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The relation between X-ray activity and rotation in intermediate-mass G giants

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ABSTRACT

I study the relation between X-ray activity and rotation among intermediate-mass single G giants. The results show evidence that the quiescent coronal activity of these stars, as measured by their X-ray surface flux, increases linearly with the angular rotation velocity and with the inverse of the Rossby number. Even the most rapidly rotating G giants do not reach the canonical $\log(L_X/L_{bol}) \approx -3$ saturation level. The effect of rapid rotation on these stars could result mainly in an increased coverage of their surface with magnetic close loop structures. The empirical activity-rotation relationship accounts for the occurrence of a maximum of magnetic activity in the atmosphere of intermediate-mass stars as they evolve off the main-sequence near the bottom of the red giant branch. Remarkably, the relation between X-ray to bolometric luminosity ratio and the Rossby number or rotation period for G giants differs from the power law dependence with an index of about –2 that is observed for main-sequence stars. Possible implications for the dynamo generation of magnetic fields on giants are discussed.

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

1. Introduction

One major topic of 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 and age. One magnetic field diagnostic for cool stars is coronal X-ray emission. In particular, the relationship 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 (Petsov et al. 2003). A relation between X-ray luminosities and projected rotation velocities has been reported for late-type dwarfs (Pallavicini et al. 1981). It was then refined by studying the dependence of the X-ray to bolometric luminosity ratio to the Rossby number (Noyes et al. 1984; Mangeney & Praderie 1984). For main-sequence stars 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 et al. 2000).

The connection between rotation and activity becomes less evident among giants (Maggio et al. 1990; Gondoin 1999). In particular, the X-ray activity of low-mass ($M < 1.5\ M_\odot$) giants has an evolutionary behavior different from that of intermediate-mass ($1.5\ M_\odot < M < 3.0\ M_\odot$) giants (Pizzolato et al. 2000). The X-ray luminosity of the lower mass stars decreases, on average, during post-main sequence evolutionary phases, while the intermediate-mass stars show a trend of increasing emission levels with age followed by a sharp decrease of X-ray emission at spectral type K1. The evolution of intermediate-mass G – K giants features two competing effects, namely a deepening convection zone that strengthens the dynamo, and rapid spin-down that weakens it. Up to now, no conclusive connection has been established between the X-ray coronal emission of these stars and the evolution of their rotation rate. It is argued that the rapid change of the star internal structure through this regime makes it very unlikely that the efficiency of the dynamo acting inside a giant star can be just parameterized by a surface rotation rate and a spectral type (Stepien 1994). This paper reports on the results of an investigation to test whether such a relation exists among intermediate-mass giants. The study uses recent X-ray observations of a sample of stars with similar masses and evolutionary status and with known rotational periods. Section 2 describes the sample selection and Sect. 3 presents the analysis. The results are discussed in Sect. 4.

2. Sample selection

Giants with $1.8\ M_\odot < M < 3.5\ M_\odot$ have A and late B-type progenitors on the main sequence that have no outer convection zones and that are typically rapid rotators (Abt & Morell 1995; Royer et al. 2002). As they evolve off the main sequence, in the shell hydrogen burning stage, they develop thin outer convection zones. These giants then rapidly traverse the F and G spectral types zone of the H-R diagram which is relatively devoid of stars and is known as “the Hertzsprung gap”. During this rapid evolution, the internal structure of these stars changes

Table 1. Spectral type, bolometric luminosity, effective temperature, radius, mass and X-ray luminosity in the 0.3–10 keV band of the sample stars. References to X-ray data (last column) are as follows: (1) Maggio et al. (1990); (2) Hünsch et al. (1998); (3) Gondoin (2003a); (4) Gondoin (2002); (5) Gondoin (2005); (6) Gondoin (2004); (7) Gondoin (2003b).

