A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
08.01.2; 08.12.1; 08.03.5; 13.25.5

ASTRONOMY
AND
ASTROPHYSICS
27.6.1995

Coronal X-Ray Emission of Cool Stars in Relation to Chromospheric Activity and Magnetic Cycles

A. Hempelmann[1], **J.H.M.M. Schmitt**[2], **and K. Stępień**[1,3]

[1] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany
[2] Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstr., D-85748 Garching, Germany
[3] Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland

Received date; accepted date

Abstract. We study the relationship between the coronal X-ray emission of single, main-sequence F-K stars and the characteristics of their magnetic cycles. We use X-ray data primarily from the ROSAT all-sky survey (RASS) as well as data acquired by us in the ROSAT pointed program, and the published data of the Mt. Wilson CaII H+K monitoring program. According to their CaII H+K long-term variability characteristics, we divide the stars into three groups: non-variable, regular variable and irregular (chaotic) variable stars. We show that the regular and the irregular stars differ mainly in their Rossby-numbers (Ro): regular stars have almost always $Ro < 1$ whereas the irregular group is characterized by $Ro > 1$; further, the X-ray surface flux distributions differ significantly between these three groups. We discuss to what extent stars exhibiting constant Ca II fluxes can be considered "Maunder minimum" stars, and demonstrate – in a statistical sense – that cyclic chromospheric activity also implies cyclic coronal activity. From a reanalysis of the flux-flux relation between the calcium excess flux density (ΔF_{Ca}) and F_{X}, we find different relations between the regular and the constant stars on one hand and the irregular stars on the other hand. Performing regression analysis in the form of a power law, the coefficient κ is derived to be $\kappa \approx 1$ for constant and regular stars whereas $\kappa \approx 2$ for the more active irregular stars. We discuss our findings in the context of a transition from a nonlinear to a linear dynamo regime when going from irregular to regular stars.

Key words: stars: activity – stars: late-type – stars: coronae – X-rays: stars

1. Introduction

Magnetically induced stellar activity is thought to have its roots in the interaction of stellar rotation and turbulence. This interaction is believed to lead to the generation of magnetic fields by dynamo processes in the interior of a star; because of magnetic buoyancy the magnetic fields produced in the stellar interior may ultimately rise to the surface, where they manifest themselves directly or indirectly in the many indicators of stellar activity such as star spots, chromospheric plages, ultraviolet and X-ray emission.

Previous studies of the coronal X-ray emission of late-type stars have focused on the dependence of coronal activity on stellar structure, rotation and age, and the relations between the different activity indicators. However, a magnetic dynamo operating in the convection zone of a cool star with differential rotation will produce a non-stationary field as is manifested in the 11 year spot cycle of the Sun, and in the long-term variability of the CaII H+K core emission, observed by the Mt. Wilson Observatory monitoring program (Wilson 1978, Vaughan 1980, Vaughan et al. 1981, Baliunas et al. 1985, Donahue 1993, Baliunas et al. 1995). From the point of view of coronal X-ray emission the solar cycle manifests itself as a modulation of the observed total X-ray output, which becomes progressively larger as one moves to higher and higher energies. In soft X-rays ($0.1 < E_{\mathrm{keV}} < 0.3$), the modulation is about an order of magnitude (cf., Kreplin 1970), in hard X-rays the modulation is at least two orders of magnitude (Wagner 1988), and in the γ-ray regime, where emission is observed only during transient events, no γ-ray flares are observed during a few years around solar minimum.

Turning to stars, the best studied indicator for cyclic variability, i.e., the monitoring of the CaII H+K core emission variability, is hampered by the fact that the Mt. Wilson emission measure, S, contains several contributions of non-magnetic origin, such as photospheric and absorption line wing contributions and a basal term of non-magnetic heating of the chromosphere (cf., Schrijver, Dobson & Radick 1989, and references therein). These non-magnetic contributions to the S-index may significantly exceed the magnetic ones by a large margin, and hence, the appearence of CaII H+K emission line variability, which one would like to use as a tracer for magnetic fields,

---

Send offprint requests to: Alexander Hempelmann (e-mail ahempelmann@aip.de)

can be strongly depressed by these constant contributions of non-magnetic origin.

Coronal X-ray emission on the other hand is the only observable thought to be of purely magnetic origin (cf., Linsky 1985; Stępień & Ulmschneider 1989), although this view is not universally accepted (cf., Mullan & Chang 1994). In the stellar context, X-ray emission will then be the best parameter to study magnetic cycles, but unfortunately, X-ray observations of stars are typically snapshots and, except for the Sun, the X-ray data are far inferior to the Ca data in terms of temporal coverage. Consequently, the investigation of the relationship between coronal X-ray emission and magnetic cycles must be restricted to comparative studies of the different classes of the CaII H+K cycle phenomenology. The purpose of this paper is then to combine the X-ray data obtained in the ROSAT all-sky survey (RASS) with the published time-series of the Mt. Wilson CaII H+K S-index (Duncan et al. 1991; Donahue 1993, Baliunas et al. 1995) in an attempt to study – to our knowledge for the first time – the relationship between coronal X-ray emission and cycle behaviour as established from the ground-based Ca II monitoring program.

A visual inspection of the plots presented in the paper by Baliunas et al. (1995) clearly shows that three types of dynamical behaviour exist, which we denote as "stationary", "linear" and "nonlinear". As "stationary case" we consider all non-variable stars, as "linear case" all stars with a regular behaviour, and as "nonlinear case" all stars exhibiting irregular variability. We therefore empirically classify our sample stars into constant, regular and irregular stars, will assume that these three classes reflect basic differences of the underlying dynamo, i.e, the "stationary", the "linear" and the "nonlinear" dynamo. Then, we have to ask which stellar parameter is responsible for switching from one dynamo status to another.

The constant stars are – in a way – most challenging. It is not clear a priori whether they are really magnetically inactive – as it was observed for the Sun during its Maunder minimum (Eddy 1976) – and therefore constant, or, whether "normal" variability is simply not visible because of strong non-magnetic contamination of the observed Mt. Wilson S-index. In principle, this question should be answered by X-ray observations, since obviously the mean level of coronal X-ray activity of the "Maunder minimum stars" is expected to fall below the X-ray level of the regular class. However, because some solar activity was also observed during the Maunder minimum phase but at a rather low level of spot activity, one actually expects X-ray activity at or below the minimum value of the normal solar cycle, rather than a total lack of any X-ray emission. In the other case of an undetected cycle, one expects X-ray emission at a level typical for the regular class.

A first preliminary study of RASS data (Hempelmann et al. 1993) showed that most of the constant stars were not detected as X-ray sources by ROSAT. Therefore, we pursued a ROSAT pointing program to observe suspected "Maunder minimum stars". We will present here the results for the first five stars.

Another issue relevant to magnetic cycles is the observation of cyclic variability of stellar X-ray emission. In analogy to the Sun, such cycles should be observable in X-rays, since, first, the Sun clearly varies over the solar cycle (Maggio et al. 1987) and, second, the scattering in the coronal activity-rotation relations is too large to be explained by observational errors alone. For example, Hempelmann et al. (1995) find a substantial scatter $\sigma \approx 0.35$ in the mean X-ray surface flux log $F_{\rm X}$ vs. the Rossby number, implying amplitudes between minimum and maximum activity of the order of ten. If the observed scatter is indeed due to magnetic cycles, and not mainly the consequence of short-term variability, the observed deviations of individual values from the regression curve actually carry information and can be used as a signature of cyclic variability. For this purpose, we will correlate these deviations with the cycle phases, whenever this phase can be derived from the published Mt. Wilson CaII H+K values.

The phase information from the CaII H+K program is very important also from the point of view of the relationship between coronal X-ray emission and the strength of chromospheric activity. Is this relationship different for the three dynamical classses? A possibly existing fine structure in the flux-flux relation may be visible only in case of dramatically reduced scatter which can be expected from quasi-simultaneous X-ray and CaII H+K observations.

Several authors have investigated this in respect of the question of coronal heating important flux-flux relation. Assuming a power law,

$$F_{\rm X} \propto (\Delta F_{\rm Ca})^{\kappa} \tag{1}$$

where the excess flux density, $\Delta F_{\rm Ca}$, is the magnetic fraction of $F_{\rm Ca}$, κ was derived by regression analysis. The results reach from $\kappa \approx 3$ (Ayres, Marstad & Linsky 1981, Stępień 1994) to a value of ≈ 1.5 (Schrijver 1987, Schrijver, Dobson & Radick 1992). A quadratic dependence was found by Rutten et al. (1991). We feel that the discrepancies can be caused by three reasons:

i) Merging of different classes of stars which may have different κ,

ii) possible systematic errors in the subtracted non-magnetic terms of $F_{\rm Ca}$, and

iii) large uncertainties as the consequence of the snapshot character of the used observations, in connection with stellar variability. For example, the lowest scatter around the fit was found by Schrijver, Dobson & Radick (1992) who used simultaneously observed optical and X-ray data.

