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X-RAY ACTIVITY AS STATISTICAL AGE INDICATOR: THE DISK G-K GIANTS

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ABSTRACT

We have studied, for a sample of late-type disk giant stars, the dependence of coronal emission on age as defined by metallicity and kinematics indicators. We find that the mean level of X-ray emission for stars with strong metallic lines ($\sim 10^{29}$ ergs s^{-1}) and/or small peculiar velocities is larger by about one order of magnitude than the mean level of emission for stars with weak lines ($\sim 10^{28}$ ergs s^{-1}) and/or high peculiar velocities. Hence, we suggest that the X-ray activity can be used as a statistical age indicator for late-type giants, as well as the classical metallicity or kinematics indicators.

We have investigated if metallicity itself can explain the observed difference in X-ray emission, and we find that the spread in metallicity typical of the Galactic disk accounts for less than 50% of this difference. To explain the observations we argue that other effects should be invoked, such as changes in the efficiency of the stellar magnetic dynamo or the influence of metallicity itself on the coronal heating processes.

Subject headings: stars: coronae — stars: evolution — stars: late-type — X-rays: stars

1. INTRODUCTION

One of the most intriguing results of the *Einstein Observatory* (Giacconi et al. 1979) stellar observations is the large spread in X-ray luminosity among stars with similar spectral types and luminosity classes (Vaiana et al. 1981; Helfand & Caillault 1982). For the late-type dwarfs, clear observational evidences have been presented (Stern et al. 1981; Vaiana 1983; Micela et al. 1985, 1988, 1990; Bookbinder 1985; Maggio et al. 1987; Feigelson & Kriss 1989) that the X-ray luminosity, for a star of a given mass, statistically decreases with advancing stellar age. At the same time, the stellar rotation rate has been proven to be a relevant parameter in determining the X-ray emission level of late-type main-sequence stars (Pallavicini et al. 1981; Walter 1981, 1982; Maggio et al. 1987). Another parameter linked to the internal stellar structure, namely the Rossby number, has been often invoked to explain the observed spread in the UV and X-ray emission from the stellar outer atmospheres (Noyes et al. 1984; Micela, Sciortino, & Serio 1984; Vilhu 1984; Mangenay & Praderie 1984; Simon, Herbig, & Boesgaard 1985; Schmitt et al. 1985; Maggio et al. 1987). The detailed dependence of X-ray luminosity on rotation and the Rossby number, as well as age, is still the subject of debate. It is not clear also to what extent age can be considered a proxy for rotation and/or the Rossby number.

The heating of the atmospheric layers above the temperature minimum in solar-like stars is nonthermal in nature, and the emission from these layers is considered as an indicator of the level of surface magnetic activity. The magnetic field is likely sustained by a dynamo mechanism, whose action is theoretically expected to depend on the interaction between the differential rotation and the subphotospheric convection of the star. Since both the rotation rate and the stellar internal structure change during stellar aging, the chromospheric and coronal emission are also expected to vary on evolutionary time scales. In particular, the decay of the observed X-ray emission with age is usually attributed to the magnetically driven spin-down of the star. A similar decay has been shown for the emission originating in the stellar chromospheres and transition regions (Wilson 1963; Skumanich 1972, Herbig 1985; Simon et al. 1985).

Up to date, only a few studies have been carried out on the evolution of the stellar outer atmospheres along the giant branch in the H-R diagram. Stars crossing the Hertzsprung gap for the first time seem to show a trend of increasing surface flux in the C IV (1549 Å) transition region line emission, followed by a rapid drop upon reaching the base of the ascending red giant branch (Simon 1984). A similar behavior has been noted by Maggio et al. (1990), who have recently presented the results of a magnitude-limited X-ray survey of late-type giant and supergiant stars observed with the *Einstein Observatory*. However, no detailed analysis has yet been performed on the age dependence of the transition region and coronal emission for stars evolving beyond the main sequence. Most recently, Dupree, Hartmann, & Smith (1990) have compared the level of the Mg II (2800 Å) chromospheric emission for three different groups of Population I and II stars, namely the Hyades giants, the M67 giants, and a small sample of metal deficient field giants. After an initial decay of about one order of magnitude from the emission level of the Hyades stars, these authors show evidence of what appears to be a resurgence of the Mg II surface line flux in the halo giants with respect to the old-disk M67 members.

In the present paper we study the dependence of X-ray emission on age for a subsample of the G and K disk giants in the survey of Maggio et al. (1990), limited to a restricted range of $B-V$ colors ($\sim$0.8–1.1). The selected sample contains stars with similar effective temperature, but different masses and ages. We note that, because of the differences in evolutionary time scales, any separation into "young" and "old" giants will also imply a separation into high- and low-mass stars.

