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The rotation-activity correlation among G and K giants in binary systems

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ABSTRACT

Aims. The present study aims (i) to test the existence of a correlation between magnetic activity and rotation among G and K giants in binary systems and (ii) to test whether parameters other than rotation play a role in determining the X-ray emission level of intermediate-mass giants.

Methods. The method consists in testing the existence of correlations between measured stellar parameters including the X-ray surface flux, rotation period, Rossby number and surface gravity of a sample of G and K giants with masses included between 1.5 $M_\odot$ and 3.8 $M_\odot$.

Results. I found evidence that the X-ray surface flux F_X of intermediate-mass G and K giants is correlated with their rotation period P as previously observed on single G giants. Confidence in the degree of correlation is not higher when the Rossby number is used in place of the rotation period, but it significantly improves when stellar gravity g is taken into account. The empirical relation given by $\log(F_X) = -0.73 \times \log(P) + 0.64 \times \log(g/g_\odot) + 7.9$ differs from the power-law dependence with an index of about −2 between X-ray to bolometric luminosity ratio and the rotation period that is observed for main-sequence stars. The X-ray surface flux of single G giants and of intermediate-mass G and K giants in close binary systems, such as RS CVn systems, also depends on the stellar gravity. This dependence could result from the effect of gravity on the electron density and emission measure of the X-ray emitting plasmas, as well as on the characteristic sizes of coronal magnetic loops. The measured X-ray surface-flux dependence on gravity is, however, not as steep as the one predicted by simple models of hydrostatic loops that assume a fixed ratio between the coronal energy losses by thermal conduction and by radiation.

Conclusions. I conclude that (i) a relation exists between the rotation and X-ray activity level in giants, (ii) that this relation is not directly dependent on the presence of a companion and applies to all intermediate-mass giants with either G or K spectral type, and (iii) that gravity is an important stellar parameter in determining the X-ray surface flux of intermediate-mass giants.

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

1. Introduction

One major topic in studying stellar activity is to explain how phenomena seen on the Sun and stars, and especially magnetic phenomena, depend on stellar parameters such as rotation rate, mass, age, and binarity. One magnetic-field diagnostic for cool stars is coronal X-ray emission. In particular, the relation between the coronal radiative flux density and the average surface magnetic-flux density is nearly linear for solar active regions, as well as for entire stars (e.g. Fisher et al. 1998; Schrijver & Zwaan 2000), over 12 orders of magnitude in absolute magnetic flux (Pevtsov et al. 2003). The relation between X-ray activity and rotation is now well-established for late-type dwarfs (e.g. Pallavicini et al. 1981; Noyes et al. 1984; Mangeney & Praderie 1984). At a given spectral type, the relation indicates a power law with an index of about −2 between the X-ray luminosity and the Rossby number or the rotation period up to a saturation level estimated to $\log(L_X/L_{bol}) = -3$ (Patten & Simon 1996; Randich 2000). For giants, in contrast, the connection between rotation and activity is less evident (Maggio et al. 1990; Gondoin 1999).

The X-ray activity of low-mass ($M < 1.5\ M_\odot$) giants has a different evolutionary behavior from intermediate-mass ($1.5\ M_\odot < M < 3.8\ M_\odot$) giants. The X-ray luminosity of the lower mass stars that have an outer convection zone on the main sequence keeps on decreasing, on average, during post-main sequence evolutionary phases (Pizzolato et al. 2000). In contrast, the intermediate-mass giants, which develop outer convective envelopes only as they evolve off the main sequence, show a trend toward increasing emission levels with age, followed by a sharp decrease in X-ray emission at spectral type K1. It has been argued that the rapid change of the star's internal structure through this regime makes it very unlikely that the efficiency of the dynamo acting inside a giant star can be parameterized just by a surface rotation rate and a spectral type (Stepien 1994). However, the quiescent coronal activity of intermediate-mass single G giants, as measured by their X-ray surface flux, has recently been found to increase linearly with the inverse of the rotation period or with the inverse of the Rossby number (Gondoin 2005a). The empirical activity-Rossby number relationship accounts for two competing effects, namely a deepening convection zone that strengthens the dynamo and rapid spin-down that weakens it. The relation explains the occurrence of a maximum of magnetic activity in the atmosphere of intermediate-mass single stars as they evolve off the main-sequence near the bottom of the red giant branch. Although these results support the existence of a rotation-activity relationship among intermediate-mass giants, they were obtained on a limited sample of single intermediate-mass G giants. Hence, in spite of some evidence of a period-activity relationship among intermediate-mass giants, questions remain largely unanswered: "how fundamental is the

Table 1. Spectral type, bolometric luminosity, effective temperature, radius, mass, and X-ray luminosity in the 0.3–10 keV band of the sample of giant stars in close binary systems.