The purpose of this paper is then to study the relationship between chromospheric and coronal activity from the point of view of the cycle properties of the underlying star. In Sect. 2 we discuss the data used in our analysis and in particular discuss the criteria used to determine the cycle properties of our stars. Section 3 contains our basic results; we specifically present a comparison between the coronal activity of stars with different cycle properties, we discuss to what extent we are able to indentify stars in their "Maunder minimum state", we present statistical evidence that regular (from a chromospheric point of view) stars also exhibit coronal activity cycles, and finally we

Table 1. Basic data, and stellar X-ray fluxes

Star HD	Dist. [pc]	V	$B-V$	ref.	$P_{\rm rot}$ [d]	ref	X-rate [cts/s]	error [cts/s]	log $F_{\rm X}$ [erg/cm^2/s]	Ca S	$P_{\rm cyc}$ [y]	phase	type
1835	20.4	6.4	0.66	gl	7.70	2	0.260	0.030	6.10	0.338	9.1		5
2454	30.3	6.0	0.43	bs			$\leq$ 0.024		$\leq$ 5.21	0.173*			1
3229	35.7	5.9	0.44	sk			0.111	0.016	5.82	0.219*	4.9		5
3443	13.5	6.3	0.72	gl			$\leq$ 0.021		$\leq$ 4.90	0.176*	long		6
3795*	18.9	6.1	0.70	gl			0.003	0.001	3.99	0.153*			1
4628	6.9	5.8	0.88	gl	38.00	2	0.031	0.012	4.64	0.210	8.4	0.95	2
6920	20.0	5.7	0.60	gl	15.20	3	0.086	0.017	5.41	0.188*			5
9562*	14.7	5.7	0.65	gl			0.004	0.001	4.01	0.137*			1
10476	7.5	5.2	0.84	gl	35.20	1	$\leq$ 0.010		$\leq$ 4.03	0.175	9.6	0.70	2
10700	3.6	3.5	0.72	gl			0.053	0.013	4.17	0.173*			1
12235	21.7	5.9	0.62	gl			$\leq$ 0.036		$\leq$ 5.09	0.153*			4
13421	19.2	5.6	0.56	sk			$\leq$ 0.008		$\leq$ 4.42	0.132*			1
16160	7.2	5.8	0.97	gl	48.00	1	0.048	0.017	4.68	0.200	13.2	0.85	2
16673	24.4	5.8	0.52	sk	7.40	3	0.137	0.026	5.75	0.214*			3
17925	7.9	6.1	0.87	gl	6.60	2	1.080	0.069	6.32	0.670			3
18256	25.6	5.6	0.43	sk			0.047	0.012	5.35	0.179*	6.8		2
20630	9.3	4.8	0.68	gl	9.24	1	1.139	0.067	6.10	0.370	5.6		3*
22049	3.3	3.7	0.88	gl	11.30	2	2.041	0.077	5.65	0.500			3
25998	22.2	5.5	0.54	gl	2.60	2	0.811	0.042	6.40	0.279*			5
26913	22.7	6.9	0.70	sk	7.20	2	0.404	0.040	6.45	0.370	7.8		3*
29645	20.8	6.0	0.57	sk			$\leq$ 0.009		$\leq$ 4.58	0.139*			1
30495	13.0	5.5	0.64	gl	7.60	2	0.403	0.027	5.97	0.308*			3
32147	9.2	6.2	1.06	gl			$\leq$ 0.037		$\leq$ 4.61	0.264*	11.1		2
33608	30.3	5.9	0.46	sk			0.094	0.017	5.71	0.214*			5
35296	15.9	5.0	0.53	gl	3.56	1	1.237	0.053	6.39	0.315	long		6
39587	9.9	4.4	0.59	gl	5.20	2	1.725	0.064	6.22	0.320			3
43587	18.2	5.7	0.61	gl			$\leq$ 0.017		$\leq$ 4.71	0.157*			1
75332	28.6	6.2	0.49	sk			0.410	0.040	6.46	0.274*			3
76151	11.8	6.0	0.67	gl			0.097	0.019	5.51	0.225*			5
76572	38.5	6.3	0.43	sk			$\leq$ 0.014		$\leq$ 5.08	0.146*	7		6
78366	21.7	6.0	0.57	gl	9.67	1	0.321	0.030	6.14	0.270	12.2	0.16	2*
81809	20.0	5.8	0.65	gl	40.20	1	0.031	0.012	4.93	0.175	8.2	0.05	2
82885	9.2	5.4	0.77	gl	18.60	1	0.267	0.026	5.57	0.265	7.9		5
88737	28.6	6.0	0.56	sk			0.200	0.024	5.96	0.232*			5
89744	23.8	5.8	0.54	sk	12.30	2	$\leq$ 0.006		$\leq$ 4.36	0.137*			1
95735	2.5	7.5	1.51	gl	48.00	2	0.143	0.023	4.80	0.411			1
97334	23.8	6.4	0.60	sk	7.60	2	0.310	0.032	6.26	0.327*			3
100180	25.0	6.2	0.57	sk	14.00	2	$\leq$ 0.030		$\leq$ 5.19	0.165*	12.9		6
100563	28.6	5.8	0.46	sk			0.201	0.024	5.99	0.198*			3
101501	9.1	5.3	0.74	gl	16.68	1	0.297	0.033	5.63	0.300			3
103095	8.8	6.4	0.75	gl			$\leq$ 0.016		$\leq$ 4.80	0.183*	7.3		2
106516	34.5	6.1	0.46	sk	6.91	1	0.052	0.013	5.54	0.210			3
107213	17.9	6.3	0.50	sk			$\leq$ 0.006		$\leq$ 4.67	0.134*			4
114378	18.9	5.1	0.45	gl	3.00	2	0.382*	0.057	6.00	0.238	long		6
114710	8.3	4.3	0.58	gl	12.40	3	0.311	0.027	5.43	0.190	16.6		5
115383	13.0	5.2	0.58	gl	3.30	3	1.136	0.061	6.37	0.315			3
115404	11.5	6.6	0.92	gl	18.47	1	0.135	0.025	5.53	0.480	12.4		5
120136	16.1	4.5	0.48	gl			0.569	0.042	5.91	0.191*	12		5
124570	23.8	5.5	0.54	sk	5.60	4	$\leq$ 0.012		$\leq$ 4.59	0.136*			1
124850	13.5	4.1	0.52	sk			0.924	0.054	5.90	0.207*			5
126053	16.4	6.3	0.63	gl			$\leq$ 0.009		$\leq$ 4.64	0.154	long		6
131156	6.8	4.7	0.76	gl	6.31	1	2.451	0.079	6.31	0.460			3
141004	10.6	4.4	0.60	gl	25.80	1	0.058	0.014	4.75	0.160	long		6
142373*	17.9	4.6	0.57	gl			0.006	0.002	3.84	0.144*			1

Table 1. continued

Star	Dist. [pc]	V	$B-V$	ref.	$P_{\rm rot}$ [d]	ref	X-rate [cts/s]	error [cts/s]	log $F_{\rm X}$ [erg/cm^2/s]	Ca S	$P_{\rm cyc}$ [y]	phase	type
143761	18.2	5.4	0.60	gl			$\leq$ 0.013		$\leq$ 4.49	0.148*			1
149661	10.9	5.7	0.81	gl	21.07	1	0.214	0.021	5.58	0.360			3
152391	15.9	6.6	0.75	gl	11.10	2	0.290	0.026	6.11	0.435	10.9	0.25	2
154417	21.3	6.0	0.58	gl	7.78	1	0.204	0.023	5.94	0.268	7.4		3*
155885	5.4	5.1	0.86	gl	21.11	1	0.354*	0.080	5.46	0.370	5–6	0.50	2*
155886	5.4	5.1	0.86	gl	20.69	1	0.354*	0.079	5.46	0.320	5–6	0.80	2*
156026	5.4	6.3	1.16	gl	18.00	2	0.163	0.042	5.20	0.730*	21		6
157856	43.5	6.4	0.46	sk			$\leq$ 0.037		$\leq$ 5.52	0.202*	16		6
159332	24.4	5.6	0.48	sk			$\leq$ 0.008		$\leq$ 4.49	0.143*			4
160346	12.3	6.5	0.96	gl	36.00	3	0.046	0.013	4.96	0.230	7.0	0.82	2
161239	25.6	5.7	0.65	sk			$\leq$ 0.028		$\leq$ 4.88	0.135*	5.7		6
165341	5.1	4.2	0.86	gl	19.70	2	1.339*	0.062	5.70	0.310	5.1		3*
166620	10.8	6.4	0.87	gl	42.00	2	$\leq$ 0.009		$\leq$ 4.39	0.169	15.8	0.85	2
182101	34.5	6.3	0.44	sk			0.074	0.014	5.81	0.212*	5		5
187013*	21.3	5.0	0.46	gl			0.082		5.29	0.153*	long		6
187691*	18.9	5.2	0.56	gl			0.020		4.62	0.148*	5.4		4
190007	13.2	7.5	1.12	gl	29.30	2	0.069	0.017	5.32	0.700	13.7	0.93	2
190406	17.5	5.8	0.61	gl	13.94	1	0.062	0.014	5.31	0.190	2.6		5
194012	27.0	6.2	0.51	sk			0.041	0.011	5.40	0.190*	5.4		5
201091	3.4	5.2	1.17	gl	35.37	1	0.260*	0.029	4.95	0.600	7.3	0.50	2
201092	3.4	6.0	1.37	gl	37.84	1	0.130*	0.029	4.66	1.000	11.7	0.50	2
206860	17.5	6.0	0.58	gl	4.86	1	0.406	0.035	6.24	0.320	6		5
207978	34.5	5.5	0.42	sk			$\leq$ 0.005		$\leq$ 4.35	0.153*			1
212754	27.8	5.8	0.52	sk			$\leq$ 0.021		$\leq$ 4.94	0.141*			4
216385	26.3	5.2	0.48	sk			$\leq$ 0.006		$\leq$ 4.22	0.142*			1
224930	11.9	5.8	0.67	gl			0.023	0.010	4.77	0.178	10		6

