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X-ray spectroscopy of the active giant β Ceti: the SAX LECS view

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Abstract. We present an X-ray observation of the active giant β Cet, performed with the Low Energy Concentrator Spectrometer (LECS) on-board the SAX satellite. The resulting X-ray spectrum is well fit by an optically-thin plasma model with two discrete temperatures, and the inferred coronal metallicity is compatible both with the abundances derived from a re-analysis of the ASCA SIS spectrum of the same object, adopting the same plasma emission code (MEKAL), and with accurate photospheric abundances recently reported in the literature. The remarkable similarity between the X-ray spectrum of β Cet and the one of the active binary Capella, also observed by SAX, rises again the issue of how some putative He-burning clump giants, like β Cet, manage to retain (or regain) a relatively high X-ray activity level. Some implications of the new Hipparcos parallaxes, relevant for the coronal properties of β Cet and the Hyades giants, are also discussed.

Key words: stars: individual: β Cet– stars: abundances – stars: activity – stars: late-type – X-rays: stars

1. Introduction

The first extensive efforts to model and fit X-ray spectra of stellar coronal sources date back to the era of the *Einstein* satellite. However, the limited spectral resolution of the Imaging Proportional Counter (IPC) on-board *Einstein* allowed to test the thermal nature of the X-ray emission from late-type stars, but not to probe effectively the temperature distribution of the coronal plasma or its metal abundance. According to the results of the *Einstein* spectral survey reported by Schmitt et al. (1990), the emission from such a class of X-ray sources originates from optically-thin plasmas with temperatures of few times 10^6 K in the coronae of main-sequence F and G stars, reaching $\simeq 10^7$ K in the yellow giants, and a little more in the coronae of the most active (X-ray luminous) stars, identified as RS CVn-like binaries. As a consequence, the X-ray spectra of most coronal sources, especially those which suffer little interstellar absorption, show the largest photon flux at energies below $\simeq$ 1 keV, while they drop sharply for energies beyond a few keV; hence the soft X-ray spectral region below $\simeq$ 1 keV is of great importance for any diagnostic of the properties of the emitting plasma.

These *Einstein* data showed that β Cet, a single K0 III star, is a relatively bright X-ray source with respect to other stars of similar spectral type and located near the base of the red giant branch (Maggio et al., 1990), despite its apparently low rotational velocity ($v \sin i = 3$ km s^{-1}; (Gray, 1982)). The analysis of the IPC spectrum of β Cet (Schmitt et al., 1990), with a Raymond-Smith plasma emission model assuming solar abundances, yielded a single-temperature best-fit model with temperature of 0.8 keV and a flux of 1.5×10^{-11} erg cm^{-2} s^{-1}, in the 0.2–4.0 keV band.

Some improvement in the diagnostic power of the thermal structure of stellar coronae has been achieved with the observations of the Position Sensitive Proportional Counter (PSPC) on board ROSAT, thanks to its slightly better spectral resolution and larger sensitivity. In fact, the X-ray spectral analysis results now available confirm that the X-ray emission from late-type stars is not isothermal: model spectra with at least two components are required in most cases to provide an acceptable fit, but more complex models, such as power-law emission measure distributions (Preibisch, 1997) or detailed coronal loop model spectra (Maggio & Peres, 1997) provide a comparable fit quality with a physically sounder description of the observed emission and a deeper insight on the structure of stellar coronae.

The recent volume-limited sample study of late-type giants observed with ROSAT (Hünsch et al., 1996) confirms that β Cet is the single giant star with the highest X-ray luminosity in the solar neighborhood ($D < 30$ pc), and in absolute terms one of those with the highest observed X-ray flux, thanks to its proximity (note that the new Hipparcos Catalogue[1] places β Cet at $29.38^{+0.63}_{-0.69}$ pc, about twice the distance previously determined). An intriguing issue is whether β Cet is still in the phase of crossing the Hertzsprung gap for the first time, as its high ac-

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[1] The Hipparcos Catalogue, 1997, ESA SP-1200, available through the service for astronomical catalogues of the Strasbourg astronomical Data Center (CDS) at http://cdsweb.u-strasbg.fr/Cats.html

