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# X-ray activity and evolutionary status of late-type giants

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**Abstract.** We study the evolution of stellar activity in a volume-limited sample of single giants within 35 pc distance from the Sun as measured by the amount of soft X-ray emission. This sample of 36 stars is assumed to be complete for absolute magnitude $M_{\rm V} \lesssim 3.0$ and for X-ray luminosities $L_{\rm x} \gtrsim 1.5 \times 10^{28}$ erg s$^{-1}$. We use ROSAT data to determine stellar activity, *Hipparcos* parallaxes to place stars into the HRD, and the empirically well tested evolutionary code by P. Eggleton (see Pols et al. 1998) together with Kurucz colour tables to derive individual masses and ages. Based on more X-ray data and much improved HR diagram positions, we confirm the suggestion by Hünsch & Schröder (1996), that stellar activity evolution is strongly coupled to stellar mass and that it is a very common feature among giants with $M \gtrsim 1.3 M_\odot$.

Most pointed ROSAT observations on the giant branch (GB) and also in the "K giant clump" (with masses betweeen about 1.3 and 2.3 $M_\odot$) resulted in detections at typically solar levels. This indicates that magnetic activity mostly (for $M \gtrsim 1.3 M_\odot$) even survives the He-flash and, possibly, also persists on the asymptotic giant branch. The more massive stars ($\gtrsim 3 M_\odot$) show even a larger amount of activity in their advanced evolutionary stages (blue loop giants).

**Key words:** stars: activity – stars: coronae – stars: evolution – Hertzsprung-Russel (HR) diagram – stars: late-type – solar neighbourhood

## 1. Introduction

X-ray emission is considered as an unambiguous indicator of stellar activity. Often highly variable, it is believed to come from hot ($\gtrsim 10^6$ K) plasma confined by magnetic fields. The origin of such magnetic fields is generally attributed to a stellar dynamo, which results from the interaction between rotational and convective motions.

Stars away from the main sequence (MS) are especially interesting for studying the evolution of stellar activity, since different masses (and thus ages) and evolutionary histories act together. If we find out, how long – and under which evolutionary circumstances – stellar activity can last, we will learn more about the nature of the driving dynamo process(es) and its energy source.

For late-type MS stars, relations between age, rotation and stellar activity (i.e. coronal X-ray emission) are well established from observations of stellar clusters – see, e.g., Caillault (1996). However, the situation becomes more complicated in the case of late-type giant stellar activity. This is not astonishing, considering the complex inner structure and the generally shorter evolutionary time scales of evolved stars. Moreover, previous studies of giants were severely hampered by inaccurate masses and ages, resulting from the poorly known distances. Only recently, the *Hipparcos* parallaxes have provided much improved distances for many evolved stars. This is an especially important point since evolutionary tracks of giants of very different mass come very close or even cross each other in the HR diagram.

Although rotational velocities of the photospheres of evolved, expanded stars are generally much lower and more difficult to obtain, Gray (1989) was able to present clear evidence of strong rotational braking at spectral types G 0 to G 3: Single giants appear to lose their angular momentum by magnetic braking while crossing the Hertzsprung gap. Nevertheless, various forms of activity are observed for far more evolved giants.

An unambiguous activity indicator for giants and cool stars in general is coronal X-ray emission, since at low gravities hot coronal plasma necessitates some confining agent – presumably magnetic fields. Early X-ray observations suggested an "X-ray dividing line" (XDL) in the HR diagram beyond which, on its low temperature side, there would be no coronae (Ayres et al. 1981). For a long time this was well accepted as a matter of fact, since it fitted into the general concept of mutual exclusion of hot stellar coronae and massive cool winds, as originally proposed by Linsky & Haisch (1979). The XDL was also confirmed by the first inspection of the ROSAT all-sky survey (RASS), on the basis of a flux-limited sample of bright late-type giants (Haisch et al. 1992).

With deep pointed ROSAT observations, however, a substancial number of cooler giants, which are known to have cool winds (the so-called "hybrid stars", Reimers et al. 1996), were detected as X-ray sources. Furthermore, Hünsch et al. (1998b)

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present evidence that even some M-type giants might be genuine X-ray sources. A recently finalized catalogue (Hünsch et al. 1998a) of 450 detected sources, all identified with late-type evolved stars in the reprocessed and more sensitive RASS version, contains 26 entries with $B-V \geq 1.3$. These findings and other recent evidence (e.g., Ayres et al. 1997) suggest that stellar activity can survive, at least in some cases, into very late evolutionary stages.