HD	Name	Sp. type	L ($L_\odot$)	$T_{\rm eff}$ (K)	R ($R_\odot$)	M ($M_\odot$)	Parallax (mas)	L_X (10^{30} erg s^{-1})	Ref.
4502	ζ And	K1 III (...)	73.8	4620	13.4[a]	2.1	17.98 ± 0.83	3.89 ± 0.66	1, 2
7672	39 AY Cet	G5 III (DA)	25.5	5045	6.6[b]	2.1	12.74 ± 0.72	20.33 ± 0.51	1, 2
13480	6 ι TZ Tri	G5 III (F5 V)	108	5370	12[b]	3.0	10.68 ± 0.92	7.72 ± 0.42	1, 2
28591	V 492 Per	K1 III (...)	51.3	4620	11.2	1.7	8.47 ± 0.87	2.63 ± 0.27	2
29317	3 Cam	K0 III (...)	259	4715	24.1	3.3	6.58 ± 0.78	2.26 ± 0.48	1, 2
32357	12 BM Cam	K0 III (...)	145	4720	18[b]	2.9	5.22 ± 0.92	15.48 ± 1.48	1, 2
34029	α Aur	G1 III (G8 III)	77.6	5700	9.2[c]	2.56	77.29 ± 0.89	2.40 ± 0.82	1, 2
	SS Cam	K0 IV-III (F5 V-IV)	19.1	4770	6.4[a]	1.5	3.09 ± 1.69	6.83 ± 1.82	1, 2
57364	AR Mon	G8 III (K2-3 III)	33.8	5200	7.178[d]	2.48	3.62 ± 1.22	6.61 ± 0.56	1, 2
62044	75 σ Gem	K1 III (...)	52.5	4630	12.3[e]	1.9	26.68 ± 0.79	7.08 ± 2.20	1, 2
69148	HR 3245	G8 III (...)	109	5070	13.5	3.1	6.93 ± 0.74	0.68 ± 0.22	2
72688	Vx Pyx	K0 III (...)	52.1	4945	9.8	2.4	7.65 ± 0.59	9.98 ± 0.88	2
73343	RZ CnC	K1 III (K3-4 III)	41.8	4595	10.2[a]	1.6	3.25 ± 1.56	18.32 ± 13.20	1, 2
81025	HR 3725	G2 III (...)	45.8	5415	7.7	2.4	7.55 ± 1.09	1.03 ± 0.24	2
102509	93 DQ Leo	G5 III-IV (A6-7 V)	28.6	5045	7[b]	2.2	14.40 ± 0.86	3.60 ± 0.81	1, 2
153751	ϵ UMi	G5 III (...)	273	5070	20.0	3.7	9.41 ± 0.67	9.69 ± 0.27	2
196574	71 Aql	G8 III (...)	281	4945	22.8	3.8	8.50 ± 1.00	0.15	1
	FF Aqr	G8 IV-III (sdO-B)	21.3	5010	6.12[a]	2.0	7.91 ± 1.50	69.87	2
209813	HK Lac	K0 III (F1 V)	89.3	4580	15[b]	2.0	6.62 ± 0.61	22.70 ± 4.52	1, 2
213389	V350 Lac	K2 III (...)	52.9	4570	11.6	1.6	8.18 ± 0.56	7.59 ± 0.59	1, 2
217188	AZ Psc	K0 III (...)	29.1	4660	8.3	1.5	6.78 ± 0.88	3.63 ± 0.51	2
222107	λ And	G8 III-IV (...)	22.5	4825	6.8	1.6	38.74 ± 0.68	4.22 ± 1.13	1, 2

[a] From Strassmeier et al. (1993); [b] from Schrijver & Zwaan (1991); [c] from Hummel et al. (1994); [d] from Williamon et al. (2005); [e] from Kövari et al. (2001).

rotation-period relation in determining the surface flux of G and K giants in binary systems?" and "how is this relation affected by major stellar parameters such as mass or gravity?"

The present paper reports on the results of an investigation that aims to verify whether the relation between the X-ray surface flux and the rotation period or Rossby number recently established for single G giants can be extended to a larger sample of intermediate-mass G and K giants in binary systems. A second objective of the paper is to test whether gravity plays a role in determining the X-ray emission level of intermediate-mass giants. Section 2 describes the selected sample of stars, and Sect. 3 presents correlations between their X-ray surface flux, rotation period, Rossby number, and surface gravity. Possible explanations for the obtained correlations are discussed in Sect. 4.