References: gl: Gliese (1969), sk: Gottlieb (1978), bs: Hoffleit & Jaschek (1982)
1: Donahue (1993), 2: Noyes et al. (1984), 3: Baliunas et al (1985), 4: Stimets & Giles (1980)
asterisk: detailed information are given in Chapt. 2;
types: 1–constant, 2–regular, 3–irregular, 4–undetermined (constant or regular) 5–undetermined (regular or irregular) 6–probably regular, but with very uncertain cycle duration and amplitude.

discuss the relation between the excess Ca flux (i.e., a choromospheric activity indicator) and X-ray flux with respect to the cyclic stellar properties. In the last section we then summarise our conclusions.

2. Observations and Data Selection

Almost all previously published X-ray studies were based on data obtained with the *Einstein Observatory* or *EXOSAT* satellites. With the ROSAT all-sky survey (RASS) an extensive, homogeneous, and – from the X-ray point of view – unbiased data set has now become available; detailed information on the ROSAT all-sky survey as well as the PSPC detector used for the RASS observations can be found in Trümper et al. (1991) and Pfeffermann et al. (1986).

The ROSAT PSPC data were reduced to a source count rate in the (0.1–2.4 keV) band with a procedure which identifies an X-ray source by a maximum-likelihood method, subtracts the background level, corrects telescope vignetting, and compares the source position with the optical position of the sample star (cf. Fleming et al. 1993 for details). Then the count rate is transformed to a flux by multiplying it by a conversion factor of $6 \cdot 10^{-12}$ erg cm^{-2} ct^{-1} which is appropriate for the essentially unabsorbed X-ray spectrum of a nearby active star.

Five stars (i.e, HD's 3795, 9562, 142373, 187013 and 187691) were observed by us within a ROSAT pointing program. HD 187013 and HD 187691 were observed with the HRI because of a nearby companion star, the others with the PSPC. The conversion factor of the HRI observation was taken as five times the PSPC conversion factor, which is typical for nearby late-type stars with essentially no interstellar absorption at X-ray wavelengths.

Our stellar sample consists of single, late-type main sequence stars of spectral type F–K, for which long-term monitoring of their chromospheric activity has been available in a quantitative form (Duncan et al. 1991, Donahue 1993). These data consist of mean S-values averaged over one year, however, for many of these stars published time-series are not available for the time period after 1985. In these cases we have taken S from Figs. 1a–1e in the paper by Baliunas et al. (1995) in order to determime reliable S-values at the time of the ROSAT observations. Cycle periods and phases as they are given in Tab. 1 were taken from this paper, too.

Piters et al. (1995) have observed quasi-simultaneously to RASS a large sample of cool stars to measure their Ca S. Many of these stars are also included in this paper. Hence, we can compare our S estimates with the direct observations. We find, in general, excellent agreement. We find substantial disagreement between our estimates and their S measurements only for three stars, i.e., HD's 95735, 126053 and 165341. These stars have been classified by us into the classes 1,6, and 3 respectively. None of these stars is in the regular class, which we will focus upon later on, and therefore we expect none of our conclusions to change if our extrapolated S-values are replaced by the actual measurements.

In Tab. 1 we present the optical and X-ray information for all of our sample stars. In particular, we provide the HD number, distance, V-magnitude and $B-V$ colours in Cols. 1–4; an asterisk in Col. 1 indicates that pointing data were used to derive the X-ray count rates. Column 5 provides a code indicating the source of the optical data, Col. 6 the rotation period (whenever known), and Col. 7 the source of this information. Column 8 contains the derived X-ray count rate together with its error in Col. 9 (values marked with an asterisk are explained below); in Col. 10 we give the derived X-ray surface flux density. Finally, the CaII H+K data (the S-value at the time of ROSAT observation, cycle period and phase of ROSAT observation) are given in Cols. 11–13. An asterisk in Col. 11 means that the S-value and phase were estimated from Figs. 1a–1e in the paper by Baliunas et al. (1995). In all other cases, the CaII H+K parameters were taken from the time series (annual means) published by Duncan et al. (1991) and Donahue (1993). In Col. 14 we classify the star according to the type of its CaII H+K long-term behaviour; the numbers 1–3 denote the constant, regular and irregular classes, respectively, while the number 4 denotes the ambiguous cases where on the basis of the available data we could not decide whether a star is constant or regular. A similar ambiguity between regular and irregular behaviour is indicated by the number 5, while finally, the number 6 denotes stars which show regular behaviour but of a very uncertain cycle period and amplitude; for example, stars with a pure long-term trend fall in this category. An asterisk in this Col. 14 indicates that our classification and that of Baliunas et al. (1995) are discrepant; these stars will be discussed in more detail below.

Inspection of Tab. 1 shows that quite a large number of stars fall in categories 5 and 6, while only a few stars (5) fall in category 4. While the assignment to a given category is not defined mathematically, it is reassuring to note that only a few discrepancies (7) with Baliunas' et al. (1995) classification arise, which we discuss now case by case. HD 78366 shows a light curve more complicated than a simple sine curve plus a trend. Baliunas et al. (1995) found two periods, and therefore, HD 78366 should be classified as irregular. However, each structure of the light curve observed between 1966 and 1978 has been reobserved twelve years later. This is certainly not to be considered as an irregular behaviour, hence we decided to classify HD 78366 as regular. The situation is even more obscure in cases of HD 155885 and HD 155886. The latter was classified as irregular by Baliunas et al. (1995), the former as possibly regular with a period of $\approx$ 6 years. From the data given by Duncan et al. (1991) we find both stars to be cyclic variable, with the same period of 5–6 years. Since the two stars have identical stellar parameters, we may also expect a similar magnetic behaviour, if the dynamos operate in the regular regime. The finding of identical periods is a strong hint in this direction. Finally, HD 154417 has been classified by us as irregular although Baliunas et al. (1995) found a period of 7.4y. However, a visual inspection of Fig. 1c of their paper shows a strong discrepancy of the form of the curve between the time intervals of 1967–1980 and 1980–1991. Hence, the temporal variations should be classified as irregular rather than regular. The same arguments apply to HD 20630, HD 26913 and HD 165341 which we also consider irregular.

The S-index was transformed into a CaII H+K stellar surface flux density (F_{Ca}) following Rutten (1984). In order to reduce F_{Ca} to its magnetic fraction, ΔF_{Ca}, we used in a first step the values of F_{min} given by Rutten et al. (1991); then, we improved F_{min} as described in Sect. 3. 4. Finally, the S-amplitude was reduced to the amplitude of ΔF_{Ca}.

Our main source of information for the basic stellar data such as a distance and its error, optical magnitude, colour $B-V$, and information on close optical companions were the catalogues by Gliese (1969), Gottlieb (1978) and Hoffleit & Jaschek (1982). Derived parameters such as absolute magnitude, bolometric correction, effective temperature and stellar radius were calculated using the corresponding formulae and relationships given by Lang (1974, 1992). The correct source identification was checked by a comparison of optical and X-ray position. Table 1. includes a few binary stars with known or suspected magnetically active companion stars. Because the companion is then expected to be an X-ray source, too, the observed count rates were reduced to the values given in Tab. 1 with the following ad hoc procedure: in case of HD 114378 by one half because of an identical spectral type and a nearly identical brightness of the companion star; in case of HD 155885/6 it was also equally divided on both components for the same reason; in case of HD 201091/2 we chose partitions of 2/3 and 1/3 respectively because the component A is twice as luminous as B with the same rotation period; in case of HD 165341/2 the count-rate of component A was reduced to 85% which corresponds to its optical contribution, but the component B was then rejected from the statistics because of the large uncertainty of its value; for the same reasons we have rejected HD 131156 B and HD 219834 B.

For 23 stars no X-ray source could be detected at the optical position. In those cases, upper limits were calculated from the X-ray background level.

