Prospective study of the coronae of G-K giants using XMM

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ABSTRACT

I have combined spectrally determined effective temperatures with recently available *Hipparcos* magnitude and parallaxes to position nearby single giants in the HR diagram and to estimate their masses. Analysis of published X-ray luminosities, rotational velocities and lithium abundances suggest that (i) an X-ray dividing line (XDL) exists at spectral type K1 only for the most massive giants (M $\geq 2.5 M\odot$), (ii) the XDL occurs near the knee at the bottom of the red giant branch (RGB) where the rotational velocities of these stars are minimum, (iii) lithium is mostly found among massive G giants and its abundance decreases on the right side of the XDL. These results reinforce the hypothesis that rotational braking induced by a deepening of the outer convection zone inhibits the generation of magnetic fields at the bottom of the RGB on massive giants which have fast rotating main sequence A and B progenitors without outer convection zone. Conversely, solar-type activity weakens earlier in the evolution of lower mass stars. The deepening of the outer convective envelope and the decreasing gravity of massive giants as they evolve up the RGB clearly affect the structure of their coronae and could explain the XDL. The XMM mission payload is well suited to study this drastic physical change using high spectral resolution on nearby active giants and high throughput on the low X-ray luminosity side of the XDL.

1. Introduction

One major topic of stellar activity is to explore how solar phenomena, and especially magnetic fields, depend on stellar parameters such as rotation rate, mass, and age. One magnetic field diagnostic for cool stars is coronal X-ray emission. The yellow and red giants form a very valuable class of stars for studying independently effects resulting from the variation of stellar parameters which are otherwise closely related for main sequence stars (Gondoin et al. 1987). Specially, a transition among late type giants from hot coronae and transition regions to cool winds is indicated by various dividing lines in the HR diagram. These include the X-ray dividing line (Ayres et al. 1981) which lie in the HR diagram around spectral type K1. Also, rotation velocities measurements (Gray 1989) indicate a strong rotational braking. At the present time no conclusive connection has been established between these two discontinuities, essentially because X-ray fluxes and rotation rates have been measured on different samples of giants with unprecisely known masses and evolutionary status. The recent availability of stellar parallaxes provided by the *Hipparcos* star catalogue (ESA 1997) enables an accurate determination of the positions of single field giants into a theoretical HR diagram and a reliable estimate of their masses. The present study combines these new astrometric data with previously published X-ray fluxes, rotational velocities and lithium abundances in order to provide a revised insight on the connection between activity, rotation and convection during the evolution of cool giants. Section 2 describes the selected sample and its position in the HR diagram. Section 3 is a survey of published lithium abundances, rotational velocities and X-ray fluxes. The effect of mass on the evolution of solar-type activity along the giant branch is discussed in section 4 and prospective contributions of the ESA XMM mission are presented.

2. Sample selection

A first list of candidate single G-K giants was established using the sample of Haisch (Haisch et al. 1990) and the sample of Maggio (Maggio et al. 1990). From these two samples, I extracted all luminosity class III stars of spectral type G and K and systematically rejected visual and spectroscopic binaries. This initial sample was complemented by an extraction of single G and K stars from a list of 144 giants with accurate rotational velocities measured by de Medeiros & Mayor (1995). Parallax values, V magnitude, B-V and V-I color indices have been obtained from the *Hipparcos* catalog for 96 stars. Spectral type, effective temperature and gravity of 59 stars of this initial sample were found in the Catalogue of [Fe/H] determination from Cayrel de Strobel (1996). The spectrally determined effective temperatures of this catalogue were combined with the B-V and V-I color indices to estimate the effective temperature of the remaining giants. The absolute magnitude of all giants were calculated from the V magnitude and parallaxes given in the *Hipparcos* catalogue. The stellar luminosities were derived from the absolute magnitudes using the bolometric correction vs effective temperature data of Flower (1996). Figure 1 shows the positions of the sample giants in the HR diagram. Evolutionary tracks have been ploted as infered from grids of stellar models provided by G. Schaller et al. (1992). Candidate FK Comae type stars are also represented in this diagram. The mass of each giant was estimated from its position with respect to theoretical evolutionary tracks assuming a first crossing of the HR diagram. The sample was divided in three groups of giants according to stellar masses. These are the low mass ($1\ M\odot \leq \mathrm{M} < 2\ M\odot$), the intermediate mass ($2\ M\odot \leq \mathrm{M} < 2.5\ M\odot$) and the high mass group ($2.5\ M\odot \leq \mathrm{M} < 5\ M\odot$). Each group contains approximately the same number of stars.