Our first goal is to investigate whether X-ray activity can be used as a statistical age indicator for giant stars, at least as good as metallicity. A second goal is to understand if this classical age-dependent parameter, namely the metallicity, can be invoked to explain the wide range of X-ray luminosities observed among stars which occupy the same region in the

[1] It is with sadness that we announce the death on 1991 August 25 of Giuseppe S. Vaiana, who contributed so much to our knowledge of solar atmospheres and coronae and X-ray sources.—ED.

H-R diagram. This concern derives from the notion that much of the broad-band soft X-ray emission results from line emission (bound-bound transitions) from highly ionized elements. Hence, younger stars with higher metallicity may show enhanced X-ray emission with respect to older metal-poor stars, under the same thermodynamic conditions of the coronal plasma. Such a direct dependence of X-ray luminosity on metallicity could be an additional cause of the changes in the X-ray emission level, together with the aging of the magnetic dynamo which is presumed to power the stellar coronae.

Because of the paucity of giant stars in the open clusters observed by the *Einstein Observatory*, we have used the statistical methods of age determination linked to the metallicity and the kinematical properties of the selected stars. The relationship between stellar age, metallicity and kinematics dates back to the pioneering work of Roman (1952) and we will take advantage of these age indicators to carry on our statistical investigation.

This paper is organized as follows: in § 2 we describe the basic properties of our sample, data analysis and results are presented in § 3, § 4 is devoted to the discussion, and § 5 is devoted to the summary and conclusions.

2. THE SAMPLE

The selected sample consists of those stars in common between the sample studied by Roman (1952) to investigate the statistical relationship between kinematic and spectroscopic properties of G and K disk stars, and the sample observed with the *Einstein* Imaging Proportional Counter (IPC, Gorenstein, Harnden, & Fabricant 1981).

In her paper, N. Roman studied 641 stars of spectral types in the range F5–K5 brighter than visual magnitude $m_v = 5.5$; about 60% of them are giants of spectral type G and K. She reported measurements of the peculiar velocity for most of the sample, while assigning about half of the stars to one of four metallicity groups, according to the intensity of their spectral lines: (a) strong-line stars; (b) weak-line stars; (c) "4150" stars, which are weak-line stars with strong absorption in the CN band near $\lambda \sim 4150$ Å; and (d) "weak CN" stars, having CN lines weak with respect to the nearby continuum. In the following we will maintain the subdivision into strong-lined stars (SL), which are those in the group (a) above, and weak-lined stars (WL) including groups (b), (c) and (d).

The X-ray data for the stars in our sample are from the X-ray survey of Maggio et al. (1990). This survey includes all the giant and supergiant stars of the Yale Bright Star Catalog (Hoffleit & Jaschek 1982, hereafter BSC) and its Supplement (Hoffleit, Saladyga, & Wlasuk 1984), with spectral types later than F0, observed by the IPC. Since the BSC + Addendum is complete to a magnitude fainter than the limiting magnitude of the Roman sample, the X-ray survey sample contains all the giant stars in the Roman sample observed with the IPC.

Maggio et al. (1990) have evaluated the X-ray fluxes in the 0.16–4 keV band assuming a thermal spectrum from a thin plasma with solar abundances at log $(T) \approx 6.5$ K, and negligible absorption. The energy band is slightly wider than the nominal IPC BROAD band, but the additional radiative contribution in the range 3.5–4 keV never exceeds 1% of the total in the range of temperature of interest. An uncertainty of $\sim$20% in the conversion factor from count rates to fluxes is introduced by a variation of the assumed coronal temperature in the range 3×10^6–3×10^7 K. To evaluate X-ray luminosities the trigonometric parallaxes quoted in the BSC were used. For the three stars in our sample for which the BSC does not report parallax measurements and Maggio et al. (1990) do not report L_X values, we have used the distances quoted in the Sky Map 2000 Catalog (Hirshfeld & Sinnott 1982). Errors in the X-ray luminosities are dominated by the uncertainty in the distance (up to factor of 2 for the most distant stars).

The final selected sample results in a total of 66 stars of spectral type G5–K5 for which both X-ray luminosities and peculiar velocities are known. The classification in metallicity classes, according to the scheme of Roman (1952) is available for 45 of these stars. The relevant properties of the sample stars are summarized in Table 1.

