Baliunas et al., 1995), and sufficient X-ray flux at Earth to permit its efficient observation. We have started a long-term monitoring program of this star with XMM-*Newton*, observing it once every 6 months, with the aim, over the XMM-*Newton* lifetime, of searching for clearly defined cycles and compare their characteristics with the ones of the Ca II cycle in the same star as well as with the characteristics of the solar cycle.

HD 81809, was once considered a good "solar analog", but in fact it is a visual binary system, with a maximum separation of 0.4 arcsec and a period of about 35 yr (Pourbaix, 2000), so that tidal effects are likely to be negligible. The masses of the two components are $M_1 = 1.7 \pm 0.64\,M_\odot$ and $M_2 = 1.0 \pm 0.25\,M_\odot$, with spectral types G2 and G9 and apparent magnitudes $V_1 = 5.8$ and $V_2 = 6.8$ respectively. Both components are slow rotators, with $v \sin i = 3$ km/s (Soderblom, 1982. The Hipparcos parallax appears not to be correct because of the system's binary nature, and has been revised (Söderhjelm, 1999) to $\pi = 29.1 \pm 1.1$ mas, which we adopt here. Such parallax (together with the apparent magnitude) implies that the stars are not on the main sequence, but rather subgiants.

In the Ca II S index HD 81809 shows a very clear cyclical behavior, with a shape rather similar to that of the Sun and an 8.2 year period. All Mt. Wilson S index observations are plotted in Fig. 1. The binary is not resolved, either in the Mt. Wilson data nor in the X-ray observations described below. However, the very clear and regular modulation evident in Fig. 1 points to the activity to be dominated by one of the two components.

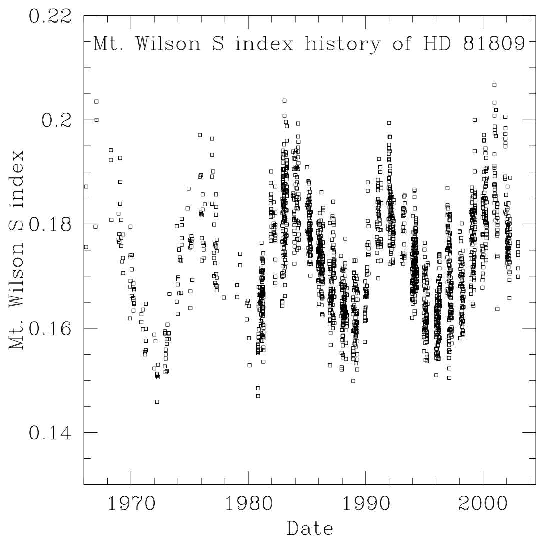

Fig. 1. Evolution of the Mt. Wilson S index of HD 81809 from 1966 to the end of 2002 (see Baliunas et al., 1995 for details).

3. Observations

Monitoring observations of HD 81809, executed every 6 months by XMM-*Newton*, started in April 2001. Each 'snapshot' is a nominal 7 ks exposure. All observations up to May 2003 were taken with the medium filter, while the last observation was taken with the thick filter (following a policy change for the observatory).

All data sets were processed in the same way using the SAS V. 5.4.1 package. High background time intervals were removed prior to further processing and spectra were extracted for each observation, for the pn as well as for each of the MOS cameras. The pn and MOS spectra were simultaneously fit, using XSPEC, with a single temperature optically thin plasma model (APEC). The metal abundance was frozen at $Z = 0.3\,Z_\odot$, to reduce the number of free variable and allow as consistent as possible a comparison among the different data sets. An interstellar absorption component was not necessary to obtain a good fit. For all of the observations, pn and MOS data produced consistent spectral parameters.

In all cases except for the June 2002 observation the single temperature model provided a good fit to the data, with temperatures consistently around 0.35 keV. Nevertheless, a single temperature fit was also performed for the June 2002 data to have a homogeneous data set. X-ray luminosities were computed for both a ROSAT-like 0.2–2.5 keV band and for a Yohkoh-like 0.73–2.5 band. The resulting spectral parameters are reported in Table 1, and a long-term light curve of the X-ray luminosity of HD 81809 is plotted (together with the S index) in Fig. 2.

During the June 2002 observation the X-ray luminosity of HD 81809 is at its maximum, and to obtain a good fit to the spectrum a second temperature component, as well as a different coronal abundance, were needed. The best fit temperatures were $T_1 = 0.51$ keV, $T_2 = 1.3$ keV, i.e. even the lower temperature component is significantly hotter than during the other observations. The relative emission measure of the two compo-

Table 1. Best-fit spectral parameters for the 6 XMM-*Newton* observations of HD 81809 discussed here. Count rates in cts s^{-1}, luminosity in erg s^{-1}, temperature of the plasma in keV.