3. Observational data survey

3.1. Lithium abundances

Li abundances of 12 of the sample stars have been found in the Brown et al. (1989) catalogue, 8 of which have masses $\geq 2.5 M\odot$. Upper Li detection limit have been found for an additional

26 stars of which 21 have masses $< 2.5M\odot$. Significant Li abundance has therefore mainly been found on massive giants and rarely detected on low mass (M<$2M\odot$) giants. This indicates that Li is more abundant on cool giants that have evolved from A and late B main-sequence progenitors without outer convection zones. These stars should have not depleted their lithium while on the main sequence and may not have enough time for sufficient convective mixing during their rapid evolution accross the Herzsprung gap (Fekel et al. 1987). On the contrary, lithium is most likely depleted in the outer-most convective layers of a low mass star maybe just as the star move off the main sequence (Richer & Michaud 1993).

Mass-dependant Li abundance could explain why a large number of cool chromospherically active giants show excess Li abundance with respect to typical inactive stars of the same spectral type (Pallavicini et al. 1992). Indeed, chromospherically active giants of the present sample are mainly found among $\geq 2.5M\odot$ stars most likely because of their higher rotation velocities. The hypothesis that Li is mass dependant on giants also explain that fast spinning giants do not completely lose Li by the time they reach B-V = 1.28 while slow rotators already show a drop in Li between B-V = 0.45 and 0.60 (Wallerstein et al. 1994). Again, fast spining G and K giants are in average more massive than slow rotating ones of the same spectral type. Their Li excess is most likely the results of their evolution from main-sequence A and late B progenitors rather than a consequence of their high rotation rate.

Among the sample stars with M$\geq 2.5M\odot$, Li abundance seems to decrease for effective temperature cooler than T_{eff}=4800 K, i.e as the stars ascend the RGB. Following the classical first dredge-up theory (Iben 1967), this decay could be the consequence of the important deepening of the outer convective zone which mixes a significant fraction of the star mass. Lithium would then be depleted on the K giants surface due to this convective mixing with internal material devoid of this element, or through direct Li destruction by inward transport.

3.2. Rotation velocities

Accurate *v sin(i)* measurements obtained with CORAVEL by de Medeiros and Major (1995) or by Gray (1989) have been found for 66 stars of the sample. The CORAVEL *v sin(i)* are precise to about 1 km/s. They are ploted in figure 2 as a function of T_{eff} for different mass ranges. Massive M$\geq 2.5M\odot$ giants exhibit a minimum in projected rotation velocities around T_{eff}=4800 K. The sharp decrease in the rotation rate coincides with the strong deepening of the convection zone at the bottom of the RGB. This is a strong support for the conclusion that the spin-down of massive giants around spectral type K1 is due to mixing (Bohm-Vitense 1992). Figure 2 also shows that projected rotational velocities slightly increase for $T_{eff} <$ 4800K as the stars ascend the RGB. This constitutes a strong argument against magnetic braking as an alternative explanation (Gray 1989) and reinforces the hypothesis of angular momentum redistribution as the most likely cause of the rotation spin-down of massive giants. Increasing rotation velocities towards $T_{eff} <$ 4800K could be due to the expansion of the outer enveloppes of giants as they evolve up the RGB.

The outer enveloppes of giants, because of their low mass, do not carry angular momentum so that equatorial velocities are expected to scale with radii when the stars ascend the RGB.

Low mass and intermediate mass stars have in average lower rotation velocities while FK Comae candidates have the highest *v sin(i)*. These correlate well with their X-ray luminosities.