3. ANALYSIS AND RESULTS

In Figure 1 we plot X-ray luminosities versus peculiar velocities for the stars in our sample; square symbols indicate stars classified as RS CVn systems by Strassmeier et al. (1988). With the exclusion of the RS CVn systems (four objects), stars with high X-ray luminosities preferentially have small peculiar velocities with a relatively low dispersion, while stars with low X-ray luminosities show a larger mean peculiar velocity and a greater dispersion. The RS CV–like systems show an anomalous behavior with respect to the other giants, having large velocities and high X-ray emission levels. The X-ray emission of such systems may result enhanced with respect to that of normal giant stars, due to fast surface rotational velocities induced by tidal coupling with the orbital motion (Walter & Bowyer 1981; Pallavicini et al. 1981; Majer et al. 1985), or because of the physical interaction between the surface magnetic structures of the system components (Walter, Gibson, & Basri 1983). For this reason we have excluded such systems from the following analysis.

In Figure 2 we report the velocity distributions (normalized to the number of stars in each sample) for stars with log $(L_X) \geq$

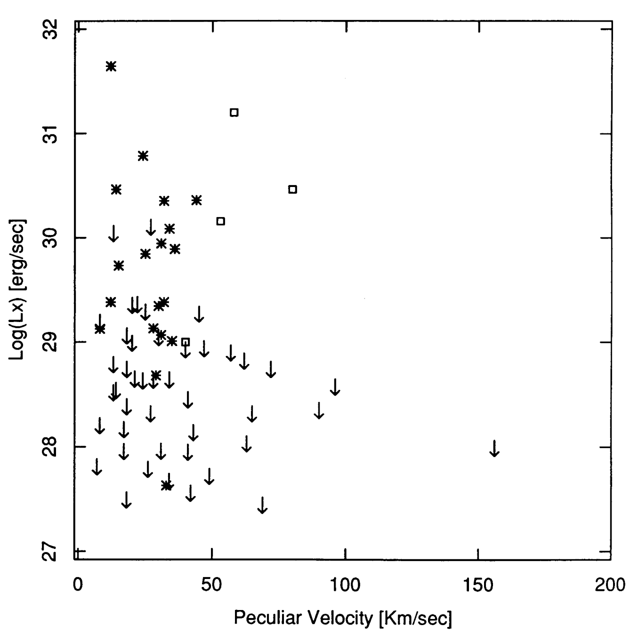

FIG. 1.—Scatter plot of X-ray luminosities vs. peculiar velocities for the stars in our sample. Arrows indicate upper limits in L_X; square symbols indicate stars classified as RS CVn systems. The high X-ray luminosity stars tend to have lower peculiar velocities than the low X-ray luminosity stars.