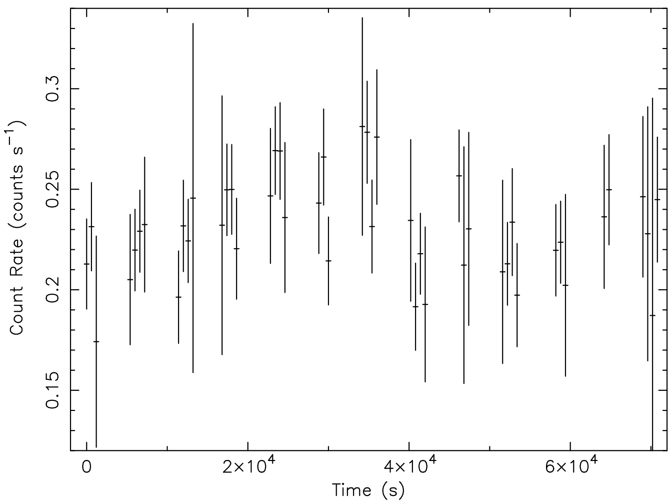

Fig. 1. The light curve of the SAX LECS observation of β Cet.

tivity level suggests (Maggio et al., 1990; Haisch & Schmitt, 1996), or if it is a He-burning clump giant (Ayres et al., 1995), as expected on the basis of photospheric element abundances and evolutionary time-scale arguments.

The ASCA satellite, with its CCD-based detectors, has allowed to get stellar X-ray spectra with the highest spectral resolution available so far in non-dispersive detectors, in the bandpass 0.5–10 keV. Driven by this characteristics, most studies on stellar coronal physics based on ASCA data have addressed the issue of the element abundance in the emitting plasma.

The ASCA SIS spectrum of β Cet, observed during the PV phase, was fitted with a two-temperature MEKA model (Drake et al., 1994) in which all the individual element abundances were left free to vary. The fitting results were interpreted as evidence of peculiar abundance ratios, similar (but with some discrepancy) to those expected as result of the so-called first ionization potential (FIP) effect (Meyer, 1985). To allow a more direct comparison with our own SAX observation we have reanalyzed the ASCA spectrum using the updated and improved MEKAL plasma emissivity model, as reported below.

Most recently, β Cet has been observed with the SAX X-ray astronomy satellite (Boella et al., 1997), as one of the coronal sources selected for the AO-1 program. In this paper we present the results of the analysis of its X-ray spectrum, acquired with the Low Energy Concentrator Spectrometer (LECS, (Parmar et al., 1997)), which covers the energy range 0.1–10 keV with a spectral resolution $\Delta E/E \simeq 20\%$ at 1 keV and scaling as $E^{-1/2}$. As demonstrated by an extensive set of simulations presented by Favata et al. (1997a), LECS spectra allow to get fair diagnostic capabilities for the global metallicity of coronal plasmas, thanks to the wide spectral coverage. The region below the carbon edge ($E \simeq 0.3$ keV) is particularly important because typical coronal sources show a large photon flux in that region and a continuum emission with few and relatively weak lines, while the region around 1 keV is dominated by line emission from the Fe L complex.

2. The SAX LECS X-ray observation

The SAX observation was performed on Dec. 9–10, 1996, and resulted in an effective exposure time, for the LECS, of 14.3 ks. This exposure time is significantly shorter ($\simeq$ 60% less) than the scheduled exposure time for the source, because the LECS was operated during Earth dark time only, at the date of the observation. Thus, the statistics for the spectrum discussed in the present paper allow only for a preliminary spectral analysis: in particular, we have focused our attention on the re-determination of the coronal metal abundance in this source, to be compared with new accurate estimates of the photospheric abundances (Luck & Challener, 1995).

The light curve of the LECS observation (Fig. 1) shows evidence for a variation on time scales of about half a day, with a flux change of the order of 50%, but no evidence for a flaring behavior. Given the count rate of the source, it is impossible to perform time-resolved spectroscopy.