HD	Name	Sp. type	L ($L_\odot$)	$T_{\rm eff}$ (K)	R ($R_\odot$)	M ($M_\odot$)	$L_{\rm X}$ (10^{30} erg s^{-1})	Ref.
6903	ψ^3 Psc	G_0 III	86.7	5270	11.2	2.8	0.82 ± 0.13	1, 2
33798	V390 Aur	G_8 III	24.7	4970	6.7	1.8	5.04 ± 0.84	3
82210	24 Uma	G_4 III-IV	14.9	5280	4.6	1.9	1.95 ± 0.32	1,2
85444	ν^1 Hya	$G_{6/8}$ III	166	5000	17.2	3.5	4.69 ± 2.27	1, 2
111812	31 Com	G_0 III	88.7	5320	9.3–11.1	2.8	9.24 ± 2.90	1, 2
117555	FK Com	G_5 III	21–59	5080	5.9–9.9	2.0–2.7	$55.7^{+45.2}_{-25.4}$	4
141714	δ CrB	$G_{3.5}$ III	34.3	5180	7.4	2.4	$2.41^{+1.45}_{-0.94}$	1, 2, 5
145001	κ Her	G_8 III	149	4990	16.3	3.4	2.98 ± 0.49	1, 2
163993	92 Her	G_8 III	59.4	5010	10.2		3.03	2
199178	V1794 Cyg	G_5 III	17–24	5450	4.6–5.5	1.7–1.9	27.65 ± 7.75	6
205435	ρ Her	G_8 III	35.8	5210	7.3	2.4	1.073	2
223460	HR 9024	G_1 III	61–104	5110	10–13	2.8–3.1	$28.20^{+9.50}_{-11.29}$	2, 7

substantially. The thin convective shells prior to early G give way to rapidly deepening convection zones at mid-late G. The increasing convection zone depth combined with fast rotation is likely to trigger dynamo processes that generate the magnetic fields that, by analogy with the Sun, cause the X-ray emission of the outer stellar atmospheres. A large fraction of the yellow giants are able to hold their high rotation until mid-G spectral types. Beyond this point, rotation velocity measurements (Gray 1989) indicate a strong rotational braking. At the same evolutionary stage, a transition is observed from hot coronae and transition regions to cool winds (Ayres et al. 1981). However, no relation has been found between the X-ray activity decay of these stars and the spin-down of their rotation rate. Either such a correlation does not exist, or it has not been detected, possibly because intermediate-mass giants form a inhomogeneous sample of stars with different masses and evolutionary status. Moreover, X-ray luminosity measurements, often used as activity indicators and $v \sin i$ data are altered by the large range of stellar radii among giants and by the projection effect of the star rotation axis onto the line of sight.

In order to avoid these ambiguities, a sample of single intermediate-mass G giants with similar masses and evolutionary status and with known rotation periods was defined from the list of single giants established by Gondoin (1999). The rotation periods were extracted from Young et al. (1989) who have compiled an extensive tabulation of measured values of the Ca II H and K S-index using many published sources. The list of giants also includes rapidly rotating FK Comae-type stars whose periods have been determined photometrically by rotational modulation studies of their light curves. The absolute magnitude of the sample giants were calculated from the V magnitude and parallaxes given in the Hipparcos catalogue (ESA 1997). The stellar luminosities were derived from the absolute magnitudes using the bolometric correction vs. effective temperature data of Flower (1996). The stellar radii were then estimated from the effective temperatures. Table 1 gives the spectral type, bolometric luminosity, effective temperature, radius, mass and X-ray luminosity of the sample stars. Figure 1 shows their positions in the H-R diagram. The mass of HD 163993 (92 Her) could not be estimated due to its H-R diagram position in the red giant clump region (Girardi et al. 1998). The X-ray luminosities of most stars were derived from *Einstein* measurements of count rates in the 0.16–4.0 keV band (Maggio et al. 1990) and from *ROSAT* measurements in the 0.1–2.4 keV band (Hünsch et al. 1998) using energy conversion factors and Hipparcos parallaxes. Flux errors in the *ROSAT* and *Einstein* bands are estimated to be typically within a factor of two or less for bright sources. I calculated the fluxes in the *ROSAT* and *Einstein* spectral bands normalized to the *XMM – Newton* flux in the 0.3 to 10 keV band using optically thin plasma emission models with temperatures representative of those found in the coronae of active G giants. The results indicate that, for plasma temperatures ranging from