TABLE 1

Properties of Selected Stars

HR	HD	m_v	$B-V$	M_v	Distance (pc)	L_x (erg s^{-1})	v_{pec} (km s^{-1})	Code[a]
3	28	4.61	1.04	0.34	71.4	<29.00	40	WR
163	3546	4.37	0.87	2.21	27.0	<28.06	156	W
188	4128	2.04	1.02	0.97	16.4	29.73	15	S
271	5516	4.42	0.94	−0.81	111.1	30.78	24	S
469	10072	4.98	0.89	−0.25	111.1	30.35	32	W
617	12929	2.00	1.15	0.45	20.4	<27.57	18	...
1256	25604	4.36	1.07	−0.07	76.9	<28.86	13	S
1346	27371	3.65	0.99	0.89	35.7	29.35	30	S
1373	27697	3.76	0.98	0.37	47.6	29.07	31	S
1396	28100	4.69	0.98	0.42	71.4	<29.43	20	S
1407	28292	4.97	1.13	−0.03	100.0	<29.36	25	...
1411	28307	3.84	0.95	1.74	26.3	29.38	32	S
1457	29139	0.85	1.54	−0.49	18.5	<28.02	41	...
1467	29317	5.05	1.07	−0.36	120.0	30.36	44	S
2574	50778	4.07	1.43	0.78	45.5	<28.42	90	...
2973	62044	4.28	1.12	0.56	55.6	31.20	58	SR
2990	62509	1.14	1.00	1.01	10.6	27.63	33	W
3403	73108	4.60	1.17	0.62	62.5	<29.12	30	...
3431	73840	4.98	1.42	1.79	43.5	<28.52	41	...
3547	76294	3.11	1.00	0.83	28.6	<28.24	17	W
3706	80499	4.79	0.93	1.60	43.5	<28.46	18	S
3748	81797	1.98	1.44	−1.31	45.5	<28.70	24	...
3771	82210	4.56	0.77	2.68	23.8	29.95	31	S
3851	83805	5.62	0.95	1.90	55.6	<28.71	34	W
3903	85444	4.12	0.92	0.73	47.6	29.89	36	S
3994	88284	3.61	1.01	0.77	37.0	<28.39	27	W
4057	89484	2.61	1.15	−0.68	45.5	<28.39	65	W
4246	94247	5.10	1.36	1.12	62.5	<29.06	20	...
4301	95689	1.79	1.07	−0.31	26.3	<28.28	8	S
4521	102328	5.27	1.27	0.62	85.0	29.13	28	...
4668	106760	5.00	1.14	1.71	45.5	<29.01	47	S
4932	113226	2.83	0.94	1.00	23.3	28.68	29	S
5340	124897	−0.04	1.23	−0.11	10.3	<27.51	69	...
5563	131873	2.08	1.47	0.04	25.6	<28.03	31	...
5601	133165	4.40	1.04	1.39	40.0	<28.59	13	S
5681	135722	3.47	0.95	0.86	33.3	<28.21	43	W
5714	136726	5.02	1.37	0.90	66.7	<28.81	18	...
5763	138481	5.02	1.59	1.53	50.0	<28.72	21	...
5854	140573	2.65	1.17	1.27	18.9	<27.74	34	...
5889	141714	4.63	0.80	0.36	71.4	30.46	14	W
5947	143107	4.15	1.23	1.05	41.7	<28.71	28	...
6009	145000	5.00	0.95	−3.45	500.0	31.64	12	S
6132	148387	2.74	0.91	1.28	19.6	<27.88	7	S
6148	148856	2.77	0.94	−0.33	41.7	29.38	12	S
6299	153210	3.20	1.15	0.66	32.3	<28.10	63	...
6566	159966	5.05	1.08	1.56	50.0	<28.81	72	W
6705	164058	2.23	1.52	−0.78	40.0	<28.61	14	...
6869	168723	3.26	0.94	2.08	17.2	<27.63	42	W
6935	170474	5.39	0.96	0.96	76.9	<29.34	45	W
6945	170693	4.82	1.19	1.43	47.6	<28.89	62	...
6970	171391	5.14	0.92	0.54	83.3	30.09	34	S
6973	171443	3.85	1.33	−0.13	62.5	<28.64	96	...
7117	174980	5.27	0.92	1.78	50.0	<28.97	57	W
7125	175306	4.66	1.19	−1.45	166.7	30.16	53	WR
7310	180711	3.07	1.00	0.60	31.3	<28.03	17	W
7333	181391	5.01	0.92	2.40	33.3	29.01	35	W
7478	185734	4.69	0.97	−1.08	142.9	<30.18	27	S
7615	188947	3.89	1.02	−0.23	66.7	<29.13	18	W
7884	196574	4.32	0.95	−0.68	100.0	29.13	8	S
7942	197912	4.22	1.05	0.10	66.7	<29.43	22	W
7949	197989	2.46	1.03	1.24	17.5	<27.79	49	S
7956	198134	4.92	1.32	−1.59	200.0	<30.11	13	...
8167	203387	4.28	0.90	1.87	30.3	29.85	25	S
8684	216131	3.48	0.93	1.49	25.0	<27.86	26	S
8961	222107	3.82	1.01	2.31	20.0	30.46	80	WR
8987	222643	5.28	1.37	1.16	66.7	<29.26	8	...

[a] Codes: (W) weak-line stars, (S) strong-line stars, and (R) RS CVn.