3. Results

3.1. Coronal Activity of Constant, Regular and Irregular Stars

In Fig. 1, the cumulative F_{X} distributions of constant, regular and irregular stars are shown. In these distribution functions upper limits were included using survival analysis techniques

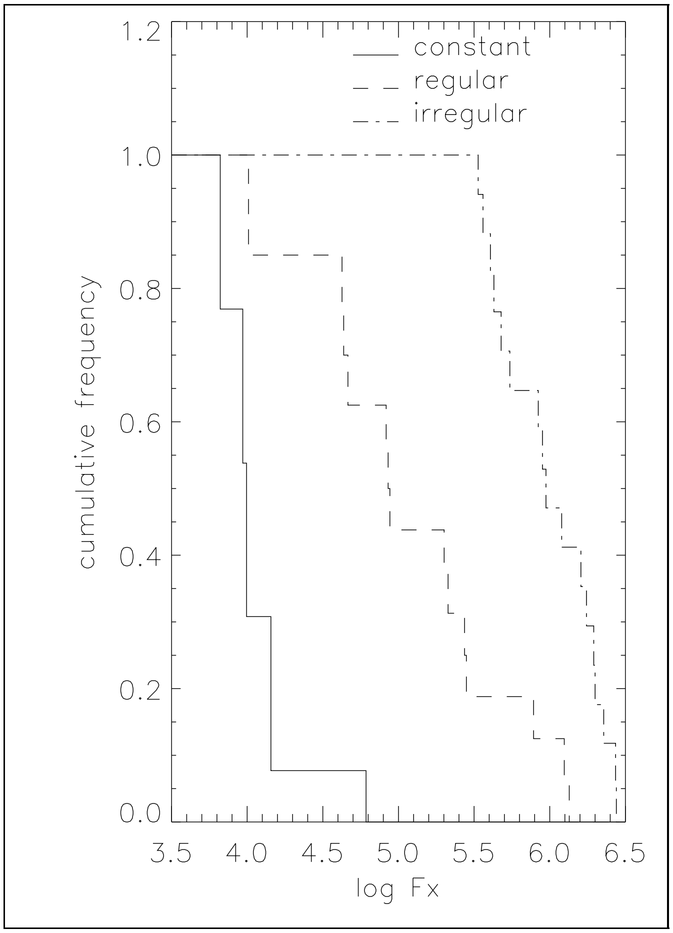

Fig. 1. Cumulative frequency distributions of the coronal X-ray emission of the constant (N=14), the regular (N=16) and the irregular (N=17) stars. N is the number of stars.

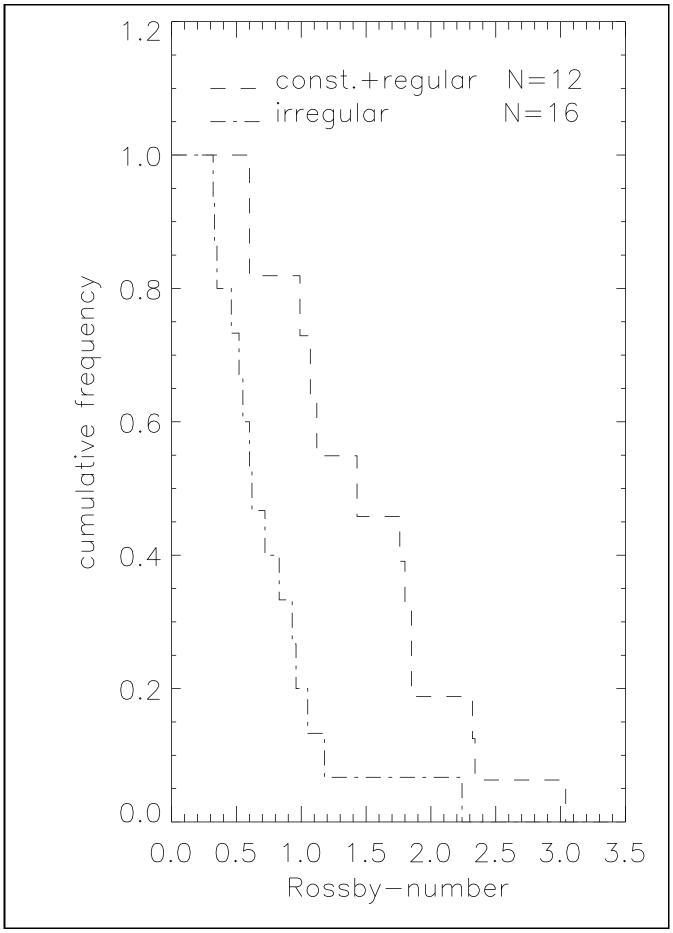

Fig. 2. Cumulative frequency distributions of the Rossby-numbers of the regular and the irregular stars.

as implemented in the ASURV package (La Valley, Isobe & Feigelson 1992; for a description of the methods see Feigelson & Nelson 1985).

It is obvious from Fig. 1 that the three groups differ significantly in their coronal activity as measured through $F_{\rm X}$; specifically we find
$< \log F_{\rm X} >= 4.05 \pm 0.08$ for constant stars,
$< \log F_{\rm X} >= 5.05 \pm 0.16$ for regular stars,
$< \log F_{\rm X} >= 6.00 \pm 0.08$ for irregular stars,
where $F_{\rm X}$ is measured in erg cm^{-2} s^{-1}.)
While interesting this result is not surprising because the same qualitative differences are known from the CaII H+K data (cf., Vaughan 1980) and chromospheric and coronal activity is closely correlated (cf. Sect. 3. 5).

Next we wish to check whether the coronal X-ray emission is quantitatively correlated with characteristics of chromospheric cycles. Naturally the length and amplitude of a cycle are defined only for regular stars, to which the following analysis is restricted. From our fits, we calculated the ratio of the amplitude of the CaII H+K excess flux density to the mean excess flux density and correlated it to log $F_{\rm X}$. We find no significant correlation between both parameters, and also we find no correlation between coronal activity and cycle duration, in agreement with a similar result obtained by Saar & Baliunas (1992) for chromospheric activity.

The grouping of stars into various classes (cf., Tab. 1) was made with a qualitative criterion, with the idea in mind the qualitative differences of non-variability, regular and irregular behaviour are connected with different regimes of the magnetic dynamo, which itself is a function of stellar rotation, and turbulent motions in the stellar interior. It is then of course suggestive to compare the distributions of Rossby numbers (the Rossby number is defined as the ratio of the rotation period to the convective turnover time, τ_c, at the bottom of the convection zone; τ_c was taken from the paper by Stępień 1989) of that of regular stars with the irregular class in Fig. 2; note that the same exercise can unfortunately not be carried out for most of the constant stars which in general do not reveal their rotation periods. It is obvious from Fig. 2 that both groups of stars are clearly separated in Rossby number: the region of slow rotation with $Ro > 1$ is clearly the domain of the regular class including also the three constant stars of known rotation periods, whereas fast rotation with $Ro < 1$ is the domain of an irregular or chaotic long-term behaviour. The enhanced appearence of irregular stars around $Ro \approx 0.5$ appears somewhat surprising; more than half of the irregular star sample lies in the interval between 0.3 and 0.7. It is unclear whether this is incidental or of a deeper significance.

3.2. Maunder Minimum Stars

Where can we expect to find stars in a "Maunder minimum" state? From Fig. 1 one sees that about 1/3 of the constant stars show surface flux densities $F_{\rm X}$ typical for stars in the regular class. We can, therefore, assume that they do belong to the regular class, but with cycles hitherto undetected. However, about 2/3 of the constant stars exhibit a level of coronal X-ray emission below the minimum activity of the regular class. Hence, we expect that possibly existing "Maunder minimum stars" may be found in this region.

What properties should a star have in its "Maunder minimum" phase? During its normal minimum phases, the Sun shows a CaII H+K flux close to the minimum value of non-magnetic origin but is still clearly variable in its S. However, would this variability also be detectable at a distance of, say, 20 parsecs, in order to decide whether the constant stars are really good candidates or they are simply normal active stars with undetectable S amplitudes? (The distance of 20pc is typical for the stars of the Mt. Wilson program.) An inspection of the published time-series of S (Duncan et al. 1991, Donahue 1993, Baliunas et al. 1995) shows that the expected relative error of the solar value (annual mean) is at the 2% level. However, the peak-to-peak amplitude of the solar S variability is $\approx$ 10% (cf. Donahue 1993, Fig. D. 1). Hence, the Sun should be detectable as a variable star at stellar distances, thus implying that the members of the constant class are really good candidates of "Maunder minimum stars".

Consequently, we will classify a cool star to be of the "Maunder minimum" type if the star is non-variable in its CaII H+K emission, and if its level of X-ray activity is below the minimum level of the regular class.

Unfortunately, the sensitivity of the RASS is not sufficient to detect X-ray emission from low activity stars; cf., Schmitt, Fleming & Giampapa (1994). Therefore, we have started a program for pointed observations of constant stars and give the results for five stars. They are indicated in Col. 1 of Tab. 1 with an asterisk.