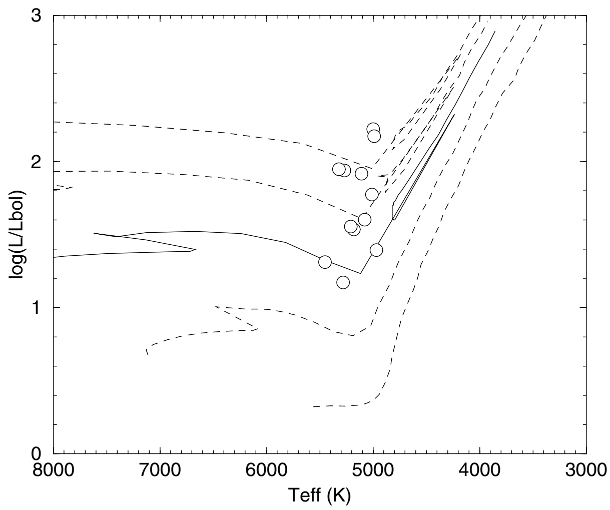

Fig. 1. H-R diagram of the sample giants compared with evolutionary tracks (Schaller et al. 1992). The lines from bottom to top describe the evolutionary tracks of 1 $M_\odot$, 1.5 $M_\odot$, 2 $M_\odot$ (solid line), 2.5 $M_\odot$ and 3 $M_\odot$ stars, respectively.

Table 2. Spectral type, rotational period, turnover convective timescale, Rossby number and X-ray surface flux in the 0.3–10 keV band of the sample stars.

HD	Name	Sp. type	P (days)	τ_c (days)	R_o	F_X (erg s^{-1} cm^{-2})
6903	ψ^3 Psc	G_0 III	9	52	0.17	$(9.1–12.4) \times 10^4$
33798	V390 Aur	G_8 III	9.8	132	0.07	$(1.5–2.2) \times 10^6$
82210	24 Uma	G_4 III-IV	10	52	0.19	$(1.2–1.8) \times 10^6$
85444	ν^1 Hya	$G_{6/8}$ III	50	120	0.42	$(1.3–3.9) \times 10^5$
111812	31 Com	G_0 III	6	50	0.12	$(1.0–1.9) \times 10^6$
117555	FK Com	G_5 III	2.4	105	0.02	$(7.9–26.6) \times 10^6$
141714	δ CrB	$G_{3.5}$ III	17	79	0.22	$(4.3–11.6) \times 10^5$
145001	κ Her	G_8 III	59	126	0.47	$(1.5–2.2) \times 10^5$
163993	92 Her	G_8 III	67	120	0.56	4.8×10^5
199178	V1794 Cyg	G_5 III	3.3	35	0.09	$(8.9–15.9) \times 10^6$
205435	ρ Her	G_8 III	56	68	0.82	3.3×10^5
223460	HR 9024	G_1 III	23	100	0.23	$(2.1–4.7) \times 10^6$

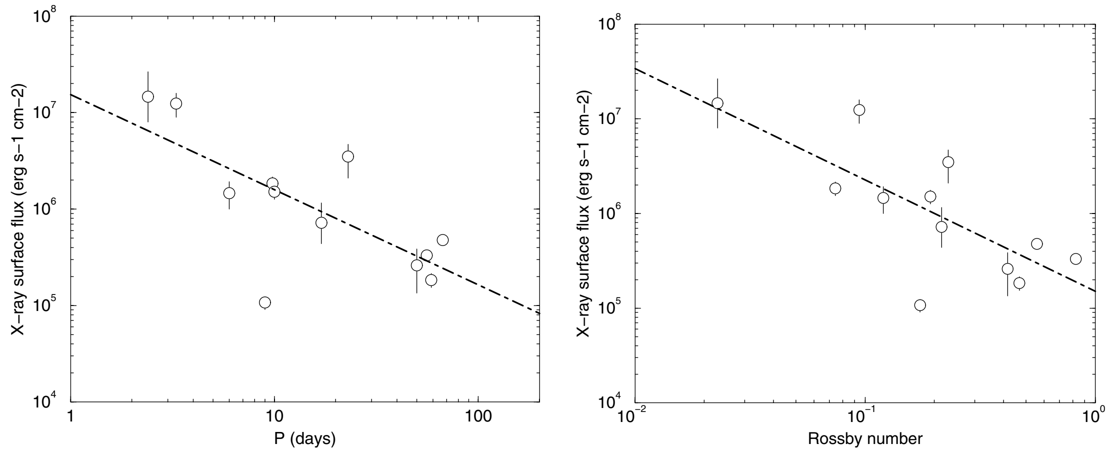

Fig. 2. X-ray surface flux of the sample giants as a function of rotation periods (*left*) and Rossby number (*right*).