The scope of this paper is to provide a clearer empirical picture of the evolution of stellar activity by relating giant coronal X-ray detections to the evolutionary status and mass. Specifically, we wish to continue the work started by Hünsch & Schröder (1996) but utilize the considerably improved, reprocessed RASS data, more ROSAT pointings, and, in particular, the much better *Hipparcos* parallaxes, since old parallaxes often yielded underestimated distances and luminosities.

## 2. The stellar sample

In this paper, we study all 36 single giant stars with $M_V < 3.0$ (shown in Fig. 1) from a volume limited sample, $d < 35$ pc, within which ROSAT is capable of detecting most coronae down to approximately solar X-ray luminosity. We selected the giants from the Bright Star catalogue (BSC; Hoffleit & Warren 1991) according to their *Hipparcos*-measured distances, also considering those giants of which their 1 $\sigma$ parallax error reaches into the 35 pc distance limit. Furthermore, we excluded 20 stars with obvious evidence for binarity, i.e., visual binaries with less than 60 arcseconds separation, spectroscopic binaries and composite-spectrum stars.

Our sample of giant stars is complete within its distance and luminosity limits. In other words, *all* single giants within a distance of 35 pc are included (see Table 1). Furthermore, their HRD positions (see Fig. 1) are all well defined – i.e., the *Hipparcos* parallax errors result in a typical uncertainty of 0.03 to 0.06 in $M_V$.

The binaries were excluded from our sample for two reasons: A lot of the closer binaries shows X-ray emission and other forms of stellar activity that is related to the binary nature and is therefore not typical of a single star at the same evolutionary stage. The responsible mechanism, transfer of orbital into rotational energy by tidal interaction, becomes insignificant for wide binaries, but it is difficult to give, in general, a safe limit. Furthermore, many HR diagram positions of individual binary components are confusingly less accurate, and it is also often not clear which one the X-ray source is.

## 3. The stellar evolution models

In order to link HR diagram positions with certain evolutionary stages, we use the fast and empirically well tested evolutionary code of P.P. Eggleton et al., which uses a self-adapting mesh and solves structure and composition simultaneously (Eggleton 1971, 1972). Convective mixing and semiconvection are treated as a diffusion process, while standard mixing-length theory is used to describe the heat transport. For the recent updates on opacities, nuclear rates and the equation of state see Pols et al. (1995) and references therein. The overshoot prescription has been described by Schröder & Eggleton (1996).

The two convection parameters (i.e., $\alpha$ = mixing length over pressure scale height, and $\delta_{\rm ov}$ for the extended mixing or "overshooting") have been calibrated in an empirical way. With an overshooting length of 0.24 to 0.32 pressure scale heights (for $M_* > 2.5 M_\odot$, increasing with mass), the resulting evolutionary tracks are precisely consistent with well-studied eclipsing binaries which include pairs with two MS components (Pols et al. 1997) and systems with a giant primary (Schröder et al. 1997). Further tests employ cluster isochrones (Pols et al. 1998) and sensitive star counts in characteristic fields in the local HR diagram (Schröder 1998). They reveal an onset of overshooting around 1.7 $M_\odot$. The evolutionary tracks used here are therefore taken from Schröder (1998), see grid 3 therein, and are based on that empirical calibration.

A critical step is the conversion of the theoretical HR diagram quantities $T_{\rm eff}$ and $\log L$ into the classical observational quantities $B-V$ and $M_{\rm V}$. We used the colour (and B.C.) tables computed by Kurucz (1991) for solar abundances. These agree fairly well with the colours of the few K and M-type giants, for which empirical $T_{\rm eff}$ exist (Di Benedetto 1993), within the uncertainties for their derived log $g$ values. We estimate those conversion-related uncertainties in $B-V$ and $M_{\rm V}$ to be of the order of 0.05, and about 0.1 towards the red end.

## 4. The giant coronal X-ray detections within 35 pc

The X-ray luminosities used in this work (see Table 1) have been taken from the catalogues published by Hünsch et al. (1998a) for the giants (luminosity classes I to III-IV, $d < 35$pc) and Hünsch et al. (1998c) for subgiants, as far as RASS detections are concerned. Values from ROSAT pointed observations have been taken from Hünsch et al. (1996), now being corrected for the actual *Hipparcos* distances.

Given the typical detection threshold of the RASS data of 0.015 cts s$^{-1}$, corresponding to $f_{\rm x} \approx 1 \times 10^{-13}$ erg cm$^{-2}$s$^{-1}$ for soft coronal sources, the limiting X-ray luminosity at 35 pc is $L_{\rm x} \approx 1.5 \times 10^{28}$ erg s$^{-1}$. This is about an order of magnitude larger than the average solar X-ray luminosity (cf., e.g., Haisch & Schmitt 1996).