2. Sample selection

A sample of intermediate-mass G and K giants with masses included between 1.5 $M_\odot$ and 3.8 $M_\odot$ and with known rotational periods was defined from a list of selected binaries established by Schrijver & Swaan (1991) and from a catalogue of active binary stars (Strassmeier et al. 1993). This initial sample was complemented by G-K giants in single-lined spectroscopic binaries with an orbital period shorter than 250 days extracted from a list of binary systems with evolved components compiled by De Medeiros et al. (2002). According to these authors, 250 days is the critical synchronization period between axial rotational motion and orbital revolution for giants in the G and K spectral regions. When unknown, the rotation period of stars with orbital periods below this critical value was assumed to equal their orbital period.

The effective temperatures of the stars extracted from the Strassmeier (1993) catalogue and from the De Medeiros (2002) list were estimated using the $T_{\rm eff}$ vs. $(B-V)$ scale of Flower (1996) or the $T_{\rm eff}$ vs. $(V-I)$ relation of Alonso et al. (1999) applied to the color indices of the intermediate-mass stellar components. For the other giants, I used the effective temperature values provided by Schrijver & Swaan (1991). The bolometric luminosities were calculated from the effective temperatures and radii (see references in Table 1). The absolute magnitudes of giants in single-lined spectroscopic binaries were estimated from their V magnitudes and Hipparcos parallaxes (ESA 1997) assuming a negligible contribution from the secondary component. Table 1 gives the spectral types, bolometric luminosities, effective temperatures, radii, masses, parallaxes, and X-ray luminosities of the sample stars. The spectral type of the companion is indicated between brackett in the third column. X-ray fluxes are estimated from (1) *Einstein* count rates (Mc Dowell 1994) and (2) *ROSAT* count rates (Voges et al. 1999) assuming emitting plasmas at a temperature of 1 keV. Figure 1 shows their positions in an H-R diagram. Masses were estimated by comparison with evolutionary tracks calculated by Schaller et al. (1992) assuming a first crossing of the HR diagram and no influence of binarity or rotation on the internal structure of the stars.

The X-ray fluxes in the 0.3–10 keV band were derived from *Einstein* count rates in the 0.16–4.0 keV band (Mc Dowell 1994) and from *ROSAT* measurements in the 0.1–2.4 keV band (Voges et al. 1999) using energy conversion factors (ECF). The coronae of giants in close binary systems (e.g., Audard et al. 2001a,b; Gondoin 2003) have plasmas covering a range of temperatures included between a few MK and a few tens MK. Assuming an optically thin emitting plasma with a temperature of 1 keV, energy conversion factors $ECF_{\rm ROSAT} = 6.83 \times 10^{-12}$ erg cm^{-2} s^{-1} ct^{-1} and $ECF_{\rm Einstein} = 18.65 \times 10^{-12}$ erg cm^{-2} s^{-1} ct^{-1} were derived using the Portable, Interactive, Multi-Mission Simulator (PIMMS; Mukai 1993). For plasma temperatures ranging between 0.2 and 4.0 keV, flux

Table 2. Spectral type, rotation period, turnover convective timescale, Rossby number and X-ray surface flux in the 0.3–10 keV band of the sample giants in close binary systems, with the rotation period assumed to be the photometric period when known or the orbital period otherwise (as indicated between in parenthesis in the fourth column).