0.3 keV to 2.4 keV, the normalized *ROSAT* and *Einstein* fluxes are included between 1.2 and 0.7 and between 1.1 and 0.9, respectively. Hence, I assumed a conversion factor of 1 between the fluxes in the reference 0.3–10 keV band and the fluxes in the *Einstein* or *ROSAT* spectral bands. The resulting errors on fluxes in the 0.3–10 keV band for *Einstein* and *ROSAT* sources are lower than 10–20%, i.e. well below the intrinsic X-ray flux variability of the stars and well below the uncertainty in the *ROSAT* and *Einstein* count rate to flux conversion factors. X-ray luminosity measurements for HD 33798 (V390 Aur) HD 117555 (FK Com), HD 141714 (δ CrB), HD 199178 (V1794 Cyg) and HD 223460 (HR 9024) were derived from the analysis of *XMM – Newton* spectra obtained in the 0.3–10 keV energy range (see Ref. in Table 1).

3. Analysis

3.1. Correlation between X-ray surface fluxes and rotation

The X-ray surface flux of the sample giants (see Table 2) were calculated from their X-ray luminosity and stellar radius. The results are plotted in Fig. 2 as a function of the rotation period. The dashed line describes the linear regression to the log–log plot. Its equation is given by:

$$\log(F_X) = (-1.0 \pm 0.3) \times \log(P) + (7.2 \pm 0.4) \quad (1)$$

where F_X is the X-ray surface flux in erg cm^{-2} s^{-1} and P is the rotational period in days. A good correlation ($r = -0.72$, $N = 12$) is obtained at a confidence level greater than 99%. Such a correlation does not appear in a log (L_X) vs. log ($v \sin i$) plot due to the spread in stellar radius and inclination angle among the sample stars. However, one star (ψ^3 Psc) deviates strongly from the linear fit. It is worth investigating whether a parameter other than rotation could be more constraining in determining the X-ray surface flux of the stars.

The correlation between magnetic activity and the onset of a convective envelope in cool stars suggests a relation to dynamo mechanisms (Parker 1977). Using this assumption Durney & Latour (1978) showed that the level of activity should be a function of the rotation period, P_{rot}, divided by a turnover convective time scale τ_c. The Rossby number ($R_o = P_{rot}/\tau_c$) is an important indicator in hydromagnetic dynamo theory that measures the extent to which rotation can induce both the helicity and differential rotation required for dynamo activity. The dependence of the X-ray luminosity relative to the bolometric luminosity on the Rossby number was confirmed for F5 through M5 main-sequence stars using both cluster and field stars (e.g. Patten & Simon 1996; Randich et al. 2000). This suggests that the Rossby number could be a better measure of "rotational effects" than the rotation period itself in determining the surface magnetic fluxes of intermediate-mass giants.

The variation of τ_c along the evolution of intermediate-mass stars has been studied using stellar evolution and stellar structure codes by several authors. Gilliland (1985) presented evolutionary tracks of convective turnover timescale for both zero-age main sequence and for stars evolved well off the main sequence. It was found afterwards that the peak in Rossby number should occur at the base of the giant branch, i.e. at a significantly cooler effective temperature than given by Gilliland (1985). This was corrected by Basri (1987) who adjusted the τ_c – $T_{\rm eff}$ distribution to reflect a cooler peak. Convective turnover times have also been estimated by Rucinski & Vandenberg (1986) for convective envelope structures computed for post main-sequence evolutionary phases. However, the above studies calculated the convection turnover time during the evolution off the main sequence of stars with 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 number of the sample stars are given in Table 2. Their surface fluxes are plotted in Fig. 2 (right) as a function of the Rossby number. The dashed line describes the linear regression to the log-log plot. Its equation is given by:

$$\log(F_{\rm X}) = (-1.2 \pm 0.3) \times \log(R_{\rm o}) + (5.2 \pm 0.3). \qquad (2)$$

Again, a good correlation ($r = -0.72$, $N = 12$) is obtained at a confidence level greater than 99.5%. This correlation between $\log(F_{\rm X})$ and the Rossby numbers calculated from turnover times derived by Gunn (1998) is slightly better than when using Rossby number derived from turnover time calculated by Rucinski & Vandenberg (1986) and even better than when using turnover time derived by Basri (1987). This suggests that the dispersion of the sample points around the best linear fit to the $\log(F_{\rm X})$ vs. log ($R_{\rm o}$) diagram could be reduced with $R_{\rm o}$ calculations tuned to the mass of each star. On the other hand, the present correlation study between the X-ray surface flux and the Rossby number is limited to a sample of stars with similar spectral types. Without the rotation period of single giants covering a broader range of spectral types, the present study does not provide conclusive evidence that the correlation between X-ray surface flux and the Rossby number is better than between $F_{\rm X}$ and the rotation period.