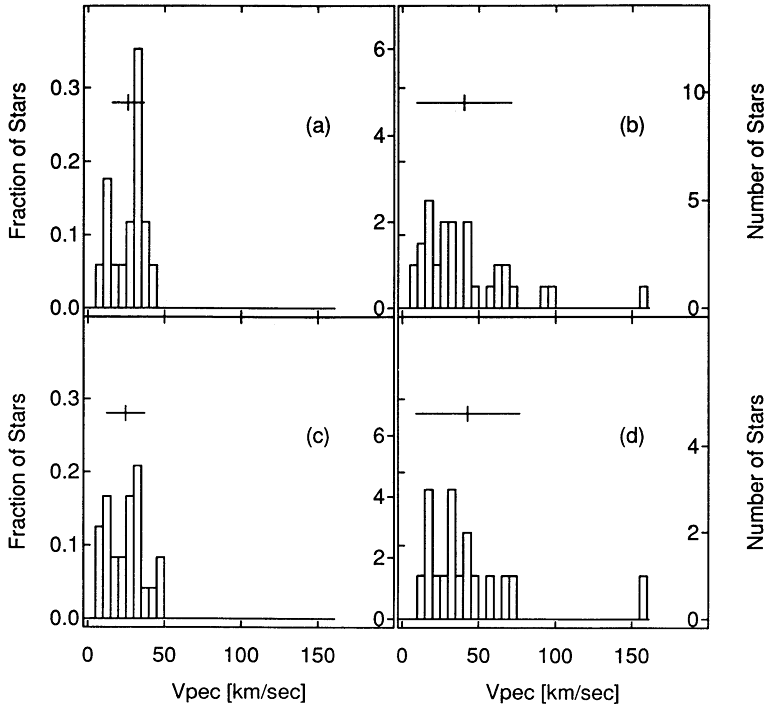

FIG. 2.—Velocity distributions for (*a*) stars with log (L_X) ≥ 29, (*b*) stars with log (L_X) < 29, (*c*) strong-line stars, and (*d*) weak-line stars. The numbers on the left represent the fraction of stars in each subsample; this scale is the same in all the panels. The numbers on the right of each panel indicate the actual number of stars. The mean value and dispersion of each distribution are also shown. Note the similarity between the distributions (*a*) and (*c*), as well as between (*b*) and (*d*).

29 (Fig. 2*a*), and for stars with log (L_X) < 29 (Fig. 2*b*). We have excluded the stars with upper limits on log (L_X) ≥ 29 because they cannot be assigned unambiguously to any of the two subsamples. We have verified that our following conclusions do not change by assigning these undetected stars either to the high- or low-luminosity sample. The break at log (L_X) = 29 is arbitrary, and corresponds to the level of X-ray emission of the less intense of the Hyades K giants, δ Tau (Stern et al. 1981: Micela et al. 1988, 1990). We have tentatively adopted this X-ray luminosity value to separate "young" and "old" disk giants because the Hyades age is usually considered the break point between young and old disk stars. For comparison, Figures 2*c* and 2*d* show the velocity distributions for strong-line and weak-line giants, respectively. In the figures, the mean values and the dispersions of the distributions are also indicated (see Table 2). We note that the strong X-ray emitting stars show a velocity distribution with a mean value and a dispersion very similar to that of the high metallicity stars. On the other hand, the velocity distribution of the low X-ray luminous stars has mean value and dispersion similar to that of the weak-line stars. The difference between the velocity distributions of high- and low-metallicity stars is interpreted as a difference in their age distributions (Roman 1952), hence our results clearly suggest that the X-ray emission level tends to separate young and old giant stars at least in the same statistical sense as the metallicity.

TABLE 2

VELOCITY DISTRIBUTIONS

Subsample	Number of Stars	Mean	Standard Deviation
log (L_X) ≥ 29	17	26.1	10.3
Strong Lines	24	24.6	12.3
log (L_X) < 29	34	40.5	30.7
Weak Lines	17	42.9	33.7

To test the dependence of coronal X-ray emission on metallicity we have computed the maximum-likelihood integral X-ray luminosity functions for the SL stars (Fig. 3, *solid line*) and for the WL stars (Fig. 3 *dotted line*). For these computations we have used techniques which take into account both flux measurements and upper bounds (Avni et al. 1980; Schmitt 1985). The mean values of log (L_X) and their 68% confidence level errors, obtained with a bootstrap technique (Schmitt 1985) with 500 replications, are the following:

$$\langle \log (L_X) \rangle_{SL} = 29.06(+0.24, -0.24)$$

$$\langle \log (L_X) \rangle_{WL} = 28.06(+0.33, -0.22) .$$

We have compared the two luminosity distributions by applying a nonparametric two-sample Wilcoxon test (Schmitt 1985; Feigelson & Nelson 1985) to the censored X-ray data. The null hypothesis we want to test is whether the X-ray luminosities of the SL sample and that of the WL sample are drawn from the same parent population. The test outcome indicates that the null hypothesis can be rejected with a confidence level of 98.3%. The same test, applied to the peculiar velocity distributions of the same samples, results in a confidence level of 97.8% to reject the hypothesis that the peculiar velocities of the SL and the WL giants are drawn from the same population. The similarity of these confidence levels confirms that X-ray emission level allows us to discriminate samples of young and old disk giants with a degree of efficiency at least similar to that given by the kinematical properties of the metallicity.