HD	Name	Sp. type	$P_{\rm rot}$ (days)	$\tau_{\rm c}$ (days)	$R_{\rm o}$	$F_{\rm X}$ (erg s^{-1} cm^{-2})
4502	ζ And	K1 III (...)	17.8	87	0.20	$(3.6 \pm 0.6) \times 10^5$
7672	39 AY Cet	G5 III (DA)	77.2			$(7.7 \pm 0.2) \times 10^6$
13480	6 ι TZ Tri	G5 III (F5 V)	14.7	52	0.28	$(8.8 \pm 0.5) \times 10^5$
28591	V 492 Per	K1 III (...)	21.3 ($P_{\rm orb}$)	81	0.26	$(3.4 \pm 0.4) \times 10^5$
29317	3 Cam	K0 III (...)	121($P_{\rm orb}$)	93	1.30	$(6.4 \pm 1.4) \times 10^4$
32357	12 BM Cam	K0 III (...)	85.0	95	0.89	$(7.8 \pm 0.8) \times 10^5$
34029	α Aur	G1 III (G8 III)	8.7	32	0.27	$(4.7 \pm 1.6) \times 10^5$
	SS Cam	K0 IV-III (F5 V-IV)	4.8	100	0.05	$(2.7 \pm 0.7) \times 10^6$
57364	AR Mon	G8 III (K2-3 III)	21.2 ($P_{\rm orb}$)	66	0.32	$(2.1 \pm 0.2) \times 10^6$
62044	75 σ Gem	K1 III (...)	19.6	91	0.22	$(7.7 \pm 2.4) \times 10^5$
69148	HR 3245	G8 III (...)	89.1 ($P_{\rm orb}$)	105	0.85	$(6.1 \pm 2.0) \times 10^4$
72688	Vx Pyx	K0 III (...)	45.1 ($P_{\rm orb}$)	126	0.36	$(1.7 \pm 0.2) \times 10^6$
73343	RZ CnC	K1 III (K3-4 III)	21.6	72	0.30	$(2.9 \pm 2.1) \times 10^6$
81025	HR 3725	G2 III (...)	66.7 ($P_{\rm orb}$)	32	2.08	$(2.9 \pm 0.7) \times 10^5$
102509	93 DQ Leo	G5 III-IV (A6-7 V)	52.0	100	0.52	$(1.2 \pm 0.3) \times 10^6$
153751	ϵ UMi	G5 III (...)	39.5 ($P_{\rm orb}$)	105	0.38	$(4.0 \pm 0.1) \times 10^5$
196574	71 Aql	G8 III (...)	205.2 ($P_{\rm orb}$)	126	1.63	0.5×10^4
	FF Aqr	G8 IV-III (sdO-B)	9.2			3.1×10^7
209813	HK Lac	K0 III (F1 V)	24.461	79	0.31	$(1.7 \pm 0.3) \times 10^6$
213389	V350 Lac	K2 III (...)	17.8 ($P_{\rm orb}$)	71	0.25	$(9.3 \pm 0.7) \times 10^5$
217188	AZ Psc	K0 III (...)	47.1 ($P_{\rm orb}$)	79	0.60	$(8.7 \pm 1.2) \times 10^5$
222107	λ And	G8 III-IV (...)	54.3	105	0.52	$(1.5 \pm 0.4) \times 10^6$

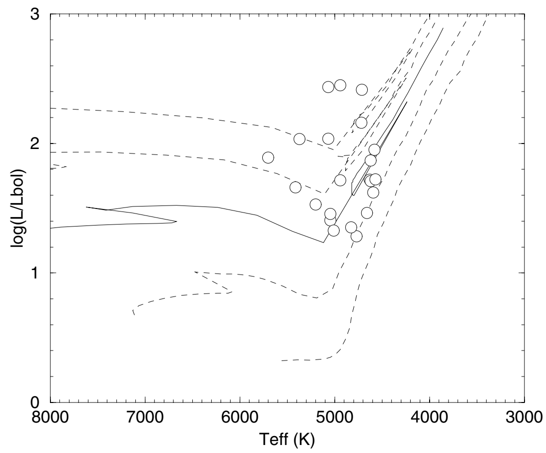


Fig. 1. H-R diagram of the sample giants compared with evolutionary tracks (Schaller et al. 1992). The lines from bottom to top describe the evolutionary tracks of 1 $M_\odot$, 1.5 $M_\odot$, 2 $M_\odot$ (solid line), 2.5 $M_\odot$ and 3 $M_\odot$ stars, respectively.

errors in the *ROSAT* and *Einstein* bands are within a factor of two, comparable with the long-term X-ray variability in active binary stars (Kashyap & Drake 1999). X-ray fluxes were converted into X-ray luminosities using Hipparcos parallaxes (see Table 1). The X-ray contributions from the stellar companions were assumed to be negligible.

3. Analysis

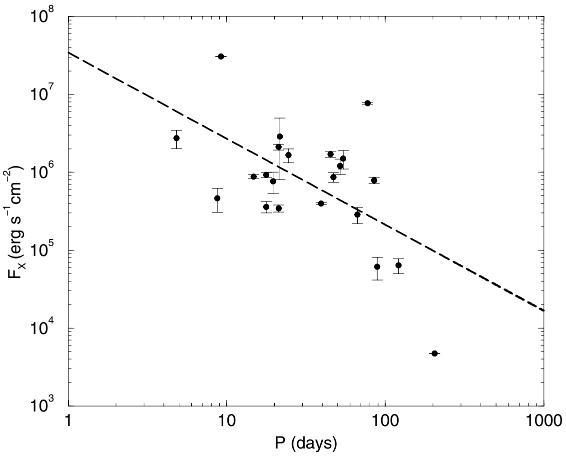
3.1. Correlation between X-ray surface flux and rotation