3.2. Empirical model of the X-ray luminosity evolution

In order to verify the relation between the X-ray surface flux and the Rossby numbers on a larger sample of giants at different evolutionary stages but with unknown rotation periods, I tried to parameterize the change in rotation rate during the evolution of intermediate-mass stars off the main sequence. G-type giants with 1.9 $M_\odot \leq M \leq 2.5\ M_\odot$ have A2 to A6 progenitors on the main sequence which are typically rapid rotators. Studies of the distribution of equatorial velocities in large samples of A-type dwarfs (Abt & Morrell 1995; Royer et al. 2002) show an average equatorial velocity of about 200 km s^{-1}. These studies also indicate that the 50 to 300 km s^{-1} equatorial velocity domain include most A2–A6 dwarfs that are neither metallic-line (Am) stars nor peculiar Ap stars.

These dwarfs evolve off the main sequence as A-type giants and rapidly traverse the F spectral type zone of the HR diagram. I established a first list of luminosity class III stars with spectral type A and F brighter than $V = 6.6$ from the list of Hauck (1986) and from the ROSAT all-sky survey catalogue of optically bright late-type giants and supergiants (Hünsch et al. 1998). From this initial list, I systematically rejected spectroscopic binaries known from the Bright Star Catalogue (Hoffleit & Warren 1991) and stars detected as variable in term of radial velocities by Künzli & North (1998). Parallax values, V magnitude and $B - V$ color indices were obtained from the Hipparcos catalogue (ESA 1997). Only stars with parallaxes greater that 4 milliarcsec were selected. Their effective temperatures were calculated from the $B - V$ color indices using the $T_{\rm eff}$ vs. $B - V$ conversion scale established by Flower (1996). Since all the stars are closer than 250 pc, no correction for reddening effect by interstellar absorption was applied. The absolute magnitude of each star was calculated from its V magnitude and parallax and converted into a stellar luminosity using the bolometric correction vs. effective temperature data of Flower (1996). Positions of the stars in the H-R diagram were compared with evolutionary tracks inferred from grids of stellar models with a near solar metallicity ($Z = 0.02$) provided by Schaller et al. (1992). I only selected A-F giants that occupy a region in the H-R diagram located between the evolutionary tracks of 1.8 $M_\odot$ and 2.5 $M_\odot$ stars. This list of A-F single field giants was complemented by a list of single G-K field giants brighter than $V = 6.75$ (Gondoin 1999) located between the same evolutionary tracks at cooler effective temperatures. Figure 3 (right) shows their projected rotation velocities (Hauck 1986; Künzli & North 1998) as a function of effective temperature. Figure 3 (right) also shows the equatorial velocity of the sample G stars with known rotation periods (black circles) calculated from their rotation period and stellar radius (see Table 1). A sharp decrease of rotation velocities is observed at about 5500 K that was reported previously (Gray 1981, 1982). It has been attributed either to a magneto-hydrodynamic braking due to stellar winds (Simon & Drake 1989; Gray 1989; Schrijver & Pols 1993) or to the expansion of the stars on the red giant branch and the rearrangement of angular momentum due to the increasing depth of the convection zones (Endal & Sofia 1978; Gray & Endal 1982). Recent studies confirmed that intermediate-mass stars retain most of their angular momentum during their evolution until mid-G spectral types. The change in rotation velocity then departs from specific angular momentum conservation of the surface layers as the stars evolve towards the bottom of the red giant branch (Gondoin 1999).