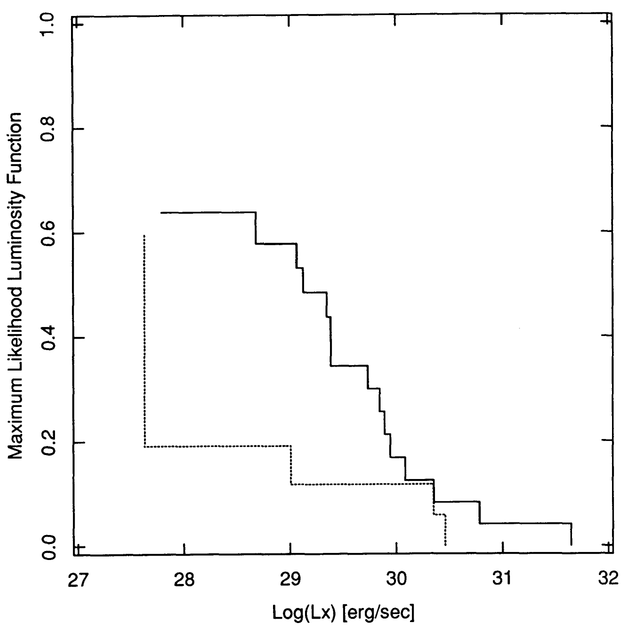

FIG. 3.—Maximum-likelihood integral X-ray luminosity functions for the strong-line stars (*solid line*; 14 detections and 10 upper limits) and the weak-line stars (*dotted line*; four detections and 13 upper limits) in our sample. The two distributions are statistically distinguishable at the 98% confidence level.

4. DISCUSSION

The previous analysis suggests that the X-ray activity level can be used as a statistical age indicator for disk giant stars. In particular, we have shown that young high-metallicity giants are on average more X-ray luminous than old low-metallicity giants. As alluded in § 1, at least two causes may concur to produce this behavior. The first is the metal abundance itself which directly affects the X-ray emission, the second is the aging of the stellar magnetic dynamo, which may affect the coronal heating processes.

Bohringer & Hensler (1989) have computed the effect of metallic abundance on the radiative cooling of the tenuous gas at various temperatures. Based on their results, for the plasma with temperature between 10^6 and 10^7 K, the expected total spread in cooling radiative power due to a range of metallicity typical of disk stars is a factor between 5 and 2, respectively. However, the spread in the observed X-ray luminosity also depends strongly on the energy response of the detector, and on the chosen energy bandpass. Our present purpose is to evaluate the expected metallicity dependence of the X-ray emission in the 0.16–3.5 keV band of the IPC, assuming that it originates from an optically thin plasma at coronal temperatures.

The observed emission from a coronal plasma is a combination of a continuum component and a line component, whose relative weight depends on the temperature and the metal abundance of the source, as well as on the spectral response of the detection instrument. In the following we use the results of Landini & Monsignori-Fossi (1990) who have evaluated the thermal spectrum from a thin plasma with solar abundance, in the spectral band 1–2000 Å, for a wide range of temperatures. The IPC is sensitive in the energy band 3.5–82.7 Å with two peaks in the spectral response at about 6 and 44 Å (Harnden et al. 1984).

TABLE 3

RATIO OF BOUND-BOUND AND FREE-BOUND EMISSION OVER TOTAL EMISSION IN THE BAND 0.16–3.5 keV, CONVOLVED WITH THE EINSTEIN IPC EFFECTIVE AREA

log (*T*) (K)	Ratio *R*
6.0	0.96
6.4	0.89
7.0	0.60
7.4	0.19

We have convolved the spectrum with the IPC effective area in the BROAD band (0.16–3.5 keV; Harnden et al. 1984), and we have computed the fraction of the metal-sensitive emission over the total emission, i.e., the ratio

$$R = \frac{\mathrm{bb} + \mathrm{fb}}{\mathrm{bb} + \mathrm{fb} + \mathrm{ff}}$$

where bb, fb, and ff represent the bound-bound, free-bound, and the free-free emission, respectively, assuming various coronal temperatures. In Table 3 we report the values of R we have obtained.

It is evident that the ratio is strongly dependent on the temperature. The metallic contribution (mainly bound-bound emission) is dominant at low T and decreases with increasing temperature, in the IPC broad band. This is due to the steady increase of the free-free emission, while the line contribution is almost constant up to about 10^7 K, and eventually decreases at higher temperatures. If we consider a plasma with abundance $z = Z/Z_\odot$ we can write:

$$\frac{F(z)}{F(z_\odot)} = 1 + R(T)(z - 1)$$

Where $F(z_\odot)$ is the emission in a plasma with solar abundance.

Since in the galactic disk the metallic abundance ranges from $Z \sim 0.4\, Z_\odot$ up to $Z \sim 2\, Z_\odot$ (Pagel & Patchett 1975), we have estimated that the total spread induced in the IPC observed emission, due to the abundance effect, is at most a factor 5 for $T = 10^6$ K, and of the order of 40% for $T = 2.5 \times 10^7$ K.