Date	pn rate	$L_{\rm X}$ (0.2–2.5 keV)	$L_{\rm X}$ (0.73–3.5 keV)	kT
2001-04-25	0.1830 ± 0.055	3.85×10^{28}	1.46×10^{28}	0.34
2001-11-01	0.3418 ± 0.024	6.42×10^{28}	2.91×10^{28}	0.40
2002-06-06	0.7456 ± 0.037	1.78×10^{29}	8.88×10^{29}	0.81
2002-11-02	0.2455 ± 0.024	5.31×10^{28}	2.31×10^{28}	0.39
2003-05-03	0.1522 ± 0.017	3.37×10^{28}	1.36×10^{28}	0.36
2003-11-22	0.0744 ± 0.012	2.05×10^{28}	7.33×10^{27}	0.33

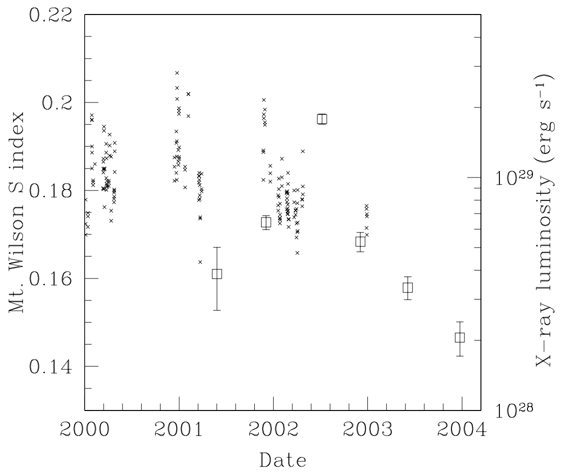

Fig. 2. Evolution of the mean (averaged over the duration of each XMM-*Newton* observation, ca. 2 hr) X-ray luminosity in the 0.2–2.5 keV band (right hand scale) of HD 81809 from April 2001 to November 2003 together with the available Mt. Wilson S index measurements (left hand scale).

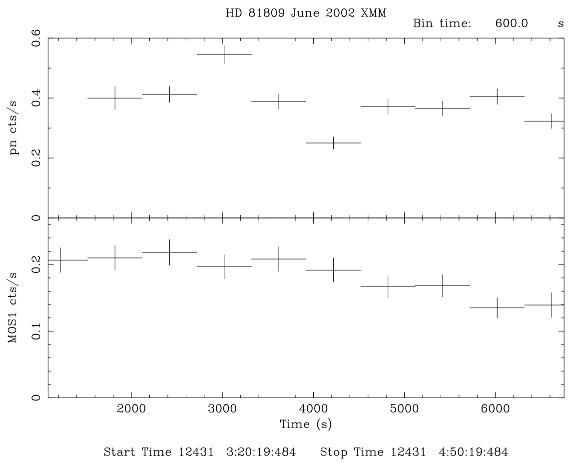

Fig. 3. Light curves (at 600 s bins) of HD 81809 during the June 2002 XMM-*Newton* observation. Top panel, pn data, bottom panel, MOS2 data.

nents was comparable, with $EM_1/EM_2 = 0.81$, and a best-fit coronal abundance $Z \simeq 0.2\,Z_\odot$. The resulting X-ray luminosity is close (within $\simeq 10\,\%$) to the one determined through the single temperature fit, justifying the approach used for a homogeneous comparison. Clearly, the "coronal state" of HD 81809 during this observation was different than during the other observations, with a significantly harder spectrum. The short duration of the June 2002 observation makes it difficult to determine if HD 81809 was undergoing a flaring event. The June 2002 observation (Fig. 3) shows significant variability, with the count rate decreasing rather irregularly during the observation, but without a clear decay (or rise) which could be associated with a "classic" flare. Also, the hardness ratio does not change significantly during the observation, pointing to a constant (rather than decreasing, as expected in the decay phase of a flare) plasma temperature.

Most solar flares have typical duration of tens of minutes (although some very long ones, up to a day, have been observed), and such short event would have a very clear signature in the two hour span of the observation. Long-duration flares, up to days, have been observed in very active stars; while HD 81809's activity level is higher than solar, even when considering surface X-ray flux rather than luminosity, it still is much less active than the very active stars in which long duration flaring events have so far been observed to be common.

4. Discussion

Very significant X-ray long term variability is present in HD 81809 (Fig. 2). This alone is a significant result, as in all X-ray active stars monitored with a sufficient time base the long term variability is very small (typically a factor ≤ 2, see Stern, 1998). The X-ray luminosity of HD 81809, which is not a high-activity star, varies by more than an order of magnitude in two years, with a systematic pattern. If the June 2002 observation were discounted as due to a long-duration flare, the total light curve amplitude would still be a factor of approximately 5. The amplitude of cycle-related modulation in the X-ray luminosity is thus higher in HD 81809 than that recently reported for 61 Cyg (a factor of 2.5, Hempelmann et al., 2003).