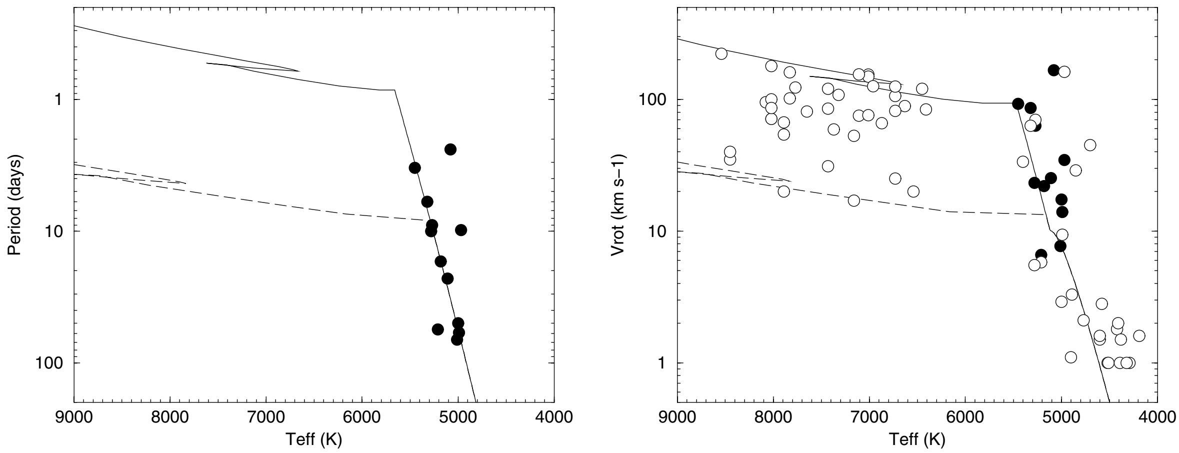

Fig. 3. Rotation period (*left*) and equatorial velocity (*right*) of the sample stars (black circles) as a function of effective temperature. The open circles in the right plot are the projected rotational velocities of A,F, G and K single field giants. The solid lines describe rotation evolution models for 2.5 $M_\odot$ (*lower curve*) and 2.0 $M_\odot$ stars (*upper curve*) with equatorial velocities of 50 and 300 km s^{-1}, respectively, on the main sequence (see text).

I calculated the equatorial velocity evolution of 2.5 $M_\odot$ and 2.0 $M_\odot$ giants using Schaller et al. (1992) evolutionary models and assuming angular momentum conservation and $v \sin i = 50$ and 300 km s^{-1}, respectively, on the main sequence. Comparisons with $v \sin i$ measurements show that angular momentum conservation alone cannot explain the decrease in rotational velocities for $T_{\rm eff} < 5500$ K. Hence, the increase of the rotation period beyond this point that may be induced by magneto-hydrodynamic braking or by a rearrangement of angular momentum was estimated from a parameterization of the sample stars period as a function of effective temperature (see Table 1). The resulting empirical models of rotation evolution are described in Fig. 3 for 2.5 $M_\odot$ (lower curve) and 2.0 $M_\odot$ stars (upper curve) with equatorial velocities of 50 and 300 km s^{-1}, respectively, on the main sequence. The rotation models were then used to estimate the Rossby numbers of the intermediate-mass stars during their evolution off the main sequence. Their X-ray luminosity was calculated from Eq. (2) assuming that the relation between the X-ray surface flux and the Rossby number found for G-type giants also hold for F and K-type giants. This assumes that the same dynamo process is responsible for the magnetic activity of these stars while there could be a smooth transition from one dynamo mode to another, or perhaps a changing mixture of different dynamo processes during the evolution of intermediate-mass giants from F to K spectral type (see Sect. 4). Figure 4 compares the predicted X-ray to bolometric luminosity ratio of the 2.0 $M_\odot$ and 2.5 $M_\odot$ reference stars with values derived from X-ray measurements (Maggio et al. 1990; Hünsch et al. 1998) performed on A, F, G and K giants with 1.8 $M_\odot \leq M \leq 3.5$ $M_\odot$. The predicted X-ray to bolometric luminosity ratio increases by four order of magnitudes between the mid-F and mid-G spectral types and then decreases sharply as the stars evolve on the red giant branch. The location of this maximum is consistent with the measurements (see Fig. 4). The X-ray surface flux dependence with the Rossby number parameterized in Eq. (2) can approximately account for the magnetic activity evolution trend of intermediate-mass cool giants beyond the line in the HR-diagram redward of which a convective envelope develops. Hotter stars emit X-rays based on non-related dynamo processes (Simon et al. 1997).