We conclude that, if the coronal heating mechanism is independent of metallicity (assuming that the composition in corona is the same as that in photosphere), the low-metallicity stars are expected to be less luminous, in the IPC bandpass, than those with high metallicity, but the amount depends strongly on the coronal temperature, and should not exceed a factor of 5, in the most favorable (low T) case.

Schmitt et al. (1990) have performed a parametric study of spectra for stars observed with the IPC, for which more than 200 total counts have been collected. These authors found that the late-type giant stars in their sample are well fitted with a thermal spectrum from a solar abundance plasma with temperatures in a narrow range around 10^7 K. However, their analysis refers to the brightest giants observed with the IPC (because of the restriction on the number of counts) and hence could be not representative of the complete sample of the giant stars. In particular, the low-metallicity giants, that are the faintest in X-rays, are undersampled in the Schmitt et al. (1990) survey. The only star (HR 5889) of the WL sample for which it has been possible to perform a temperature fit is the brightest of the low-metallicity giants. Its temperature [log $(T) = 6.93 \pm 0.4$] is very similar to that of the other giants (Schmitt et al. 1990), but an extension of this result to fainter X-ray sources in the WL sample may not be warranted. We have also verified that the hardness ratios of the detected WL stars (four objects) are in the same range as for the detected SL giants (14 objects). However, we stress that the hardness ratios are known only for the detected stars, while the difference between SL and WL stars (see Fig. 3) depends on the presence and distribution of upper limits for which it is not possible to evaluate the hardness ratios. Hence, this lack of evidence cannot be taken as proof that the coronal temperatures of giants with different metallicities are similar. The available data do not allow to explore further this point and more sensitive observations are needed to pursue it.

Neglecting for the moment possible systematic differences in coronal temperature, the expected difference in the emission between the low- and high-metallicity stars, due only to the metallicity spread of the disk giants, should be at most a factor of 3 if we consider 10^7 K as the typical coronal temperature of the giant stars. By comparing these expectations with the results of our analysis it turns out that a simple difference in abundance of the stellar atmospheres cannot explain the observed difference between the X-ray emission of low- and high-metallicity giants. In fact, the mean values of L_X for these two samples differ by one order of magnitude. The mismatch remains even if our estimate of the coronal temperature is wrong; in fact, even if the assumed temperature is lower by one order of magnitude ($T \sim 10^6$ K), the expected spread in the X-ray emission is at most a factor of 5. We conclude that the metallicity effect alone can explain only a fraction of the observed L_X spread. To explain the remaining difference of a factor of 2 we need to postulate that the low-metallicity giants have a coronal temperature as low as 10^6 K, one order of magnitude systematically lower than the temperature of the high-metallicity giants.

Since the contribution of free-free transitions to the X-ray emission increases with T, the dependence of L_X on metallicity decreases with increasing coronal temperatures. For this reason, we guess that the effect of metallicity is less pronounced for RS CVn systems than for "normal" disk giants, since these systems have coronal temperatures greater than 10^7 K (Majer et al. 1985; Schmitt et al. 1990).

In order to ascertain a possible dependence of the X-ray emission level also on classical stellar parameters, we have considered the two samples selected by L_X, studied in the previous section. Figure 4 shows the HR diagram for these giants; square symbols indicate stars with $L_X \geq 10^{29}$ ergs s^{-1}, diamonds indicate stars with $L_X < 10^{29}$ ergs s^{-1}. This plot suggests that the high X-ray emission stars are preferentially optically brighter and warmer, while low X-ray emission is typical of the cooler and fainter giants. If we apply a Kolmogorov-Smirnov test to compare the $B-V$ and M_v distributions of these high and low X-ray luminosity stars, we obtain confidence levels for rejection of the null hypothesis, that the two distributions are drawn from the same parent population, of 99.3% and 74%, respectively. To investigate whether this effect is also introduced by the selection based on