In order to improve sensitivity at the solar activity level, as required by the generally lower X-ray emission of late-type giants, we included all deep pointed ROSAT observations – see Fig. 1. Most of them have already been reported by Hünsch et al. (1996), except $\epsilon$ Sco and $\beta$ Oph (which then failed the distance criterion of $d < 25$ pc). Here, we had to adjust the X-ray luminosities according to the new *Hipparcos*-based distances, but the general picture has not changed – i.e., most giant X-ray luminosities are comparable with the Sun. The achievable threshold at 35 pc distance in a, say, 10 ksec long ROSAT PSPC pointing is $\approx 2 \times 10^{27}$ erg s$^{-1}$.

The comparison of stellar HR diagram position with well-tested evolutionary tracks yields the desired evolutionary status and an estimate of the mass for most of the X-ray detected and

**Table 1.** HRD-positions and X-ray luminosities (given in units of $10^{27}$erg sec$^{-1}$) of the volume-limited sample of 36 giants discussed in the text and plotted in Fig. 1. Detections from ROSAT pointed observations are indicated by a 'p'.

| HR | Star | $B-V$ | $d$/pc | $M_V$ | Sp. Type | $L_x$ | |
|---|---|---|---|---|---|---|---|
| 188 | $\beta$ Cet | 1.02 | 29.4 | -0.30 | G9.5III | 2771.0 | |
| 402 | $\theta$ Cet | 1.06 | 35.1 | 0.87 | K0III-IIIb | $<21.2$ | |
| 1743 | $o$ Col | 1.00 | 33.7 | 2.19 | K0IV | – | |
| 1907 | $\phi^2$ Ori | 0.95 | 35.6 | 1.33 | K0IIIb | – | |
| 2035 | $\delta$ Lep | 0.99 | 34.4 | 1.13 | K0III | – | |
| 2040 | $\beta$ Col | 1.16 | 26.4 | 1.02 | K2III | – | |
| 2102 | – | 1.05 | 27.3 | 2.47 | K1III-IV | 8.7 | |
| 2429 | $\nu^2$ CMa | 1.06 | 19.8 | 2.46 | K1III | – | |
| 2990 | $\beta$ Gem | 1.00 | 10.3 | 1.07 | K0IIIb | 4.4 | p |
| 3347 | $\beta$ Vol | 1.13 | 33.1 | 1.17 | K1III | $<9.4$ | p |
| 3771 | 24 UMa | 0.77 | 32.4 | 2.01 | G4III-IV | 2267.3 | |
| 4247 | 46 LMi | 1.04 | 29.9 | 1.45 | K0+III-IV | – | |
| 4932 | $\epsilon$ Vir | 0.94 | 31.3 | 0.35 | G8IIIab | 115.8 | |
| 5287 | $\pi$ Hya | 1.12 | 31.1 | 0.81 | K2-III-IIIb | 3.5: | p |
| 5288 | $\theta$ Cen | 1.01 | 18.7 | 0.70 | K0-IIIb | 1.4 | p |
| 5340 | $\alpha$ Boo | 1.23 | 11.3 | -0.30 | K1.5III | $<0.06$ | p |
| 5649 | $\zeta$ Lup | 0.92 | 35.6 | 0.65 | G8III | 1.9 | p |
| 5744 | $\iota$ Dra | 1.16 | 31.3 | 0.81 | K2III | 3.2 | p |
| 5777 | 37 Lib | 1.01 | 29.0 | 2.31 | K1III-IV | – | |
| 5854 | $\alpha$ Ser | 1.17 | 22.5 | 0.89 | K2IIIb | 2.0 | p |
| 5901 | $\kappa$ CrB | 1.00 | 31.1 | 2.35 | K1IVa | – | |
| 6075 | $\epsilon$ Oph | 0.96 | 33.0 | 0.65 | G9.5IIIb | 3.1 | p |
| 6220 | $\eta$ Her | 0.92 | 34.4 | 0.85 | G7.5IIIb | 56.0 | |
| 6241 | $\epsilon$ Sco | 1.15 | 20.1 | 0.78 | K2.5III | 1.6 | p |
| 6299 | $\kappa$ Oph | 1.15 | 26.3 | 1.10 | K2III | – | |
| 6603 | $\beta$ Oph | 1.16 | 25.1 | 0.77 | K2III | 1.6 | p |
| 6688 | $\xi$ Dra | 1.18 | 34.2 | 1.08 | K2-III | – | |
| 6869 | $\eta$ Ser | 0.94 | 18.9 | 1.87 | K0III-IV | 1.2 | p |
| 6913 | $\lambda$ Sgr | 1.04 | 23.7 | 0.94 | K1+IIIb | 1.2 | p |
| 7310 | $\delta$ Dra | 1.00 | 30.7 | 0.63 | G9III | – | |
| 7429 | $\mu$ Aql | 1.17 | 33.9 | 1.80 | K3-IIIb | – | |
| 7869 | $\alpha$ Ind | 1.00 | 31.0 | 0.65 | K0III | 1.5 | p |
| 7896 | $\kappa$ Del | 0.72 | 30.0 | 2.66 | G5IV+K2IV | 43.7 | |
| 8684 | $\mu$ Peg | 0.93 | 35.8 | 0.71 | G8III | 1.0 | p |
| 8694 | $\iota$ Cep | 1.05 | 35.4 | 1.05 | K0-III | $<8.2$ | |
| 8974 | $\gamma$ Cep | 1.03 | 13.8 | 2.51 | K1III-IV | 1.5 | |