The X-ray surface fluxes of the sample giants (see Table 2) were calculated from their X-ray luminosities and stellar radii. The obtained values (i.e. X-ray luminosities divided by the stellar surface area) are included between 10^5 and 10^8 erg s^{-1} cm^{-2}. These surface fluxes are comparable with the range of X-ray fluxes found for different structures in the solar corona. Coronal holes show X-ray fluxes around 10^4 erg s^{-1} cm^{-2}, while active regions show fluxes up 10^8 erg s^{-1} cm^{-2}. The surface fluxes of the sample giants are plotted in Fig. 2 (left) as a function of the rotation period, including the linear regression to the log-log plot. Its equation is given by:

$$\log(F_{\rm X}) = (-1.1 \pm 0.3) \times \log(P) + (7.5 \pm 0.5) \qquad (1)$$

where $F_{\rm X}$ is the X-ray surface flux in erg cm^{-2} s^{-1} and P is the rotational period in days. A good correlation ($r = -0.58$, $N = 20$) is obtained at a high confidence level. The probability that a random sample of 22 uncorrelated data points yields a correlation coefficient larger or equal to this value is less than 0.4%. Two stars, 39 AY Cet and FF Aqr, have X-ray surface fluxes well above other giants with comparable rotation period (see Fig. 2 left). Since the less evolved G giants are more massive than their sub-dwarf companions, these systems may have had significant mass transfer between the two component stars and are likely in a different evolutionary state than the other typical detached RS CVn stars of the sample.

The correlation between magnetic activity and the onset of a convective envelope in cool stars suggests a relation to dynamo mechanisms (Parker 1977). Durney & Latour (1978) used this assumption to show that the level of activity should be a function of the rotation period, $P_{\rm rot}$, divided by a turnover convective time scale $\tau_{\rm c}$. The Rossby number ($R_{\rm o} = P_{\rm rot}/\tau_{\rm c}$) is an important indicator in hydro-magnetic dynamo theory that measures the extent to which rotation can induce both the helicity and differential rotation required for dynamo activity. The variation in $\tau_{\rm c}$ along the evolution of intermediate-mass stars has been studied using stellar evolution and stellar structure codes by several authors (Gilliland 1985; Rucinski & Vandenberg 1986; Basri 1987). However, these studies calculated the convection turnover time during the evolution off the main sequence of stars with



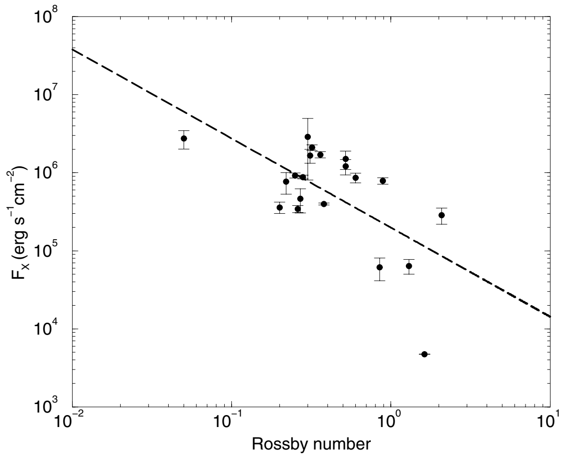


Fig. 2. X-ray surface fluxes of the sample G and K giants in close binary systems as a function of rotation periods (*left*) and Rossby number (*right*). The Rossby numbers of 39 AY Cet and FF Aqr could not be estimated due to their unknown evolutionary states, so these stars were excluded from further analysis.

masses lower than those of the sample stars. Hence, I used the calculation performed by Gunn et al. (1998) from a standard stellar evolution code (Han et al. 1994). These authors derive the convection turnover time as a function of effective temperature during the evolution of a 2.2 $M_\odot$ star. The estimated τ_c and the derived Rossby numbers of the sample stars are given in Table 2 with the exception of 39 AY Cet and FF Aqr, which are in an unknown evolutionary state and were therefore excluded from further analysis. Surface fluxes are plotted in Fig. 2 (right) as a function of the Rossby number. The linear regression to the log-log plot is described by the following equation:

$$\log(F_X) = (-1.1 \pm 0.3) \times \log(R_o) + (5.3 \pm 0.2). \quad (2)$$

Again, a good correlation ($r = -0.63$, $N = 18$) is obtained. The probability that a random sample of 22 uncorrelated data points yields a correlation coefficient that is larger or equal to this value is about 0.1%. This correlation between the X-ray surface fluxes and the Rossby numbers calculated from turnover times derived by Gunn et al. (1998) is slightly better than the correlation with the rotational period mainly because the two peculiar binaries stars 39 AY Cet and FF Aqr were excluded from the sample.