The data were reduced with the SAX-LEDAS V.1.4.0 pipeline software. The default screening criteria defined in the processing software were applied, and inspection of the light curve for both the source and the local background showed that no additional screening was necessary, as also expected given that the observation was conducted during Earth night only. The extraction of the source was performed by the pipeline process, with a source extraction radius of 8.2 arcmin (95% encircled energy fraction at 1 keV), centered on the nominal center of the field of view. Given that the source appears to be on-axis during the observation, the default extraction region is fully satisfactory. The background spectrum was extracted from the LECS standard background observation, obtained by adding up a set of long pointings of sky regions free of detectable sources. The response matrix for the observation was computed using the current release (3.01) of the LEMAT software, and the analysis was done using the XSPEC V.9.01 package. The source spectrum was re-binned so to have at least 20 counts per energy bin, and bins with energies below 0.1 and above 5.0 keV were discarded. The resulting (background-subtracted) source count rate is 0.22 cts s^{-1}, with a background count-rate, for the same region, of 0.05 cts s^{-1}.

3. Results

The LECS spectrum was fit with a MEKAL optically-thin plasma emission model with two discrete temperature components, as implemented in XSPEC. The effect of interstellar absorption was also included, but the fit converged to a zero hydrogen column density, and forcing this parameter to the best available estimate for β Cet (log $N_{\rm H} = 18.35 \pm 0.10$ cm^{-2}; (Piskunov et al., 1997)) does not have an appreciable influence on the other fit parameters.

The global abundance of metals in the emitting plasma, relative to the solar value, was left as a free parameter in the fit, i.e. we have assumed that the abundances of individual elements have the same ratios as in the solar case. The resulting best-fit model is shown in Fig. 2, together with the ob-

Table 1. 2-T model fitting results. The hydrogen column density was fixed to 2.2×10^{18} cm^{-2}. The 90% confidence ranges have been computed with the criterion $\chi^2 < \chi^2_{min} + 6.25$ (Lampton et al., 1976).

Data ID	$f_x/10^{-11}$ erg cm^{-2} s^{-1}	T_1 KeV	90% conf. range		$EM_1/10^{52}$ cm^{-3}	T_2 KeV	90% conf. range		$\frac{EM_1}{EM_2}$	Z	90% conf. range		χ^2_r	d.o.f.
ROSAT	1.7	0.19	0.10	0.36	1.35	0.61	0.50	1.66	0.26	1.13	0.36	1.25	1.06	21
LECS	1.5	0.65	0.56	0.68	6.26	1.04	> 0.74		4.49	0.67	0.51	0.93	1.07	88
SIS	2.0	0.63	0.61	0.66	7.94	1.72	> 1.00		6.24	0.69[a]	0.47	2.05	1.14	112
LECS[b]	1.5	0.60	0.50	0.71	6.14	1.03	> 0.98		4.69	0.69[a]	fixed		0.95	89

[a] Fe abundance (see text).
[b] Individual abundances fixed at the ASCA best-fit values.

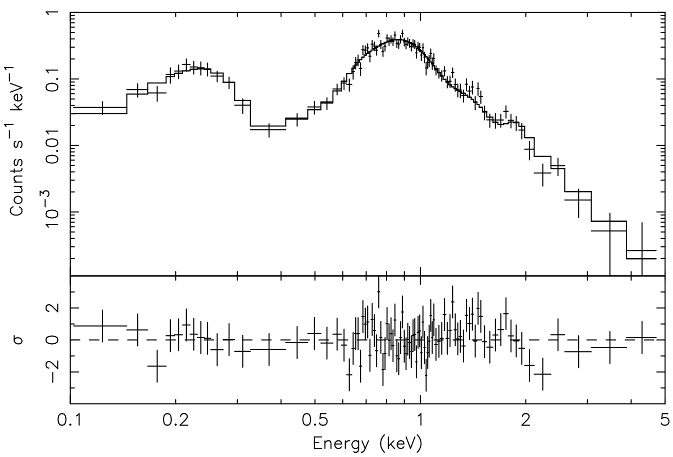

Fig. 2. The observed SAX LECS spectrum of β Cet, together with the best-fit two-temperature MEKAL spectrum, yielding a global metallicity 0.7 times the solar value.