3.3. X-ray luminosities

Einstein X-ray fluxes from A. Maggio et al. (1990) were found for 10 giants of the sample. Count rates of additional sample stars were extracted from the ROSAT source catalogue (Huensch et al. 1998). These count rates were converted into X-ray fluxes using an energy conversion factor of 4.10^{-12} ergs cts^{-1} cm^{-2}. I calculated the X-ray luminosities (L_X) of all X-ray detected stars from the *Hipparcos* parallaxes. The results are presented in figure 3 as a function of T_{eff} for different mass ranges. Stars which have been observed several times often indicate an X-ray emission variability of a factor of two to three. The FK comae stars, UZ Lib excepted, have luminosities close or above 10^{31} erg/s. Only three giants have $L_X \geq 10^{30}$ erg/s of which two (β Cet and HD 73974) have the highest *v sin(i)* of the sample. These two rapid rotating giants have masses of about 3 $M\odot$. X-ray emission has been detected mainly on massive M$\geq$2.5$M\odot$ giants which have in average higher rotational velocities. Only few ROSAT detection of stars from the sample are reported at $L_X < 10^{28}$ erg/s (Schroeder et al. 1998). It is worth to note that most of them have low mass (M<2$M\odot$) and some are located on the right side of the XDL. Upper limits of X-ray luminosities measured with Einstein (Maggio et al. 1990) are indicated in figure 3 showing a transition to luminosity lower than 10^{29} erg/s at an effective temperature of 4700 K exclusively for $\geq 2.5M\odot$ stars. This corroborates the existence of the XDL around spectral type K1, but only for massive giants. Another important result of this study is that the XDL is located at $T_{eff} = 4800$ K where rotation velocities are minimum. This suggests that the decay of coronal X-ray emission after spectral type K1 is closely related to the spin-down of $\geq 2.5M\odot$ giants at the bottom of the RGB.

4. Discussion

The mass estimate of the sample giants assume a first crossing of the HR diagram and no extinction of their visual magnitude. Within the limit of these hypothesis, the effective temperature dependance of X-ray emission, rotation velocities and lithium abundances among $\geq$2.5$M\odot$ G-K giants can be explained in term of stellar evolution as follows. These stars have A and late B type progenitors on the main sequence which have no outer convection zones and which are usually rapid rotators. They lose little angular momentum during their dwarf phase. Only as they evolve through the Herzsprung gap, in the shell hydrogen burning stage, do they develop outer convection zones. The combination of rapid rotation with convection induces a large degree of magnetic activity on the basis of the standard dynamo theory. In the Sun, both chromospheric CaII and coronal X-ray emission are known to be well correlated with surface magnetic fields. As a results $\geq 2.5 M\odot$ giants crossing the Hersprung gap are strong CaII and X-ray emitters. Rapidly rotating, chromospherically active stars classified as FK Comae could be in that short stage of evolution. As the giants approach the bottom of the RGB, a strong rotational decay occur due to angular momentum redistribution induced by a strong deepening of the outer convection zone. This rotational breaking then affect the magnetic activity of these stars as they evolve up the RGB. Although this spin-down likely explains the existence of an XDL among $\geq 2.5 M\odot$ giants, the nature of the associated structural change of the giants coronae and the way it affects their X-ray emission are still to be determined.

Gilliland (1985) indicated that the spin-down process has the effect of increasing the Rossby number, and hence leads to a decrease in classical, helicity related, dynamo-driven activity. Rosner et al. (1995) remarked that this suppression of a large-scale dynamo needs not imply the suppression of magnetic field production at small scales, driven by the turbulent motions in the convection zones of the giants. They rather suggest that a large scale organized surface magnetic flux emergence normally associated with stellar activity disappears, and is replaced by small-scale magnetic flux emergence arising from weak seed field placed in turbulent convection zones. The atmosphere of giants on the red side of the XDL would then become largely open on large spatial scale. Closed structure could remain if their spatial scale falls below the atmosphere's pressure scale height (Antiochos et al. 1986). These remaining X-ray emitting loops would become cool and the open-field regions may not be able to retain a hot coronal plasma due to the decreasing gravity of giants as they evolved up the RGB. The coronae emission of giants would then be shifted towards longer wavelength thus explaining the XDL.