While more luminous than the Sun in absolute terms, HD 81809 is a subgiant, with a typical radius of $R \simeq 3R_\odot$. The observed X-ray luminosity range corresponds(considering only the primary star) to a surface flux $4.6 \geq \log F_{\rm X} \geq 5.5$, somewhat higher than the corresponding solar values. At the same time, the Ca II surface flux $R_{\rm HK}$ is almost identical in HD 81809 and in the Sun ($\log R_{\rm HK} = -4.90$ versus $\log R_{\rm HK} = -4.92$ respectively, Baliunas et al., 1995). The X-ray surface flux of HD 81809 is plotted, in Fig. 4, together

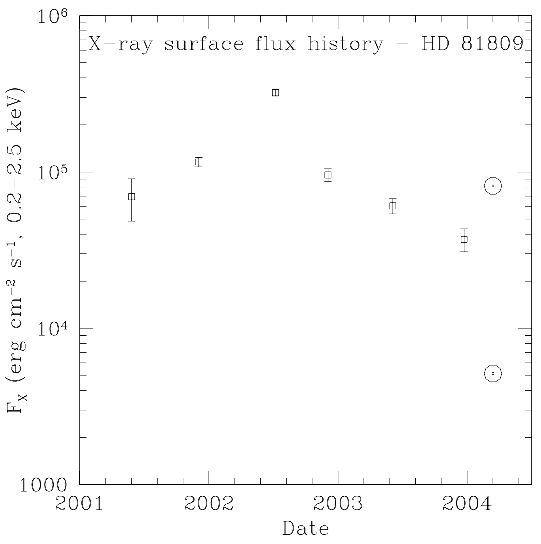

Fig. 4. Evolution of the X-ray surface flux (in the 0.2–2.5 keV band) of HD 81809 from April 2001 to November 2003. At the right of the plot also the typical X-ray surface flux of the Sun at minimum and maximum of the cycle are plotted.

with the range of values observed in the Sun during the cycle. The coronal temperature of HD 81809 is (except for the June 2002 observation) rather constant, and somewhat higher than the coronal temperature of the disk-integrated Sun. The coronal emission measure of the Sun (when filtered through the response of a CCD X-ray detector, see Peres et al., 2000 for details) has a bulk component whose temperature varies little, between 0.16 and 0.19 keV between the minimum and the maximum of the cycle, with the addition of a hotter component ($T = 0.49$ keV), which is only present at cycle maximum. Whether the June 2002 is part of the cycle behavior of HD 81809 or is an exceptional event is something which can only be clarified by further observations.

Figure 2 shows our determination of the X-ray luminosity of HD 81809 plotted together with the last years of S index measurements (due to wildfires that threatened the Mt. Wilson area, very few observations were obtained in 2003). The Ca II chromospheric cycle had a well defined maximum in 2001, and it is now in its descending phase; based on the previous cycles this will likely last well into 2005. On the other hand the X-ray luminosity suggest a cycle maximum corresponding to the June 2002 observation (independent from whether or not a flare occurred). Taken at face value, this would seem to imply a phase shift between the chromospheric and the coronal activity cycles. The last three determinations of the X-ray luminosity are consistently decreasing, as expected on the basis of the chromospheric cycle of the star. The lack of S index values in 2003 prevents us from performing a correlation analysis like that of Hempelmann et al. (2003).

5. Conclusions

We have presented clear evidence of long-term variations of the X-ray luminosity in HD 81809, a solar-type star with a well defined cycle in its chromospheric activity. The variations thus far determined have an amplitude of a factor of 10 (over the 2.5 years covered by the observations), comparable to the variations seen in the X-ray luminosity of the Sun during the solar cycle. These variations suggest the beginning of a cycle; while the observed X-ray maximum appears somewhat offset (by about 1 year) from the chromospheric one, the current descending phase of the chromospheric cycle is well reflected in HD 81809's decreasing X-ray luminosity over the last two years.

HD 81809 is the subject of a long-term monitoring program performed with the XMM-*Newton* observatory (which also includes α Cen and 61 Cyg), of which we are presenting here the first (still perforce preliminary) results. A further two years of observations (at six months cadence) are already planned on the same target, and we will re-propose the target for every AO, to ensure the continuous monitoring. While the nature of this program is such that a few more years will be necessary before a detailed analysis can be performed, the initial results presented here show that our initial choice of targets was a good one; we now can state with some confidence that the Sun is not the only solar-type star for which large amplitude X-ray variability coherent with the activity cycle in the chromosphere is present. The continuation of our monitoring program on HD 81809 will allow to compare the characteristics of its coronal cycles with the solar one.

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