Remarkably, the best-fit relations between the X-ray surface flux and the rotation period or Rossby number for G and K giants in close binary systems are fully consistent with the relations found recently on single G giants (Gondoin 2005a). This suggests that the relation between the X-ray surface flux and rotation among giants is not directly dependent on the presence of a companion (providing that mass transfer has not affected their evolution) and that it applies to all intermediate-mass giants with either G or K spectral types.

3.2. The influence of gravity on the X-ray surface flux of giants

For the Sun, it is customary to express the radiative loss rate $E_R(T_c, n_e)$ that sums all the continuum and line contribution from plasmas radiating at temperature T_c with density n_e as a product of densities and a temperature-dependent function, i.e. $E_R(T_c, n_e) = n_e^2 \times \Lambda(T_c)$. The value of $\Lambda(T_c)$ has been calculated by many authors (e.g., Tucker & Koren 1971; Rosner et al. 1978; Mewe & Gronenschild 1981; Cook et al. 1989; Landini & Monsignori-Fossi 1990; etc.), and it depends not only on temperature but also on the elemental abundances. The X-ray surface flux can be calculated by integrating the radiative loss rate in the vertical direction. For hydrostatic structures, this is achieved simply by multiplying $E_R(T_c, n_e)$ with the density scale height $H(T_c)$. Thus F_X is expected to be a function of stellar gravity.

To quantify any such dependence, I performed a least-square polynomial fit to the X-ray surface flux of giants using the rotation period or Rossby number and the stellar gravity as free parameters. Since binarity was found to play no role in the X-ray activity level other than maintaining rapid rotation (see Sect. 3.1), the test was conducted on a sample of 31 stars including both G, K giants in close binary systems (see Table 1) and single G giants (see Gondoin 2005a; Table 1). The following relations were found:

$$\log(F_X) = -0.95 \times \log(P) + 7.1 \ (\chi^2 = 1.66) \quad (3)$$

$$\log(F_X) = -1.04 \times \log(R_o) + 5.3 \ (\chi^2 = 1.62) \quad (4)$$

$$\log(F_X) = -0.73 \times \log(P) + 0.64 \times \log(g/g_\odot) + 7.9 \ (\chi^2 = 1.03) \quad (5)$$

$$\log(F_X) = -0.83 \times \log(R_o) + 0.75 \times \log(g/g_\odot) + 6.6 \ (\chi^2 = 0.90) \quad (6)$$

where $g/g_\odot$ is the gravity normalized to the solar value and χ^2 the reduced chi-square. As expected, Eqs. (3) and (4) obtained for the sample of 31 single and binary giants are similar to Eqs. (1) and (2), respectively, obtained for the smaller sample of 21 G and K giants in close binary systems. It is worth noting that their reduced chi-square are significantly greater than 1 (χ^2 = 1.66 and 1.62 for Eqs. (3) and (4), respectively). By using gravity as an additional free parameter, the improvement in the χ^2-fit statistic ($\Delta\chi^2 = 0.63$ from Eqs. (3)–(5) and $\Delta\chi^2 = 0.72$ from Eqs. (4)–(6) for 29 degrees of freedom) is significant at >99.9% confidence using the F-statistic and the reduced chi-squares are closer to 1 (χ^2 = 1.03 and 0.90 for Eqs. (5) and (6), respectively). According to the least-square method, Eqs. (5) and (6) provide an improved description of the X-ray surface flux dependence with rotation. This suggests that stellar gravity is an important parameter in determining the X-ray surface flux of giants. The best-fit relations to the X-ray surface flux of giants using stellar gravity as a free parameter are plotted in Fig. 3.

4. Discussion

I found evidence that the X-ray surface flux F_X of intermediate-mass G and K giants in close binary systems with periods lower