High resolution spectra provided by the two XMM reflection grating spectrometers RGS will provide measurements of plasma temperatures, electron densities, abundances and heating rates on a significant number of nearby X-ray luminous giants. These data will help to determine the extent to which the solar corona model apply to giants that are more active, have lower gravities, cooler effective temperatures and higher rotation rates. As an example, figure 4 shows a simulated RGS spectrum of the active giant β Ceti after a 70 ksec exposure assuming a two discrete temperature model (Maggio et al. 1998). Measured RGS spectra of nearby active giants will permit to refine such models and to relate them to physical processes in the coronae of X-ray luminous giants. On the other side of the XDL, the large throughput of the XMM telescopes will enable to search for the faint coronae of K giants and to perform spectroscopy on the brightest ones using the EPIC CCD cameras. For example, after a 30 ksec exposure, EPIC will go ten times deeper than the 3 10^{25} erg s^{-1} upper luminosity limit of the K2 giant Arcturus (Ayres et al. 1991) assuming a 0.1 keV isothermal corona. XMM has therefore the most appropriate instrumentation to investigate the wide range of X-ray luminosities of G-K giants accross the XDL and to understand how the structure of stellar coronae and magnetic activity depends on fundamental stellar parameters.

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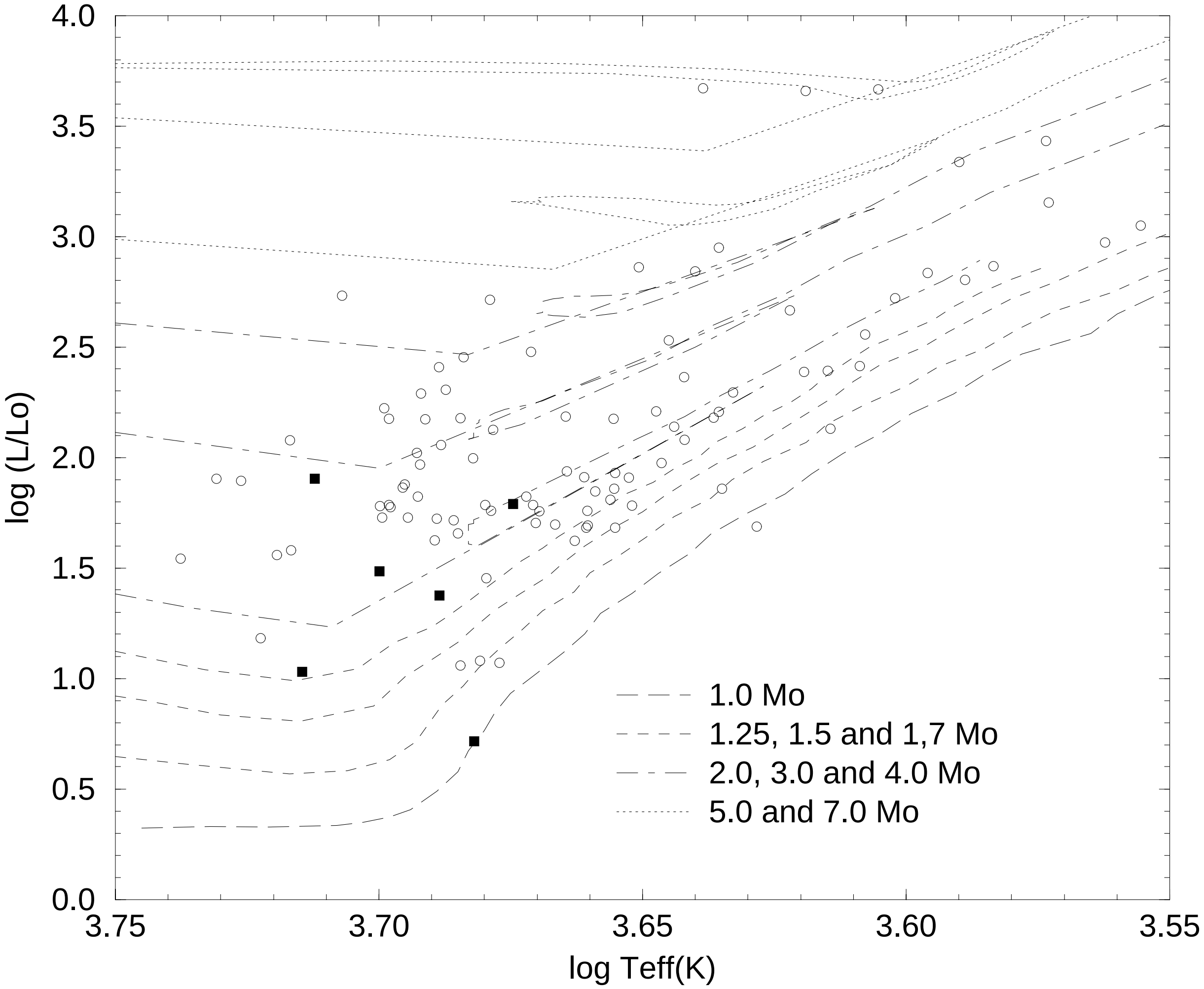