non-detected stars. Characteristic evolutionary tracks are therefore plotted in Fig. 1 for a direct comparison with the occurence of X-ray emission.

We find that the stars in the "K giant clump" are mostly invisible in the RASS but *all* deep ROSAT pointings have lead to detections – typically at a few $10^{27}$ erg s$^{-1}$ (see Fig. 1 and Hünsch et al. 1996). The same is true for the lower mass ($<1.6M_\odot$) stars found on the foot of the GB. The few remaining non-detections in the K giant clump are all from giants near the distance limit of our sample.

The mostly He-burning giants in and near the clump could, potentially, be contaminated with more massive first-time gap crossers. The evolutionary time-scales suggest that there is only one such first-time gap crossing star in our sample at best. Consequently, the detections within the K giant clump must almost entirely relate to post-GB, He-burning giants.

As derived by Schröder (1998) from a synthetic HR diagram, based on a solar neighbourhood stellar mass function (using *Hipparcos*-data) and stellar evolutionary tracks, about 85% (statistically) of any giants found in the K giant clump ($0.95 < B-V < 1.2$ and $0.5 < M_{\rm V} < 1.2$) should, according to their mass, have undergone a He-flash. The more massive stars, including those which did not undergo a helium flash, prevailingly populate the left half of the K giant clump, the less massive stars the right half. Hence, many detections stem from stellar activity that survived even the He-flash.

With regard to the few giants of high X-ray luminosity, we note that all have passed the onset of convection (between spectral type F0 and G0, see Fig. 18.19 of Gray 1992) very recently in their evolutionary history, only some $10^7$yrs ago. Either, they have a significantly higher mass ($\beta$ Cet (e in Fig. 1): 3.2 $M_\odot$, $\epsilon$ Vir (d): 2.8 $M_\odot$, $\eta$ Her (c): 2.5 $M_\odot$) and their whole GB-

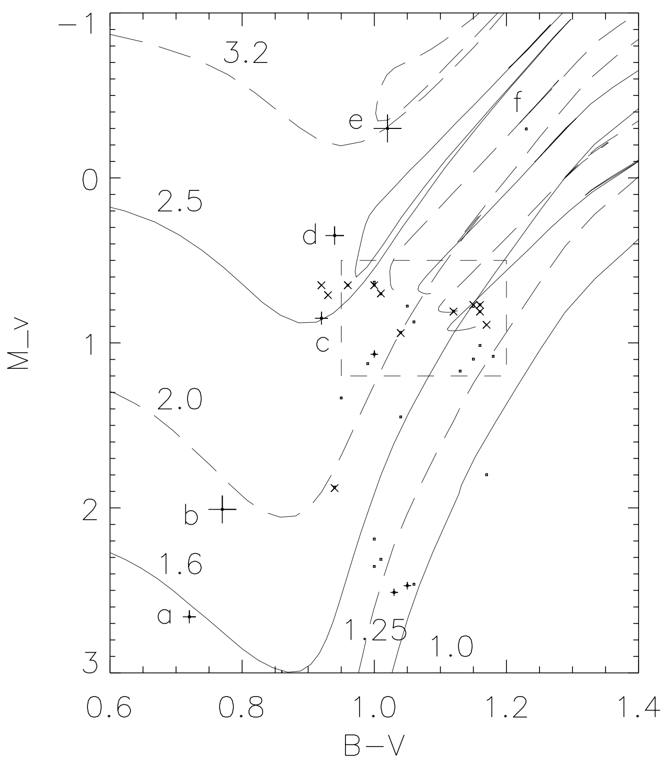


**Fig. 1.** ROSAT detections of late-type giants and evolutionary tracks. The "K giant clump" region is indicated and stars of interest are labeled, i.e., $\kappa$ Del (a), 24 UMa (b), $\eta$ Her (c), $\epsilon$ Vir (d), $\beta$ Cet (e) and $\alpha$ Boo (f), and are discussed in the text. Plus symbols are RASS detections, crosses are for pointed observations, and the symbol sizes indicate X-ray luminosity – dots are RASS non-detections (no pointed observations available, except f).