HD 187013 shows a level of activity which is typical for stars of the regular class. Further, Baliunas et al. (1995) find a long-term trend in the Ca S time series indicating a regular behaviour rather than constancy. With $\log F_{\rm X} = 4.6$, HD 187691 is as active as the Sun during maximum conditions (The mean solar value is $\log F_{\rm X} = 4.4$; Maggio et al. (1987).) Baliunas et al. (1995) find some evidence of a regular behaviour with a period of 5.4y. Hence, we have to conclude that both HD 187013 and HD 187691 are surely not "Maunder mimimum stars". The situation is, however, different in case of HD 142373. With $\log F_{\rm X} = 3.8$, we find this star distinctly below the regular class. Hence, we consider HD 142373 a good candidate for a stellar analog of the Maunder minimum phase of the Sun.

Two other stars, HD 3795 and HD 9562, with $\log F_{\rm X} = 4.0$, show an activity level only marginally below most of inactive stars of the regular group. Therefore, it is not quite clear whether these stars are of the "Maunder minimum" type, or whether they have normal cyclic activity, but happen to be in a regular minimum (solar minimum activity corresponds to that level of $F_{\rm X}$). However, because we do expect the Sun to be detectable as a cyclic star at a distance of 20pc, while both stars show constancy (cf., however, Baliunas et al. (1995) who note both stars to be weakly variable), we also consider them as good candidates for the "Maunder minimum" class.

Of course, one should check all the three candidates of the "Maunder minimum" class with a control sequence of further X-ray observations. As members of this class they are expected to maintain their low level of X-ray emission with time, and should be devoid of any cyclic variability in contrast to the regular stars, where we expect strong and cyclic variability. In this context we have to ask, however, whether magnetic cycles are observable in coronal X-rays or not. An expected long-term variability might remain undetected because of a possibly much stronger variability on shorter time-scales.

3.3. Coronal Cycles

A direct detection of a coronal activity cycle reqires a long series of systematic X-ray observations as available for the Sun. In the stellar context, such data have unfortunately not yet been obtained. Nevertheless, we can attempt to find observational indications for the existence of such coronal cycles in stars other than the Sun from statistical considerations. For this purpose we return to the coronal activity–rotation relation, studied by us using RASS data and published rotational periods derived from CaII H+K or broad-band photometry (cf., Hempelmann et al. 1995). This study resulted in new parameters of the rotation-activity relationship with a scatter around the regression curves too high to ascribe it to errors in the individual measurements. Hempelmann et al. (1995) suggested variability as primary cause of the scatter; the observed scatter of $\sigma = 0.3 - 0.5$ requires variability amplitudes of one order of magnitude, which is incidentally the value found from soft X-ray solar data during the eleven year cycle (Kreplin 1970). Note that at harder and harder energies, the observed variability amplitude becomes progressively larger.

The basic idea is to consider regular stars with known rotation periods. Hence, for such stars we can study the relationship between activity cycle phase at the time of X-ray observations and the deviations from the activity-rotation relation. If coronal cycles exist and if they are in fact the dominant source of X-ray variability of the regular stars, one expects correlation between those parameters. For this purpose we calculated the residuals between the measured and the expected surface flux densities $F_{\rm X}$; the latter from the relations

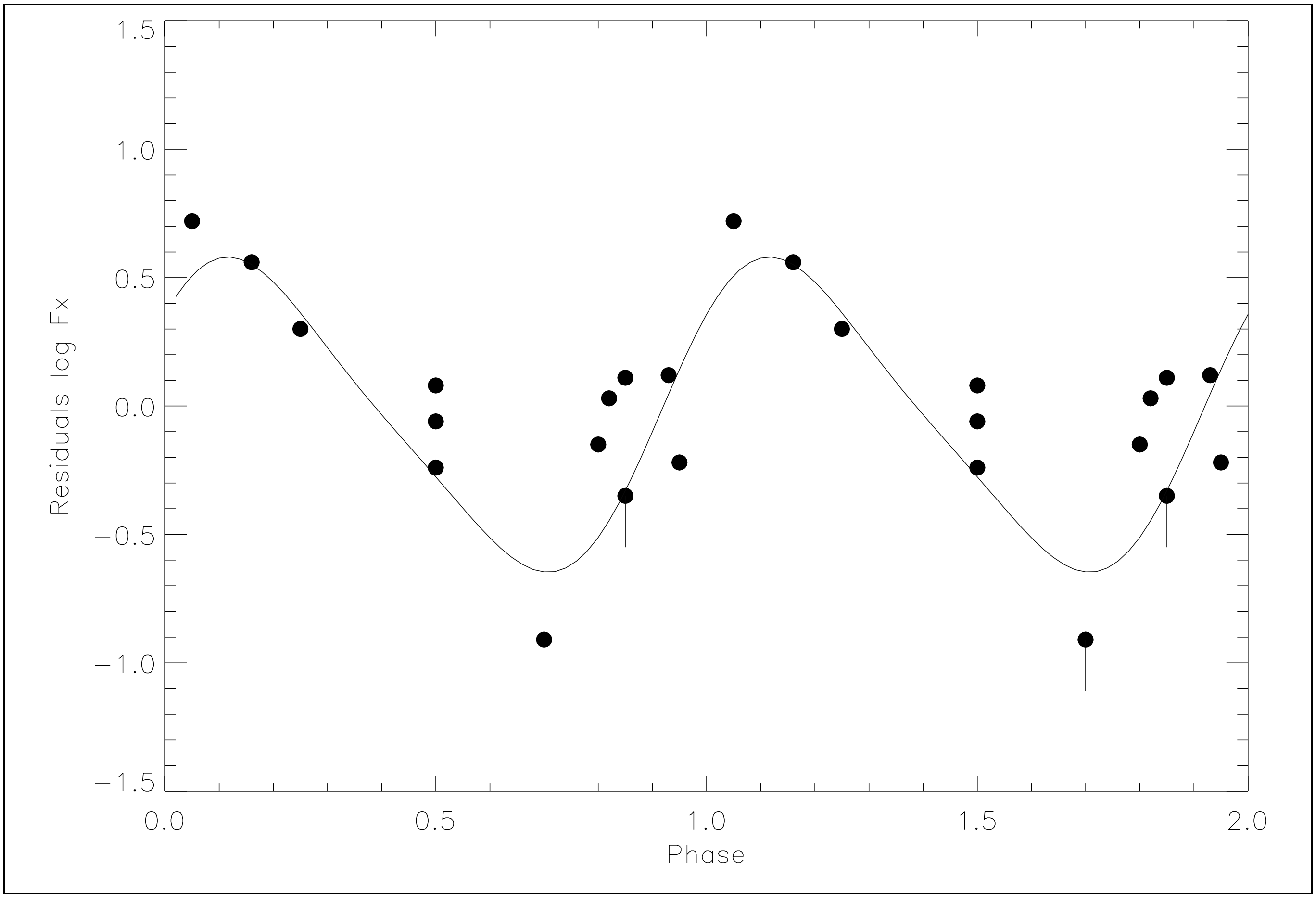

Fig. 3. $F_{\rm X}$-residuals from the activity-rotation relation according to Equ. 2 vs. cycle-phases from the chromospheric long-term variability. Minimum CaII H+K activity is adopted to phase 0.75. For better illustration, the curve is repeated in the interval between 1 and 2.

$$\log F_{\rm X} = 5.80 - 0.97 \log Ro \qquad \text{if} \qquad Ro < 1$$
$$\log F_{\rm X} = 5.64 - 3.00 \log Ro \qquad \text{if} \qquad Ro > 1 \qquad (2)$$

as found by Hempelmann et al. (1995). In Fig. 3, we plot the residuals as a function of phase of the activity cycle as determined from the CaII H+K time-series published by Donahue (1993) and Baliunas et al. (1995). For each star phase zero was chosen in such a way that minimum CaII H+K activity appears at phase 0.75. Indeed, we find the $F_{\rm X}$ residuals distributed in the expected manner: the lowest point is found at phase 0.7 (HD 10476), and the three highest points are in the phase interval 0.0 – 0.25. Further, the form of the curve (indicated by the solid line in Fig. 3) is consistent to the form of the Sun spot cycle, i.e., a more rapid increase from minimum activity to maximum activity followed by a slow decrease to the minimum at the end of the cycle. Are the deviations of the residuals from zero (as plotted in Fig. 3) statistically significant? In order to address this issue we need to test whether the observed distribution is consistent with zero or not. Since it is extremely difficult to assign proper errors to the measured residuals, we decided to tackle this question with an F-test, which is independent on the errors (as long as they are same for all data points). Specifically, we then test the hypothesis that the residuals are independent on cycle phase (i.e., $R(\phi) =$ const vs. the hypothesis that the residuals vary with phase through $R(\phi) = A$ sin(ϕ). The sum of the least squares of the residuals for our two hypotheses is found to 2.04 and 0.84 respectively. Since the number of degrees of freedom is the same for both hypotheses (12), this translates into a probability of about 6 percent, that the improvement in fit is simply due to chance. Or putting it differently, with a confidence of 2σ we can state, that in our sample of 13 stars the X-ray residuals follow the phase behaviour of the observed CaII H+K cycle. Obviously, it would be highly desirable to increase the sample at hand to improve the statistical significance of our findings. At the moment we don't consider our results conclusive but rather suggestive that the stars exhibiting cyclic variations in their Ca activity also exhibit cyclic variations in their soft X-ray output.