Fig. 1.— HR diagram of single giants (open circles) and FK Comae candidates (filled squares)

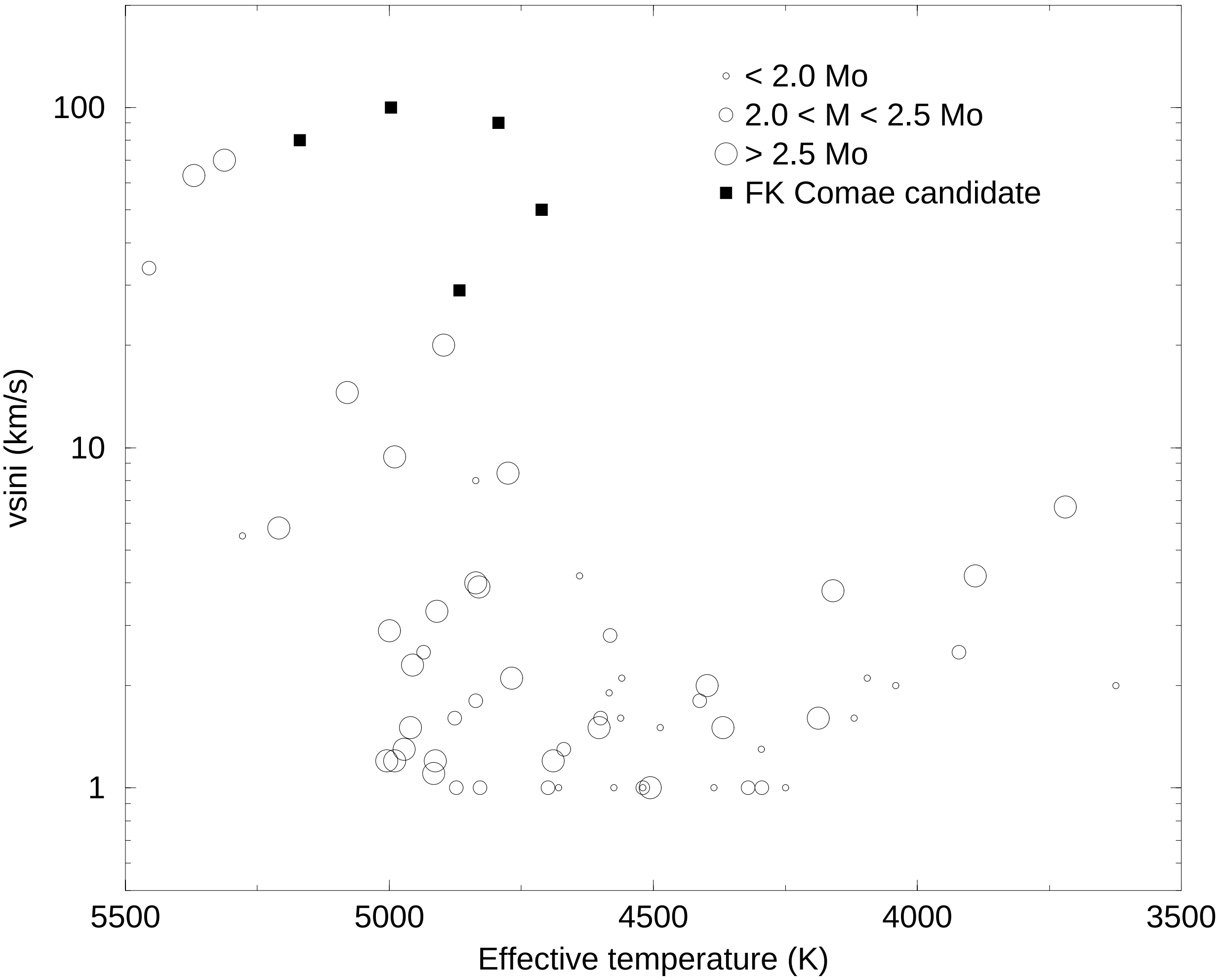