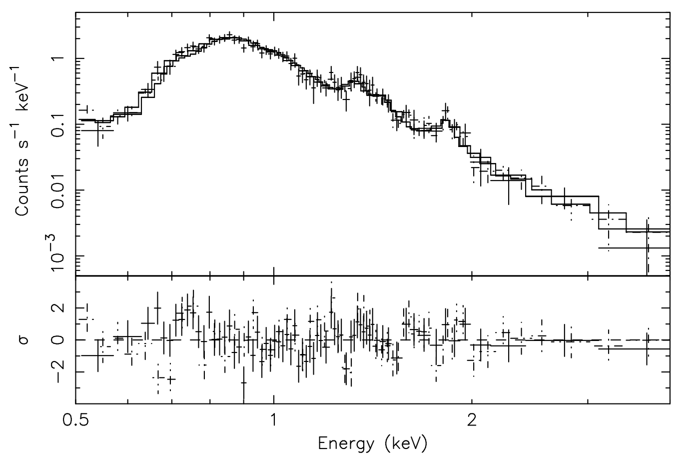

Fig. 3. The observed ASCA SIS-0 spectra (FAINT and BRIGHT mode) of β Cet, together with the best-fit two-temperature MEKAL spectrum, with individually varying element abundances.

served spectrum. The fit has a reduced χ^2 of 1.07 (with 88 degrees of freedom). The best-fit temperatures are 0.65 and 1.0 keV, with a ratio between the two emission measures of 4.5 ($EM_{\rm cool}$ = 6.3, $EM_{\rm hot}$ = 1.4, in units of 10^{52} cm^{-3}). The best-fit metallicity is Z = 0.7, with a resulting flux of 1.5×10^{-11} erg cm^{-2} s^{-1} (in the 0.2–4.0 keV band). The 90% confidence range[2] on Z is 0.5–0.9. These results are reported in Tab. 1 for ease of comparison with those obtained from the analysis of the ROSAT/PSPC data and of the ASCA SIS data described in the following. Note that a model assuming a power-law emission measure distribution, yields an equally acceptable fit (χ^2 = 1.1 for 89 degrees of freedom) with a slope α = 2.6, $T_{\rm max}$ = 1.0 keV, and Z = 0.9.

To compare the above results with those based on the ROSAT and ASCA observations, we have retrieved the relevant data from the public archives, and we have fitted the extracted spectra with the same model assumptions as in the case of the SAX LECS spectrum.

The pointed ROSAT observation of β Cet, performed in July 1992, was quite short ($\simeq$ 700 sec), but the PSPC spectrum contains about 1900 counts, thanks to the high count rate of this source (2.7 cts s^{-1} in the 0.1–2.4 keV band). Our analysis of this spectrum, assuming solar abundances, yielded a best-fit two-component thermal model with temperatures of 0.2 and 0.6 keV, and a ratio between the emission measures of the soft and hard component of $\simeq$ 0.3. The resulting X-ray flux in the 0.2–4.0 keV band is 1.7×10^{-11} erg cm^{-2} s^{-1}. If the metallicity is left free to vary, the fit converges to Z = 1.1, with no significant change of the other parameters, but the 90% confidence range is quite large, i.e. Z = [0.36 – 1.25]. Inspection of Tab. 1 shows that the dominant component at $T \simeq 0.6$ keV in the ROSAT spectrum is similar to the low-temperature component of the SAX spectrum, also in terms of emission measure, while the relatively minor component at $T \simeq 0.2$ keV shows up only in the ROSAT data. This result may explain the different emission measure ratio found in the two cases, and suggests the existence of a multi-temperature distribution of the emitting plasma.

[2] For all the analyses here reported we have consistently computed statistical uncertainties at the 90% confidence level, for three "statistically interesting" parameters at a time (usually two temperatures and one abundance), using the condition $\Delta\chi^2$ = 6.25 (Lampton et al., 1976)