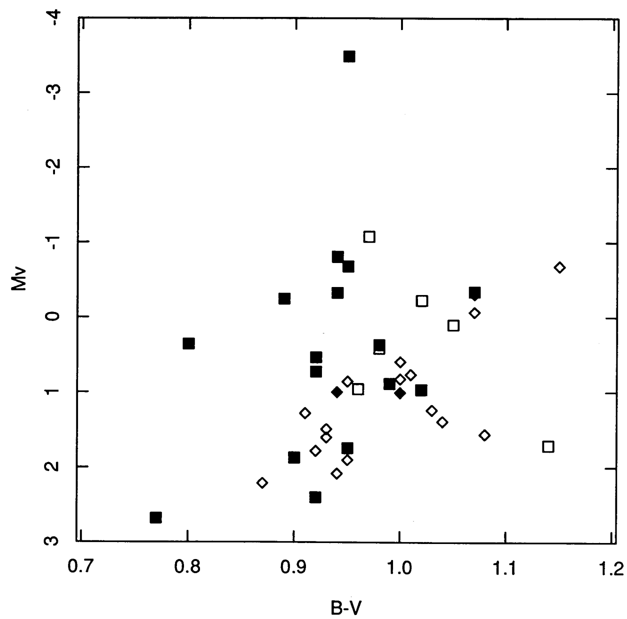

FIG. 4.—Color-magnitude HR diagram for the stars in our sample. Square symbols indicate detected stars with $L_X \geq 10^{29}$ ergs s^{-1}, while diamonds indicate stars with $L_X < 10^{29}$ ergs s^{-1} (filled symbols for detections, empty symbols for upper limits). Notice that the higher X-ray luminosity stars tend to be optically brightest and warmest.

the metal line strength, we have also compared the color and absolute magnitude distributions of the SL and WL stars. The two-sample test now yields a confidence level of 9% for rejection of the null hypothesis (i.e., the two distributions are very likely drawn from the same parent population) for the $B-V$ distributions and a level of 35% for the M_v distributions. In other words, the high and low X-ray luminosity giants seem to occupy different positions in the H-R diagram, while the SL and WL giants do not. This evidence is not inconsistent with the previous conclusion that SL and WL giants have statistically different emission level. Indeed, if we compare stars in the same region in the HR diagram, SL giants tend to be more luminous than WL giants. On the other hand, considering stars in a given metallicity class, there is a dependence of the X-ray luminosity level on the position in the HR diagram.

We conclude that the intensity of X-ray emission from the G-K giant stars depends likely both on stellar parameters such as mass, radius, and gravity (that determine the position of a star in the HR diagram) and on the metal abundances.

Obviously one can conceive an indirect influence of metallicity on the X-ray luminosity through the energy balance mechanisms. In fact, we expect that the differential emission measure of the plasma, which is governed by the balance between heating, conduction, and radiative losses, depends on the efficiency of the latter. These in turn are affected by the abundances of heavy elements in the outer atmosphere. If this is the case, there could be a systematic difference in the temperature profiles in the outer atmospheres of stars with different metallicity. This effect, combined with the "direct" metallicity effect discussed above, could contribute significantly to the observed difference in X-ray emission between high- and low-metallicity stars. A forthcoming paper will address this particular issue from the point of view of coronal loop models.

5. SUMMARY AND CONCLUSIONS

We have investigated the relationship between X-ray emission and statistical age indicators, such as peculiar velocity and metallicity, using a sample of 66 disk late-type giant stars.

Our results may be summarized as follows:

1. Stars with high X-ray luminosity ($L_X \geq 10^{29}$ ergs s^{-1}) tend to have a small mean peculiar velocity with a relatively low dispersion, while stars with low X-ray luminosity ($L_X < 10^{29}$ ergs s^{-1}) show a larger mean peculiar velocity and a greater dispersion. The peculiar velocity distributions for the high and low X-ray luminosity stars appear to be similar to the analogous distributions for stars with strong and weak metal lines, respectively.

2. The mean X-ray luminosity for strong-line stars is larger by one order of magnitude than the mean L_X for weak-line stars.

3. The above results suggest that the X-ray emission level can be used as a statistical age indicator for late-type disk giants as well as " classical " statistical age indicators.

4. We have estimated that the X-ray luminosity in the 0.16–3.5 keV energy band from an isothermal optically thin plasma can increase at most by a factor of 5 (for an assumed coronal temperature of 10^6 K) if the metal abundance changes from 0.4 $Z_\odot$ to 2 $Z_\odot$, a typical range for the Galactic disk. The expected variation of the X-ray luminosity reduces to a factor of 3 if we assume a coronal temperature of 10^7 K, which is typical of the X-ray brightest giant stars. To explain the entire difference in mean L_X we need to postulate for the weak-line stars coronal temperatures systematically lower by one order of magnitude with respect to the strong-line stars, and at the same time a difference in metal abundance of a factor of 5.

5. We have looked for possible systematic differences in coronal temperature of giants with different metallicity. The sensitivity of the instrument allows us to compare coronal temperatures and hardness ratios only for the most intense X-ray emitters. Since these stars cannot be considered representative of the entire sample, we are unable to draw firm conclusions on this problem. Further, more sensitive observations are needed to pursue this topic.

6. Finally, we have verified that giants with high X-ray luminosity tend also to be optically brighter and warmer than low-luminosity giants. We conclude that the X-ray activity level likely depends both on metallicity and on the evolutionary phase of the star.

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