Fig. 2.— Rotation velocities of single giants

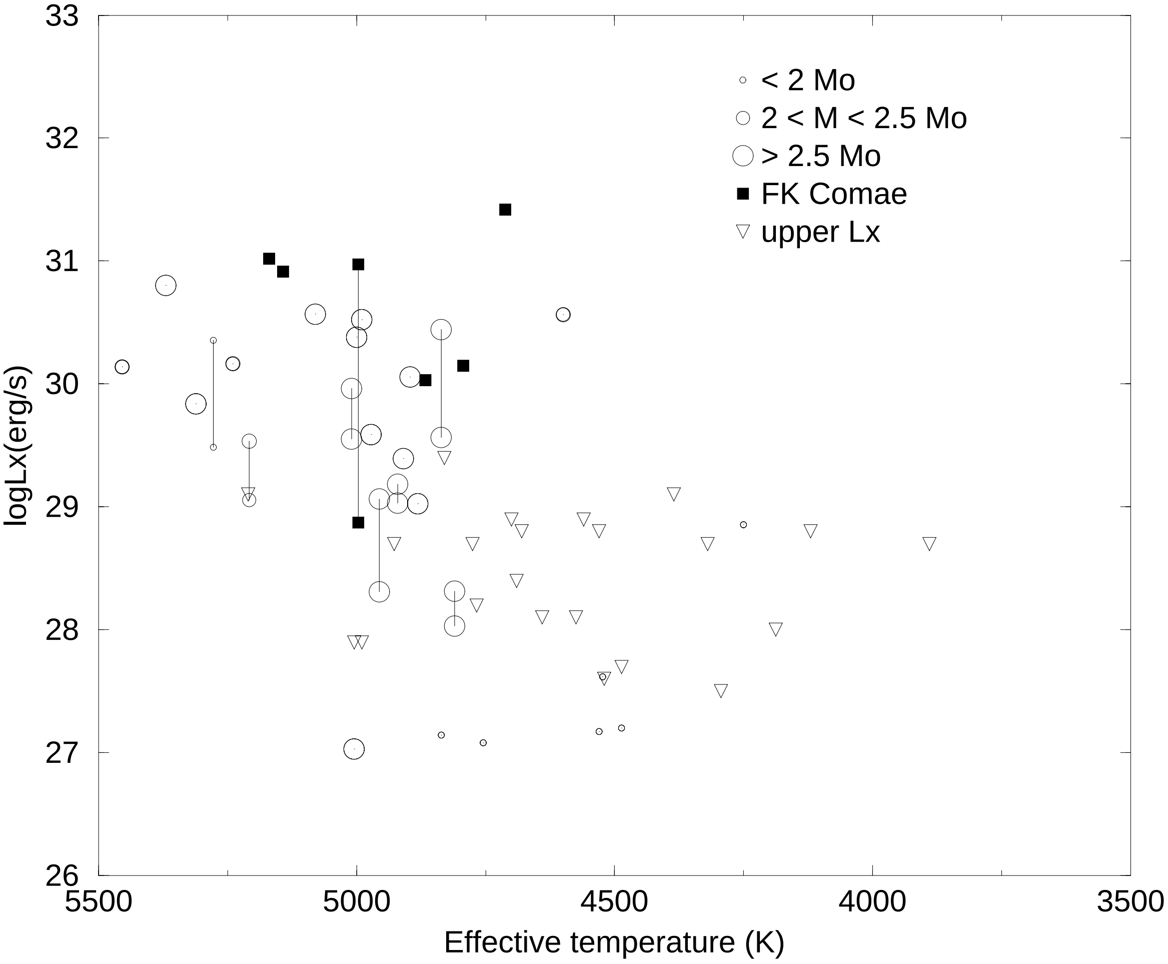

Fig. 3.