3.4. The $F_{\rm X}(F_{\rm Ca})$ and $F_{\rm min}(B-V)$ Relation

In Sect. 3. 1 we found that the three classes of constant, regular and irregular stars exhibit very different levels of coronal activity. This difference in activity suggests qualitative differences

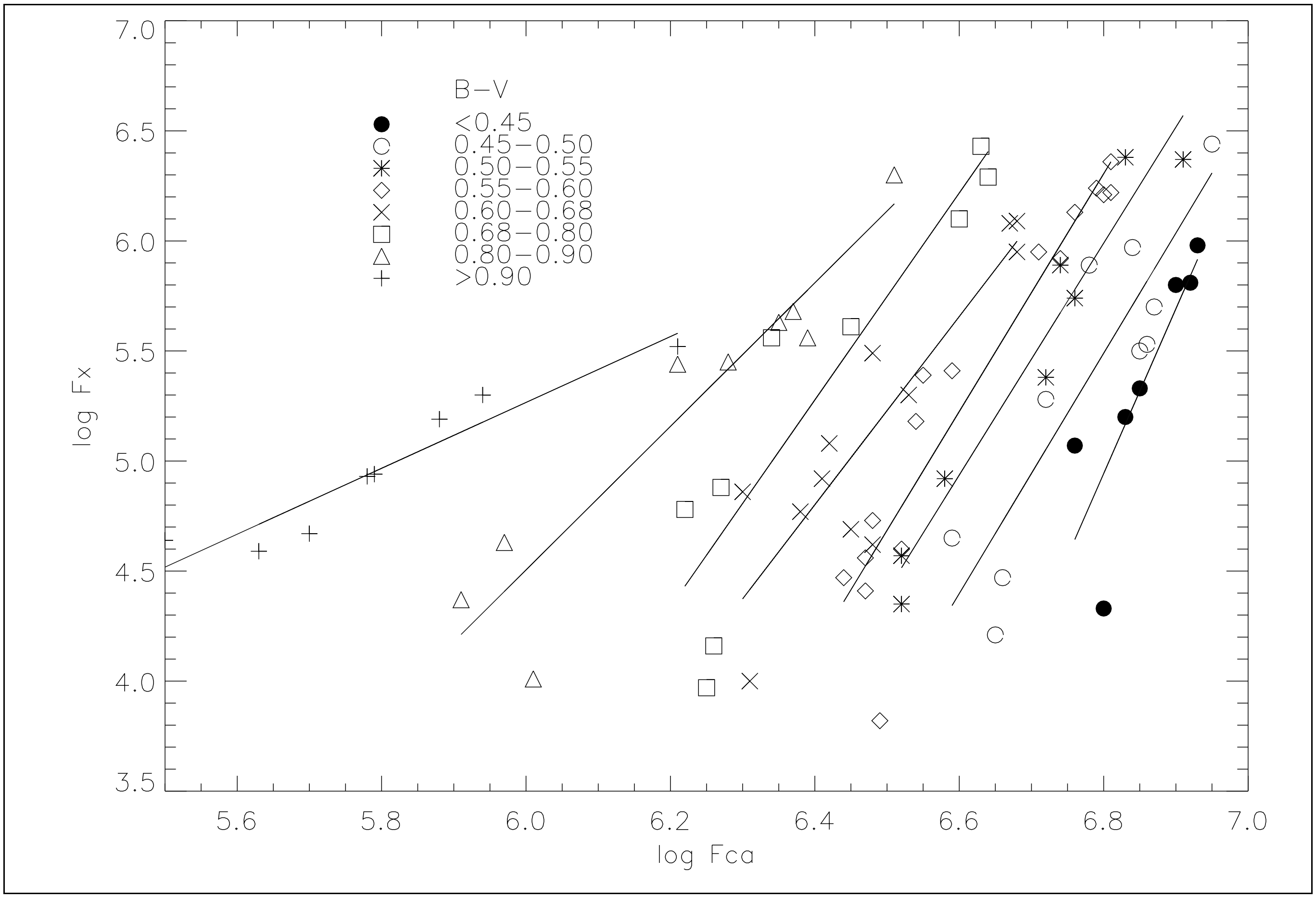

Fig. 4. Colour dependence of the coronal X-ray emission, $F_{\rm X}$, on the CaII H+K flux density, $F_{\rm Ca}$.

in the underlying magnetic fields, and therefore it is not clear a priori, whether the flux–flux relations are the same for all three classes. It might be possible that the discrepant results on the $F_{\rm X}$–$\Delta F_{\rm Ca}$ relation found in earlier papers (cf., Sect. 1) are the consequence of such qualitative differences.

In order to avoid systematic errors, we restrict the analysis to single, MS stars. We will first determine the colour dependence of the $F_{\rm X}$ and $F_{\rm Ca}$ relation, which is the carrier of information on the non-magnetic fractions of $F_{\rm Ca}$. (Schrijver 1983, Rutten 1984, Schrijver 1987, Rutten 1987, Schrijver, Dobson & Radick 1989, Rutten et al. 1991, Strassmeier et al. 1994). We can determine the relation between this non-magnetic fraction, $F_{\rm min}$ and stellar temperature exclusively for MS stars. In previous papers which derived relations between $F_{\rm min}$ and stellar temperature, samples of giants and MS stars were merged (Rutten 1987, Rutten et al. 1991) or giants only were used (Strassmeier et al. 1994). However, already Rutten (1984) found a systematic difference between the basal fluxes of MS stars and giants. This is also apparent in the corresponding figures of other papers (for example, Fig. 1 in Rutten 1987). Thus, from such merged samples $F_{\rm min}$ will be determined mainly for giants rather than for MS stars, and then a systematic error will arise in the flux–flux relations for MS stars. Giants have lower values of $F_{\rm min}$ than MS stars of identical colour. Thus the systematic error results in an enhancement of $\Delta F_{\rm Ca}$ by a small non–magnetic fraction, whose importance increases with decreasing magnetic activity. This effect will thus steepen the slope of the flux–flux relations compared to those derived with the $F_{\rm min}$ values determined solely from MS stars.

In Fig. 4, we plot the mean stellar X-ray surface flux density $F_{\rm X}$ vs. $F_{\rm Ca}$. At first sight, the rather large scatter is striking. However, using different symbols for different $B-V$ intervals in Fig. 4, one sees that stars with the same $B-V$ colours line up in approximately straight lines, with slope and $F_{\rm Ca}$ decreasing towards redder colours. As first shown by Schrijver (1987), the introduction of a colour dependent minimum flux $F_{\rm min}$ allows the rectification of the X-ray/calcium relationship by considering $F_{\rm X}$ vs. $\Delta F_{\rm Ca}$, where $\Delta F_{\rm Ca}$ is the so-called excess flux density.

As a starting point for our $F_{\rm min}(B-V)$ relationship, we construct a basic sample under considering only those stars with $B-V < 0.5$ and use their the $F_{\rm min}$ values as given by Rutten et al. (1991). This is legitimate because for stars with $B-V < 0.5$ no differences between $F_{\rm min}$ of giants and MS stars are found (Rutten 1987, Rutten et al. 1991). The hot end is a convenient starting point also from another point of view, since the differences between different pairs of diagnostics become minimal (cf., Rutten et al. 1991), and observational errors in F_{Ca} and $B-V$ are of minor influence in contrast to the cool end (cf. Stępień 1994).

For this basic sample we first calculated the excess flux density, $\Delta F_{\mathrm{Ca}} = F_{\mathrm{Ca}} - F_{\mathrm{min}}$. Next, we enlarged this sample including cooler stars in the neighbouring $B-V$ interval. An optimum value of F_{min} in this neighbouring interval was determined iteratively in such a way as to minimize the scatter around the F_{X}–ΔF_{Ca} regression curve of the enlarged sample. This procedure was repeated until the cool end was reached, thus resulting in an optimized relation of minimum excess flux densities with colour. A convenient analytical representation of the F_{min} vs. $B-V$ relation was obtained by interpolating the F_{min} values estimated for the colour intervals given in Fig. 4:

$$\log F_{\mathrm{min}} = 8.07 - 3.11(B-V) \qquad 0.40 < (B-V) < 0.51, \tag{3}$$

$$\log F_{\mathrm{min}} = 6.48 \qquad 0.51 \leq (B-V) \leq 0.59, \tag{4}$$

$$\log F_{\mathrm{min}} = 6.95 + 0.36(B-V) - 1.95(B-V)^2 \qquad (B-V) > 0.59 \tag{5}$$

It is instructive to compare our $F_{\mathrm{min}}(B-V)$ relationship to the values given by Rutten et al. (1991). They are consistent with the expectations from Fig. 1 of their paper where giants lie systematically below MS stars. While the two relations agree by definition for the hotter stars, in the $B-V$ interval beween 0.6 and 0.9 our F_{min} values exceed theirs by ≈ 40%.

In our sample stars we do not find systematic differences in the $\log F_{\mathrm{X}}$–$\log F_{\mathrm{Ca}}$ relations of Fig. 4 for stars cooler than, say, 0.9. In this spectral region the flux of non-magnetic origin is small in comparison to the magnetically induced flux. Hence, we expect that for the coolest stars a possibly existing large error of F_{min} results only in a small error of the derived excess flux densities ΔF_{Ca}.