evolution is that short. Or they have not yet arrived on the GB, such as the genuine gap-crosser 24 UMa (b in Fig. 1, 1.9 $M_\odot$). $\kappa$ Del (a), another gap-crosser, but a former F-type MS star of only 1.6 $M_\odot$, is also a conspicuous X-ray source.

## 5. Discussion and conclusion

A problem worth further consideration is the completeness of our sample. As already stated above, the input sample of bright stars can be regarded as complete down to absolute magnitude $M_{\rm V} \lesssim 3.5$, but the completeness of the X-ray detections is a more difficult matter. The typical RASS detection limit corresponds to $L_{\rm x} \approx 1.5 \times 10^{28}$ erg s$^{-1}$ at a distance of $d = 35$ pc and we know from Hünsch et al. (1996) that most "clump" giants have X-ray luminosities below $10^{28}$ erg s$^{-1}$. Therefore, many giants remain invisible in the RASS but all pointed observations have yielded detections – with the exception of the AGB giant $\alpha$ Boo (Ayres et al. 1991), which is metal-deficient (Lambert & Ries 1981) and therefore of much lower mass and older than what the evolutionary tracks for solar abundances in Fig. 1 would suggest.

It would be interesting to complete the deep pointings for all RASS non-detections in our sample, especially on the right side of the K giant clump and in the foot of the GB. That would give us an idea about the occurence of really low X-ray luminosities ($< 10^{27}$ erg s$^{-1}$). Earlier findings of apparently inactive giants on the right side of the old XDL vanished, because their luminosities, based on pre-*Hipparcos* parallaxes, had been grossly underestimated.

Our results suggest that a crucial point in the evolution of stellar activity is the actual time spent since a star has developed outer convection zones and thus stellar activity. This depends on the stellar mass: if a star has already had a large convective envelope during the long-lasting MS stage (i.e., stars with $M \lesssim 1.3 M_\odot$), then activity in the giant stage is weak at best. Larger stellar masses lead to a late (post-MS) onset of convection and stellar activity. Any such giants must have started stellar activity only recently in their evolutionary history and consequently show X-ray luminous coronae. This is in good agreement with the idea that magnetic braking and angular momentum loss is responsible for the exhaustion of stellar activity – except that stellar activity commonly survives even into post-GB evolution.

Basically the same picture has been suggested in an earlier paper (Hünsch & Schröder 1996). Now, however, it is based on more and better X-ray data and a much improved linkage between position in the HR diagram and corresponding stellar evolutionary state. The only complication arises from an individual degree of stellar activity, apparently already non-uniform from the beginning.

At least for the MS, recent measurements support the idea of magnetic braking and its dependence on a convective envelope: Wolff & Simon (1997) find essentially no angular momentum loss on the MS for stars with $M > 1.6 M_\odot$, while the braking time-scales for MS stars with $M < 1.3 M_\odot$ are at most a few hundred million years (i.e., the Hyades age). For stars of masses inbetween, the MS braking time-scales are much longer (i.e., $> 1$ Gyr), not enough to spin-down the stars.

As pointed out before, matters become more complicated with the evolution into the giant region: The observable stellar rotation (and apparent angular momentum, if rigid rotation is assumed) drops already at a vertical line in the HRD around spectral Type G3 (Gray 1989), while stellar activity is found with much more evolved giants. Therefore, Gray (1991) suggested that activity-related magnetic braking of giants could consume angular momentum which would be stored in their non-convective cores, while the convective outer layers could well be seen rotating slowly. Any post-GB stellar activity, however, would then have to live of very little angular momentum: The non-convective stellar cores become very small at the top of the GB, which acts as a bottle-neck for such an angular momentum preservation mechanism.

Hence, the here presented clear evidence for post-GB stellar activity as a quite common phenomenon provides an interesting challenge for our present theoretical understanding and stellar dynamo models. Meanwhile, further deep X-ray pointings in combination with more observations of other activity indicators and rotational velocities are needed to derive a more complete empirical picture of late-type giant activity.

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