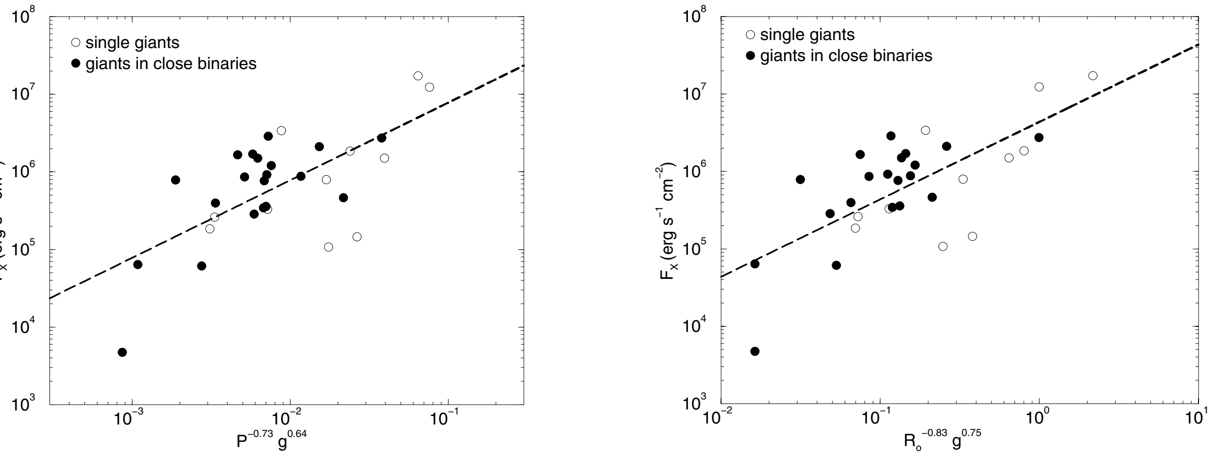


Fig. 3. X-ray surface flux of single giants (open circle) and giants in close binary systems (filled circles) as a function of a parameter defined as $P^{-0.73} \times g^{0.64}$ (*left*) and $R_o^{-0.83} \times g^{0.75}$ (*right*), where P is the rotation period in days, R_o the Rossby number and g the stellar gravity in solar unit. The dot-dashed line is the best linear fit (see Eqs. (5) and (6)).

than about 205 days is correlated with their rotation period P. For the period range from a few days up to 20 days, Schrijver & Zwaan (1991) found a similar relationship between coronal radiative losses and rotation rates in close binaries that can be approximated by $\langle F_X \rangle \approx \Omega^{0.8 \pm 0.2}$. The binary stars used in their study include main-sequence stars, as well as sub-giants and giants. Dempsey et al. (1993) also observe a decrease in the surface flux of giants with increasing period ($F_X \approx P^{-0.92 \pm 0.22} \times (B-V)^{-1.52 \pm 1.89}$) but, in agreement with Rengarayan & Verma (1983) concluded that the period-activity relation found for their sample simply results from the Roche lobes of longer period systems being able to accommodate larger stars with lower surface fluxes.

The empirical relation between the X-ray surface flux F_X and the rotation period found in this study is identical to the relation found recently on a sample of single G giants (Gondoin 2005a). This indicates that the explanation proposed by Rengarayan & Verma (1983) and Dempsey et al. (1993) does not hold for the sample of giants used in the present study. Taking into account the linear relationship between the coronal radiative flux density and the average surface magnetic flux density $|\phi|$ for solar active regions, as well as for entire stars (e.g. Fisher et al. 1998; Schrijver & Zwaan 2000), a likely interpretation is that the magnetic surface flux of intermediate-mass giants increases with the angular rotation velocity. In the orbital-period range from a few days up to 20 days, Shrijver & Swaan (2000) also noticed that the surface-averaged magnetic flux density scales as $\Omega^{0.9\pm0.3}$ when combining the activity-rotation relationship of close-binaries with the relationship $\langle F_X \rangle \approx \langle \Delta F_{\rm CaII} \rangle^{1.5\pm0.2}$ found for stars and $\langle \Delta F_{\rm CaII} \rangle \approx |\phi|^{0.6\pm0.1}$ found for the Sun observed with a moderate angular resolution.

Since high X-ray luminosity in giants seems to be correlated with the presence of large starspots (Strassmeier 2002), it is likely that the linear increase in the X-ray surface flux with angular velocity results mainly from an increasing coverage of their surface with active regions. Within the solar paradigm, if coronal loops cover a larger fraction of the star surface, it is expected that their interaction become frequent leading to a more intense flaring activity on fast-rotating giants. Such a trend has been noticed in observations of flare indicators on single G giants. In particular, recent XMM-Newton observations (Gondoin 2005b) suggest that the emission measure and temperature of hot plasma (>10^7 K) increase with the angular rotation velocity and that iron in high ionization states and large Ne abundance enhancements reminiscent of solar-flares tend to be detected in rapidly rotating G giants. Hence, the rotation-activity connection in giants seems to stem from physical processes similar to those observed in dwarfs.