— X-ray luminosities of single giants

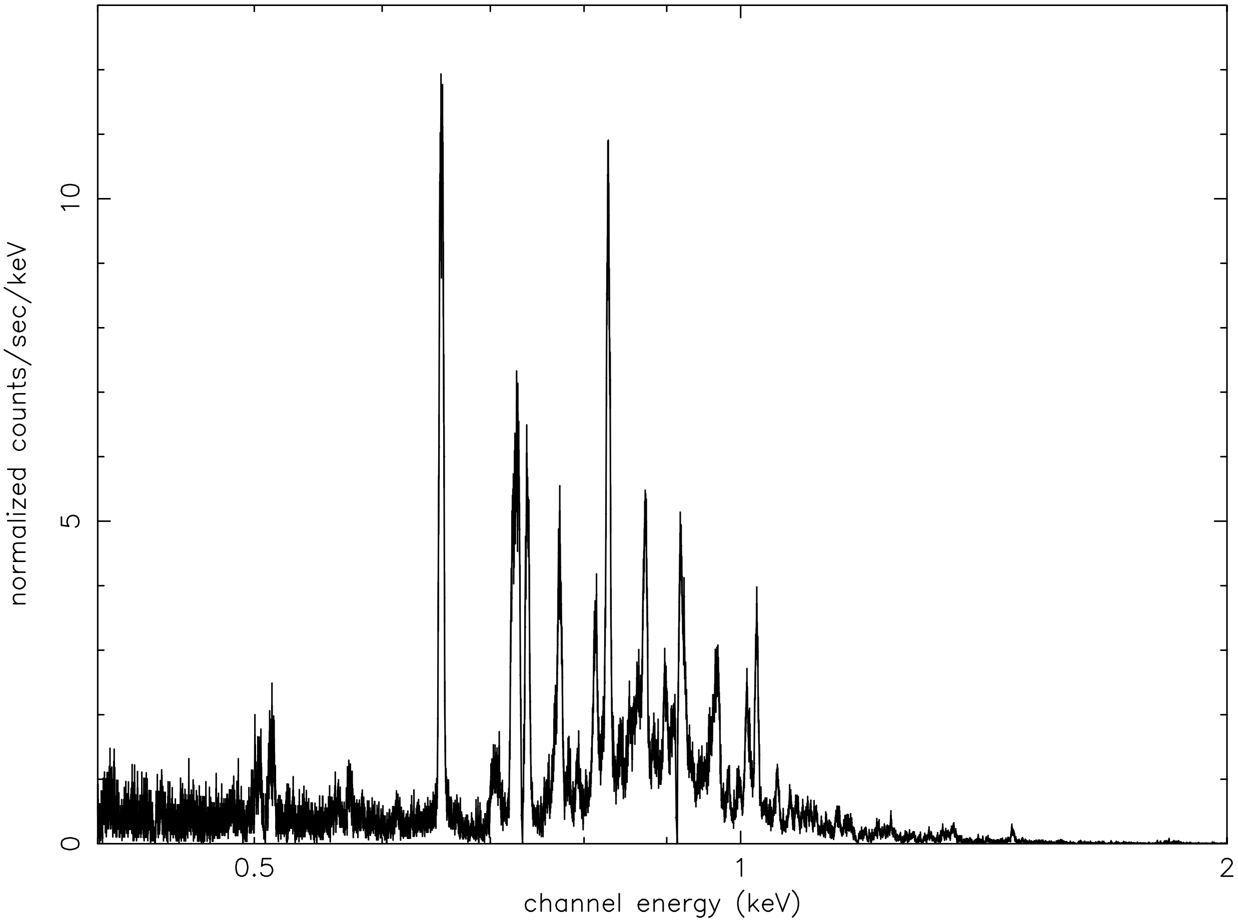

Fig. 4.— simulated RGS spectrum of the active giant βCeti