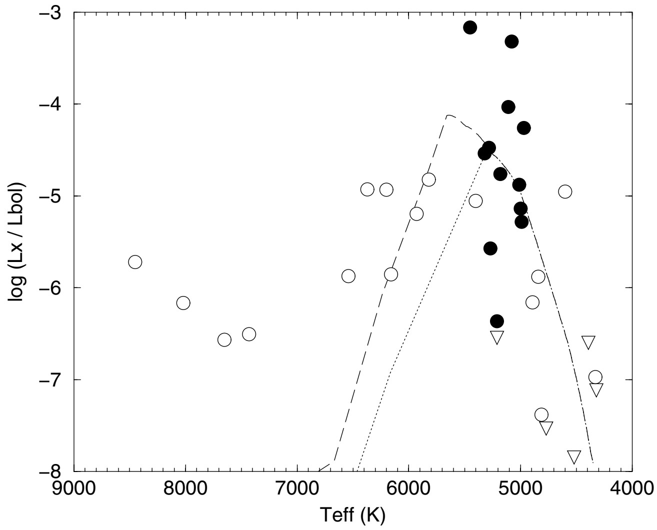

Fig. 4. X-ray to bolometric luminosity ratio as a function of effective temperature. The lines represent empirical models of $L_X/L_{\rm bol}$ evolution for 2.5 $M_\odot$ (dotted line) and 2.0 $M_\odot$ stars (dashed line) with equatorial velocity of 50 and 300 km s^{-1}, respectively, on the main sequence. A, F, G and K giants with masses included between 1.8 and 3.5 $M_\odot$ are represented by open circles. The black circles are the sample stars (see Table 1) and the triangles represent giants for which only upper limits of the X-ray luminosity are available.

4. Discussion

I found evidence that the X-ray surface flux F_X of intermediate-mass G giants is correlated with their rotation period P. This empirical activity-rotation relationship is described by $\log(F_X) = -\log(P) + 7.2$. A similar relation was reported by Walter & Bowyer (1981) from soft X-ray observations of

RSCVn systems. These authors show that the quiescent coronal activity, as measured by the ratio of the X-ray to bolometric flux, is directly proportional to the angular velocity Ω of the star with the active chromosphere in these systems. They noticed that the relation holds over two decades in Ω. For the period range from a few days up to 20 days, Schrijver & Zwaan (1991) also found that the relationship between coronal radiative losses and rotation periods in close binaries can be approximated by $\langle F_X \rangle \approx \Omega^{0.8\pm0.2}$. The binary stars used in both studies include main sequence stars, as well as subgiants and giants. It has been suggested that this linear relation is a consequence of a relation between stellar radius and orbital period in close binaries, larger stars typically being components of longer-period systems and being bolometrically brighter (Walter & Bowyer 1981; Rengarajan & Verma 1983; Majer et al. 1986). This explanation was however questioned by Dempsey et al. (1997). Obviously, it does not hold for the sample of single 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 approximately linearly 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 seem to be correlated with the presence of large starspots (Strassmeier 2002), it is likely that the linear increase of the X-ray surface flux with angular velocity mainly results 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 2005) 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 are preferably detected in rapidly rotating G giants. Hence, the rotation-activity connection in giants seems to results 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 et al. 2000; Pizzolato et al. 2003). In contrast, the present study of G giants suggests an approximately linear dependence of the X-ray surface flux with angular rotation velocity and no apparent saturation level (see Fig. 5). 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

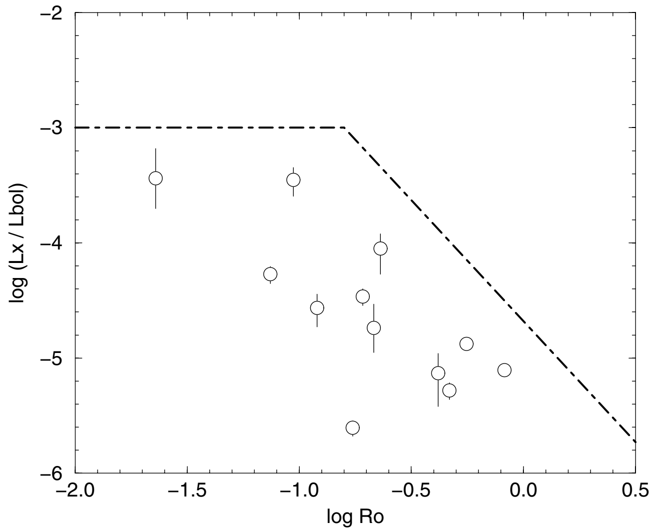

Fig. 5. X-ray to bolometric luminosity ratio as a function of Rossby number for the sample giants compared to the Randich et al. (2000) relation for cluster stars (dot-dashed line).