3.5. The F_{X}–ΔF_{Ca} Relation

With the F_{min} values derived in Sect. 3. 4, we can proceed to study the F_{X}–ΔF_{Ca} relation for our whole sample. In Fig. 5 we plot X-ray surface flux F_{X} vs. calcium excess flux ΔF_{Ca} for the detected stars; stars classified as irregular are plotted with filled circles, constant and regular stars with asterisk, and stars with ambiguous classification with open circles. Since stars with different cycle class are characterised by different X-ray surface fluxes (cf., Fig. 1 and Sect. 3. 1), stars of different cycle class also occupy different regions in the the F_{X}–ΔF_{Ca}. Irregular stars tend to be "more active" with larger X-ray surface fluxes and calcium excess densities than "less active" regular or constant stars.

Using all data points regardless of cycle class – in spite of the break visible in Fig. 5 between irregular and regular/constant stars – we find by a regression analysis according to Isobe, Feigelson & Nelson (1986) a power-law exponent (cf., Equ. 1) of $\kappa = 1.32 \pm 0.07$ and $\sigma = 0.27$ as a measure of scattering around the regression curve, i.e., good agreement with the value of $\kappa = 1.5 \pm 0.2$ derived by Schrijver, Dobson & Radick (1992).

In order to estimate the systematic errors introduced by using F_{min}-values derived from stellar samples containing giants, we also determined κ of Equ. 1 under using F_{min} as given by Rutten et al. (1991). We then find $\kappa = 1.82 \pm 0.11$ and $\sigma = 0.27$, i.e., a value significantly larger than κ as derived above. This experiment emphasises, first, how sensitively the relationship between coronal and chromospheric activity depends on the adopted level of F_{min}, and second, that the errors in κ are most likely of systematic nature.

The scatter of the data points in Fig. 5 around the regression curve (with the exception of the upper limits not shown in Fig. 5) corresponds to that of Fig. 2 by Schrijver, Dobson & Radick (1992) who used nearly simultaneously observed *Exosat* X-ray and CaII H+K observations. Note that our calcium data base should be equivalent to that obtained by quasi-simultaneous observations of F_{X} and Ca S as it is described in Sect. 2. Scatter in this order can be explained by a combination of variability on shorter time-scales than the activity cycle and, observational errors mainly in F_{Ca}.

If our sample includes either non-magnetic stars or stars of such a low level of activity that the non-magnetic fractions in F_{Ca} greatly exceed the magnetic ones, observational errors can actually place such a star far to the left side of the regression curve, or even to negative excess flux values. This can be seen from the following example: Assuming an observational error of 10% for a star with a CaII H+K S-index of 0.17, we obtain a flux (in cgs units) of $\log F_{\mathrm{Ca}} = 6.40 \pm 0.05$. Assuming further an uncertainty of $\log F_{\mathrm{min}} = 0.02$, we find for a star with $B-V = 0.66$ $\log F_{\mathrm{min}} = 6.33 \pm 0.02$. If S of this star is measured 1.5σ below its true value, it would be found below F_{min} and, hence, at negative ΔF_{Ca}! The Sun observed as a star (cf., Keil & Worden 1984) is characterised by $S \approx 0.17$ during the minimum phases of the solar cycle (cf., Fig. D. 1 in Donahue 1993). Hence, a few solar-like stars of minimum activity can be found below F_{min} as the consequence of observational errors.

In our sample, we find three stars with $\log F_{\mathrm{Ca}}$ values of 0.01 dex below $\log F_{\mathrm{min}}$: HD's 13421, 29645 and 161239, three more stars have exactly the values of F_{min}: HD's 9562, 12235 and143761. These six stars were rejected from the F_{X}–ΔF_{Ca} statistics.

So far we have considered all our sample stars as a whole. Closer inspection of Fig. 5, however, shows indication of a break at surface flux values of $\log F_{\mathrm{X}} \approx 5.7$. In Sect. 3. 1, we have shown that the range of $\log F_{\mathrm{X}} > 5.5$ is the domain of the irregular class, whereas most regular stars have $\log F_{\mathrm{X}} < 5.5$ (cf. Fig. 1). Both classes of stars are plotted in Fig. 5 with different symbols and clearly suggest a different relationship between chromospheric and coronal activity indicators for constant and regular stars on the one hand and irregular stars on the other hand. A similar break is also suggested from Fig. 9 in the paper by Stępień (1994) and also from Fig. 5 in the paper by Piters et

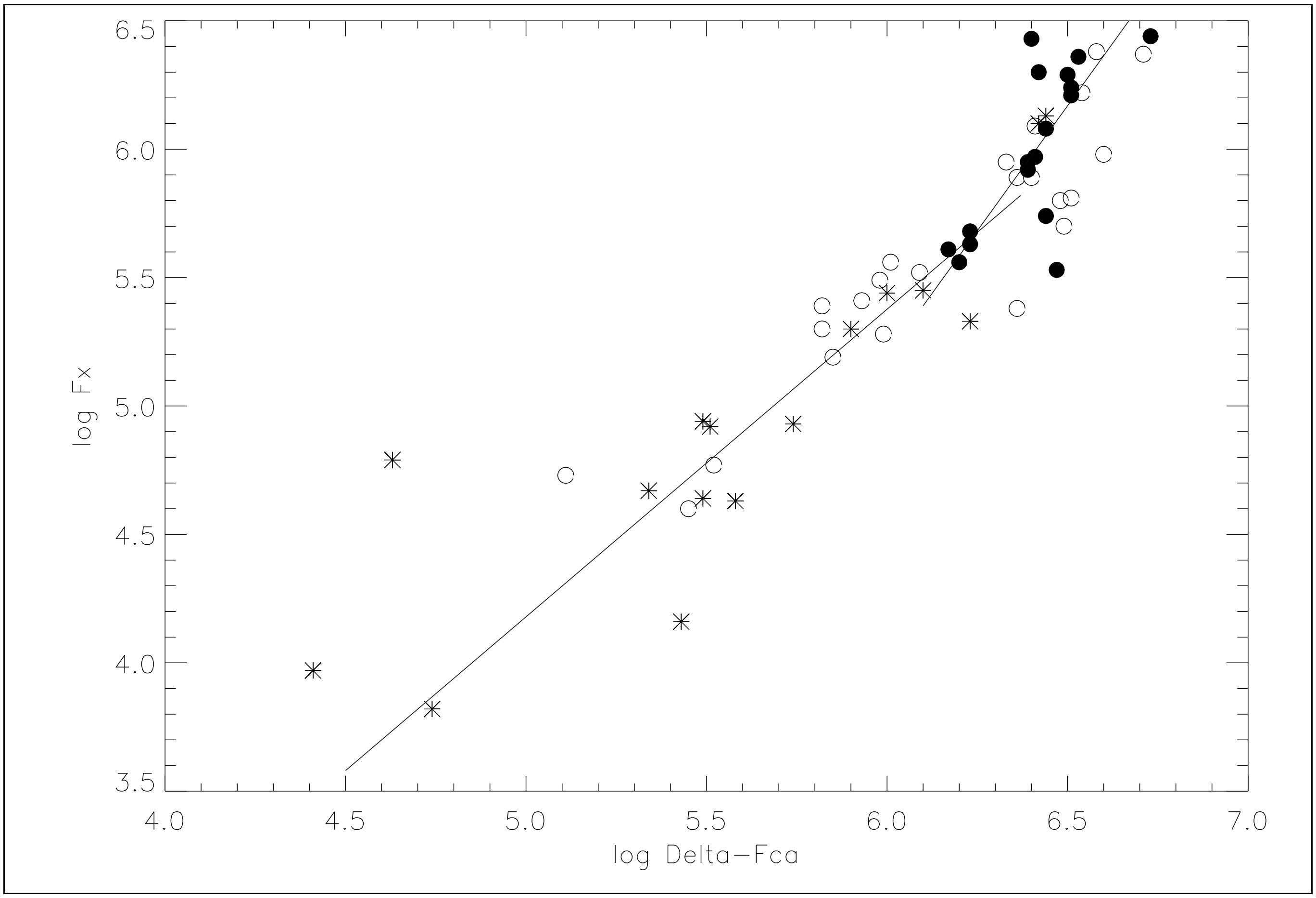

Fig. 5. The coronal X-ray emission in relation to the CaII H+K excess flux density. Only X-ray detections are depicted. The break around $\log F_{\rm X} \approx 5.7$ separates the classes of constant and regular stars (asterisks) from the irregular stars (filled circles). Ambiguously classified stars are denoted with open circles.

al. (1995), but it is not apparent in Fig. 2 by Schrijver, Dobson & Radick (1992).