There is, however, one noticeable difference. Studies of main sequence stars indicates a power-law relation with an index of about −2 between the X-ray to bolometric luminosity ratio and the Rossby number or the rotational period up to a saturation level estimated as $\log(L_X/L_{\rm bol}) = -3$ (Patten & Simon 1996; Randich 2000; Pizzolato et al. 2003). In contrast, the present study of G and K giants suggests a less steep dependence of the X-ray surface flux on angular rotation velocity and no apparent saturation level. Even the most rapidly rotating single giants do not reach the $\log(L_X/L_{\rm bol}) \approx -3$ saturation level. This difference may have important implications for the dynamo generation of stellar magnetic fields on giants.

Durney et al. (1981), Durney & Robinson (1982) and Robinson & Durney (1982) provided arguments that the dynamo number N_d is the relevant parameter describing dynamo efficiency. Making some assumptions about the form of α and Ω, Hartman & Noyes (1987) estimated that $N_d \approx R_o^{-2}$. However, Gunn et al. (1998) point out that this characterization of the dynamo effect suffers from several fundamental assumptions. In particular, calculations of τ_c are performed one pressure-scale height above the base of the convection zone, while the actual zone across which the dynamo operates is not known in giants. Also, the classical Rossby number involves the use of surface rotation rate or period and therefore does not take account of the radial differential rotation required to produce the dynamo. The use of the Rossby number to describe the efficiency of the dynamo action is therefore debatable. The present study indicates that confidence in the degree of correlation between X-ray surface flux and rotation for giants is not significantly larger when using the Rossby number instead of the rotation period.

On the contrary, the degree of correlation between the giants' X-ray surface fluxes and their rotation periods does significantly improve when gravity is used as an additional free parameter. The X-ray surface fluxes of the sample giants are included between 10^5 and 10^8 erg s^{-1} cm^{-2}. These radiative losses need to be sustained by some energy sources. In the Sun, these are provided by those mechanical motions in and below the photosphere that displace the foot-points of coronal loops and either stress the magnetic field or generate waves. Dissipation of magnetic stresses is referred to as direct current heating, and dissipation of waves is referred to as an alternating current heating. Various activity indicators including direct magnetic field measurements (Hubrig et al. 1994) suggest that the heating of coronae in late-type giants is controlled by magnetic fields, irrespective of the details of the unknown heating mechanisms.

By analogy with the Sun, we can reasonably assume that the coronae of giants are also partitioned into open-field and closed-field regions that provide the bulk of the X-ray emission. It is of interest to express the measured average surface X-ray fluxes as a sum of contributions from individual isothermal magnetic loops filling a fraction f_c of the star's coronae. For simple hydrostatic loops, the X-ray surface fluxes can be approximated as follows:

$$F_X = 3.4 \times 10^{39} \times \Lambda(T_c) \times f_c \times \frac{P_c^2}{T_c \times g} \text{ (erg s}^{-1}\text{ cm}^{-2}) \quad (7)$$

where P_c is the coronal electron pressure, and g the stellar gravity in cgs units.

Although gravity is expected to affect the pressure and electron density, relations between T_c, P_c, and g can only be obtained if an assumption is made concerning the energy balance in the corona. Hearn (1975, 1977) proposed that coronae tend to an energy loss configuration that is minimized with respect to temperature. Craig et al. (1978) and Rossner et al. (1978) used a similar approach to evaluate the conductive flux, but also included a specific heating function and a closed-loop geometry. Montesinos & Jordan (1993) note that, when the loop length is replaced by the hydrostatic pressure scale-height, the same dimensional scaling law results with a slightly different constant. In both methods the scaling law results from the fixed ratio between the coronal energy losses by thermal conduction and by radiation (Jordan 2000).

The precise powers in the scaling laws depend on the functional form adopted for the radiative power losses. For temperatures above 2×10^5 K, radiative losses of the form $\Lambda(T_c) = A \times T_c^{-\delta}$ have been used (Jordan et al. 1987; Rosner et al. 1978; Craig et al. 1978). With Hearn's method, Montesinos & Jordan (1993) found the following scaling law between T_c, P_c, and g:

$$P_c = 1.6 \times 10^{-27} \times \frac{g \times (1.5-\delta)^{1/2} \times T_c^{7/4+\delta/2}}{A^{1/2} \times (\delta+1)} \text{ (dyne cm}^{-2}). \quad (8)$$

Replacing P_c by the previous expression in Eq. (7) suggests that the X-ray surface flux of giants is proportional to their surface gravity, while measurements (see Eqs. (5) and (6)) indicate that the dependence on gravity is not as steep. Assuming that the effect of rapid rotation is mainly to populate the coronae of giants with a high density of magnetic loops filled with hot plasma, the models of Hearn (1975, 1977), Craig et al. (1978), and Rossner et al. (1978) provide a similar trend in the X-ray surface flux dependence of giants with surface gravity but do not explain the measured power-law index.

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