important implications for the dynamo generation of stellar magnetic fields on giants. When comparing partially convective stars to fully convective stars, the transition in mean activity level appears to be smooth, particularly for rapidly rotating main-sequence stars. According to Schrijver & Zwaan (2000), this suggests a smooth transition from one dynamo mode to another, or perhaps a changing mixture of three processes occuring side by side, i.e. the boundary-layer dynamo mode, the deep envelope dynamo mode and the turbulent dynamo mode. In Sun-like stars, the dynamo is likely dominated by a mode that depends on the existence of a boundary layer between the radiative interior and the convective envelope. As the convective envelope deepens, another mode may begin to dominate in which much of the dynamo action occurs in the deep interior but still relies on differential rotation. This mode could be dominant in G-giants that develop deep convection zones as they approach the bottom of the red giant branch. At later stages of evolution when rotation dies away, the decay of the large-scale dynamo apparently leaves at most a weak turbulent dynamo. Durney et al. (1993) argued that a transition to a turbulent dynamo that relies on the generation of a chaotic magnetic field throughout the convective envelope is possible with no need for differential rotation. However, using a model for global circulation in outer stellar convection zones, Kitchatinov & Rüdiger (1999) found that the differential rotation of giants is large and solar-like. The angular velocity increases strongly from pole to equator but varies only slightly with depth. In a further similarity, the diffusive times for the giants are almost the same as for the Sun. Hence, these authors concluded that the similarity in rotation laws implies a similar dynamo regime and that the luminosity class III giants behave magnetically as the Sun. One main difference between G giants and G dwarfs is the rapid evolution of the internal structure of giants. In particular, according to Stepien (1994), it is unlikely that the fast expansion of their convective zone leaves sufficient time to converge to a unified rotation-activity relation. The lower slope of the activity-rotation relationship for giants and the larger dispersion of the measurements around the best linear fit could be a consequence of this rapid evolution. Starting from a strong toroidal magnetic field generated by a dynamo in the overshoot layer below the convection envelope, Holzwarth & Schüssel (2001) considered the stability, dynamics and rise of magnetic flux tubes along evolutionary sequences of stellar models. They found that the flux loops become trapped in the stellar interior when the depth of the convective envelope exceeds about 80% of the stellar radius. These authors then suggested that flux trapping is the cause of the strong decline of stellar X-ray emission across the so-called "coronal dividing line". In the absence of a dynamo theory, and in view of the number of phenomena involved in the conversion of the generated field energy into radiative losses, it is difficult to identify processes that differ in intermediate-mass giants from what happens in main-sequence stars regarding the generation, evolution and transport of magnetic fields.

The analysis presented in this paper shows evidence for a correlation between the X-ray surface flux and the rotation period of G giants with similar evolutionary status. Confidence in the degree of correlation is slightly greater when using the Rossby number instead of the rotation period. The empirical relation between the X-ray surface flux $F_{\rm X}$ and $R_{\rm o}$ is given by $\log(F_{\rm X}) = -1.2 \times \log(R_{\rm o}) + 5.2$. I used this expression to estimate the X-ray luminosity evolution of intermediate mass giants assuming that these stars retain their angular momentum during their evolution until mid-G spectral types and that their rotation period increases afterwards with decreasing effective temperature as indicated by the sample stars. The results show an increase of the X-ray to bolometric luminosity ratio by about four order of magnitudes between the mid-F and mid-G spectral types followed by a sharp decrease as the stars evolve on the red giant branch. This trend is comparable to the temperature dependence of the X-ray to bolometric luminosity ratio observed on single field F, G and K giants. This supports the possible existence of a rotation-activity relation among intermediate-mass giants but does not provide conclusive evidence that the linear relationship between X-ray surface flux and Rossby number found for G stars also applies to F and K giants. This relation could be different for F and K giants if there is a transition in dynamo processes from e.g. a boundary layer dynamo in F-type giants to a deep envelope dynamo mode in G giants and a weak turbulent dynamo in K giants. Durney et al. (1981), Durney & Robinson (1982) and Robinson & Durney (1982) provided arguments that the dynamo number $N_{\rm d}$ is the relevant parameter describing dynamo efficiency. Making some assumptions about the form of α and Ω, Hartman & Noyes (1987) estimated that $N_{\rm d} \approx R_{\rm o}^{-2}$. However, Gunn et al. (1998) pointed out that this characterization of the dynamo effect suffers from several fundamental assumptions. In particular, calculations of $\tau_{\rm c}$ 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 dredging up of angular momentum from the core of giants to their envelope may alter the angular velocity-depth profile (Pinsonneault et al. 1989; Simon & Drake 1989). Hence, the Rossby number may not be the appropriate parameter to describe the dynamo action in giants. It is not excluded that the correlation found between the X-ray surface flux and the Rossby number of G giants is just another expression of the relation between their X-ray surface flux and their rotation period which cannot be generalized to F and K giants in different evolutionary stages.

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