The different behaviour between constant and regular stars as opposed to irregular stars is verified by a formal regression analysis. Carrying out the same analysis as above for each of these subgroups, we find for the constant plus regular stars an exponent $\kappa = 0.99 \pm 0.13$, i.e. linear relationship, while for the irregular stars we find $\kappa = 1.7 \pm 0.4$, implying a quadratic dependence as found by Piters et al. (1995). The regression curves for the two subsamples are shown separately in Fig. 5. The curves are not compatible with each other, however, it is desirable to improve the statistics for at least the irregular stars, which will likely include many of the stars which have not yet been classified unambiguously.

4. Conclusions

We have studied quantitative and qualitative differences in the coronal activity between three classes of single cool dwarf stars. The stars were classified according to their long-term variability pattern of their CaII H+K activity, i.e., into constant, regular, and irregular variable stars reflecting three basic types of a dynamic process. These three classes, different in terms of their variability pattern, also show strong differences in their mean X-ray surface fluxes, which increase from $< \log F_{\rm X} >= 4.05 \pm 0.08$ for constant stars, $< \log F_{\rm X} >= 5.05 \pm 0.16$ for regular stars, to $< \log F_{\rm X} >= 6.00 \pm 0.08$ for irregular stars, i.e., one order of magnitude for each class. Obviously, the irregular stars are the most active ones also from the point of view of X-ray emission. Since we also show that constant/regular and irregular stars are significantly different with respect to their Rossby number distribution, the above finding is consistent with the idea that in irregular stars the dynamo operates in a non-linear regime resulting in – possibly – chaotic behaviour.

However, the observation of the Maunder minimum on the Sun is in contradiction to this simple idea since it implies that also the cyclic and the constant stars operate in a non-linear regime despite the fact that they show magnetically induced activity of only minimal strength. It is then clearly of some relevance to find stars residing in the stellar analog of a "Maunder minimum" state. We argue that such "Maunder minimum stars" are to be found among the constant stars, and in particular, we have identified HD 142373, and possibly HD 3795 and HD 9562, as promising candidates for such objects. We cannot, however, at the moment claim to have definitively found cool stars in a "Maunder minimum" state, and therefore the question which stellar parameters determine the difference between "Maunder minimum stars" and normal cyclic and regular stars cannot yet be answered. It is clear, however, that the presently available samples must be biased against finding such stars since both the rotation period and long-term activity behaviour of a probably rather weak variable star must be measured.

As far as the detectability of stellar cycles in X-rays is concerned, we find rather suggestive evidence that the regular stars show variations in their X-ray emission correlated with their chromospheric (cyclic) emission. We therefore argue that stars exhibiting cyclic variations in their chromospheric Ca emission also exhibit cyclic variations in their X-ray output similar to what is known from the Sun.

Our study of the relationship between chromospheric and coronal energy losses yields – in agreement with previous studies – a good correlation between the two, once the chromospheric emission is "corrected for" by subtracting a basal flux. We have shown explicitly that the resulting power law slope between X-ray and CaII H+K surface fluxes depends very sensitively on the way this basal flux contribution is determined. Regardless of the way this basal flux is calculated, however, we find that regular/constant stars on one hand and irregular stars on the other hand obey different relationships. We therefore suspect that the large scatter of power law slopes reported on this correlation in the literature is due to a mixture of two effects, i.e., first, an inappropriate correction for basal fluxes by mixing giants and main sequence stars in the samples studied, and second, a mixing of constant/regular and irregular stars which in turn have different intrinsic slopes. Our study indicates that the constant and regular stars can be characterised by a linear relationship while the irregular stars seem to obey a quadratic one; only when the two samples are mixed together does one find intermediate relationships.

It is suggestive to interpret our findings in the context of a switch from a nonlinear to a linear dynamo regime. While regular stars appear to be similar to the Sun in many aspects as one naively expects, irregular stars appear to be fundamentally different in terms of their relationship between coronal activity and Rossby number (Hempelmann et al. 1995) and their relationship between coronal and chromospheric activity. From a theoretical point of view, such a switch has been proposed by Knobloch, Rosner & Weiss (1981), who suggest that the pattern of convection changes to convection in rolls such that the convective velocities parallel to the rotation axis become small and hence the helicity is reduced when the rotation rate of a given star is increased. As a consequence, the generated magnetic field changes in a non-linear fashion, however, in this scenario it is unclear why chromospheric and coronal activity react differently to these underlying magnetic field changes. At any rate, our large sample of stars with measured coronal and chromospheric activity parameters and established cycle properties provides clear evidence for the existence of different states of dynamo action and possibly transitions between them.

Acknowledgments: The ROSAT project has been supported by the Bundesministerium für Forschung und Technologie (BMFT) and the Max-Planck-Gesellschaft (MPG). We acknowledge the support of our colleagues from the MPE ROSAT group.

References

Ayres T.R., Marstad N.C., Linsky J.L., 1981, ApJ 247, 545

Baliunas S.L., Horne J.H., Porter A., Duncan D.K., Frazer J., Lanning H., Misch A., Mueller J., Noyes R.W., Soyumer D., Vaughan A.H., Woodard L., 1985, ApJ 294, 310

Baliunas S.L., *et al.*, 1995, ApJ 438, 269

Donahue R.A., 1993, Thesis PhD, New Mexico State University

Duncan D.K., Vaughan A.H., Wilson O.C., Preston G.W., Frazer J., Lanning H., Misch A., Mueller J., Soyumer D., Woodard L., Baliunas S.L., Noyes R.W., Hartmann L.W., Porter A., Zwaan C., Middelkoop F., Rutten R.G.M., 1991, ApJS 76, 383

Eddy, J.A., 1976, Science 192, 1189

Feigelson E.D., Nelson P.I., 1985, ApJ 293, 192

Fleming T.A., Giampapa M.S., Schmitt J.H.M.M., Bookbinder J.A., 1993, ApJ 410, 387

Gliese W., 1969, Veröffentlichungen des Astron. Recheninst. Nr. 22

Gottlieb D.M., 1978, ApJS 38, 287

Hempelmann A., Rüdiger G., Hildebrandt G., 1993, in "Physics of Solar and Stellar Coronae", eds. J.F. Linsky and S. Serio, p.381

Hempelmann A., Schmitt J.H.M.M., Schultz M., Rüdiger G., Stępień K., 1995, A&A 294, 515

Hoffleit D., Jaschek C., 1982, The Bright Star Catalogue, IVth ed., Yale University Observatory, New Haven

Isobe T., Feigelson E.D., Nelson P.I., 1986, ApJ 306, 490

Keil S.L., Worden S.P., 1984, ApJ 276, 766

Knobloch E., Rosner R., Weiss N.D., 1981, MNRAS 197, p.45

Kreplin R.W., 1970, Annales de Geophysique 26, p.567

Lang K.R., 1974, 'Astrophysical Formulae', Springer-Verlag Berlin etc.

Lang K.R., 1992, 'Astrophysical Data: Planets and Stars', Springer-Verlag New York etc.

La Valley M., Isobe T., Feigelson E.D., 1992, Bull. Amer. Astron. Soc. 1992

Linsky, J.L., 1985, Solar Phys., 100, 333.

Maggio A., Sciortino S., Vaiana G.S., Major P., Bookbinder J., Golub L., Harnden F.R., Rosner R., 1987, ApJ 315, 687

Mullan D.J., Chang Q.Q., 1994, ApJ 420, 392

Noyes R.W., Hartmann L.W., Baliunas S.C., Duncan D.K., Vaughan A.H., 1984, ApJ 279, 763

Pfeffermann, E., *et al.*, 1986, SPIE 733, 519.

Piters A.J.M., Schrijver C.J., Schmitt J.H.M.M., Baliunas S.L., van Paradijs J.,Zwaan C., 1995, A&A, in preparation

Rutten R.G.M., 1984, A&A 130, 353

Rutten R.G.M., 1987, A&A 177, 131

Rutten R.G.M., Schrijver C.J., Lemmens A.F.P., Zwaan C., 1991, A&A 252, 203

Saar S.H., Baliunas S.L., 1992, in: Proc. of the 4th Solar Cycle Workshop, ed. K. Harvey, PASP Conf. Ser. 27, 150

Schmitt, J.H.M.M., Fleming, T.A., Giampapa, M.S., 1995, ApJ submitted.

Schrijver C.J., 1983, A&A 127, 289
Schrijver C.J., 1987, A&A 172, 111
Schrijver C.J., Dobson A.K., Radick R.R., 1989, ApJ 341, 1035
Schrijver C.J., Dobson A.K., Radick R.R., 1992, A&A 258, 432
Stępień K., 1989, A&A 210, 273
Stępień K., 1994, A&A 292, 191
Stępień K., Ulmschneider P., 1989, A&A 216, 139
Stimets R.W., Giles R.H., 1980, ApJ 242, L37
Strassmeier K.G., Handler G., Paunzen E. Rauth M., 1994, A&A 281, 855
Trümper, J., *et al.*, 1991, Nature, 349, 579
Vaughan A.H., 1980, PASP 392, 396
Vaughan A.H., Baliunas S.L., Middelkoop F., Hartmann L.W., Mihalas M., Noyes R.W., Preston G.W., 1981, ApJ 250, 276
Wagner W.J., 1988, Adv. Space Res. 8, 67
Wilson O.C., 1978, ApJ 226, 379

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.