The ASCA SIS data consist of two segments of $\simeq$ 8 and $\simeq$ 3.4 ks each, taken in two different instrumental modes (FAINT and BRIGHT mode). We have extracted the relative SIS-0 spectra from the best calibrated CCD CHIP-1), and we have computed separate instrument responses[3]. The two background-subtracted spectra, yielding a mean count rate of 0.77 cts s^{-1}, have been fitted simultaneously using a two-temperature MEKAL model with individual abundances left free to vary (Fig. 3). Given the large calibration uncertainties at low energy (Dotani et al., 1996), we have analyzed the data in the spectral range 0.55 – 5 keV, the upper boundary being due to insufficient counts at higher energies. We have found best-fit temperatures of 0.63 and 1.7 keV, an emission measure ratio of 6.2, and the following element abundances, relative to solar values: O = 0.1, Ne = 0.9, Mg = 1.5, Si = 0.9, S = 0.4 and Fe = 0.7. The resulting reduced χ^2 was 1.1 with 112 degrees of freedom[4], and $f_x = 2.0 \times 10^{-11}$ erg cm^{-2} s^{-1} (0.2–4.0 keV band). These values deviate slightly from the ones reported by Drake et al. (1994), especially in the determination of the temperatures (0.4 and 0.7 keV in the previous analysis) and of the O and Ne abundances (previously both equal to 0.4), possibly due to the different plasma emission code adopted or to different calibration data employed, however all the other abundances, including the iron one, are in good agreement. The relatively large Mg abundance is worth noting: it is required to fit the line emission complex near 1.4 keV, observed in excess with respect to the model prediction if scaled solar abundances are assumed (compare the fit residuals in Fig. 2 and in Fig. 3). In any case, the uncertainties in the individual abundance values are quite large, as result of the available photon counting statistics and of the large number of free parameters in the fit. For example, the 90% confidence range for the Mg abundance is 1.0 – 2.6, 0.3 – 2.4 for the Si, and 0.5 – 2.0 for the Fe. Moreover the temperature of the hotter component is poorly constrained, because only a lower limit, $T_2 > 1.0$ keV, can be fixed.

We have also fitted the ASCA spectra over the widest possible spectral range, 0.4 – 5 keV, in order to include the relatively line-free spectral region below 0.5 keV, which is important to determine the continuum emission (Favata et al., 1997a). We obtained a slightly larger iron abundance (Fe = 0.8), but also an extremely low N abundance (< 0.15, at the 90% confidence level), due to the depressed spectral shape between 0.5 and 0.6 keV, where N VI and N VII line emission would be expected for a solar abundance plasma. To our knowledge, low best-fit N and O abundances are a common occurrence in most of the ASCA SIS spectral analyses of coronal sources published so far (see, for example, the list reported by (Drake et al., 1994)), and may be attributed to calibration problems in the instrument effective area near the absorption edge at $\simeq$ 0.5 keV (Dotani et al., 1996).

The low statistics of the present LECS spectrum, together with the spectral resolution above 0.6 keV lower than for the ASCA SIS, makes the analysis with variable individual abundances not required (an acceptable fit was already found varying only the global metallicity in the fit). However, as a consistency check we have verified that the model parameters derived from the ASCA SIS spectrum are compatible with the LECS spectrum. If the abundances are kept fixed to the ASCA-derived best-fit values, while the temperatures and emission measures are left free to vary, the fit converges to a χ^2 value statistically equivalent to the one determined before, i.e. $\chi^2 = 0.95$ for 89 degrees of freedom, thus demonstrating that this LECS spectrum is not sensitive to individual abundance variations. The best-fit temperatures are also similar, at 0.60 and 1.1 keV, with an emission measure ratio of 4.7.

4. Discussion

In the light of the controversy about the presence of significant differences between photospheric and coronal abundances in active stars it is interesting to note that the coronal and photospheric abundances of β Cet appear to be compatible with each other. The most recent photospheric abundance determinations in β Cet is the one by Luck & Challener (1995), based on a large number of Fe I lines and with ionization equilibrium balance derived directly from the spectrum using Fe I and Fe II lines. They derive a [Fe/H] of 0.13 ± 0.27, corresponding to 1.4 times solar, with the confidence region extending from 0.7 to 2.5 times solar. The confidence regions for Ca, Ni and Si are respectively 0.4–0.7, 0.8–2.5 and 1.4–3.2 times solar. They also determined a ratio between the average abundance of C, N and O versus Fe of 0.56 times the solar value.

For the Si and Fe, for which both coronal and photospheric abundance determinations are available, the results are fully compatible with each other: in fact, the 1σ uncertainties for the ASCA values overlap with those of the photospheric abundance determination.

Apart from a change in the absolute flux level, which however is within the range common in active coronal sources, the best-fit parameters derived from the SAX observation of β Cet are compatible with the parameters derived from the ASCA SIS one. The total coronal metallicity derived from the LECS spectrum is also compatible with the photospheric metallicity of β Cet. In conclusion, neither the SAX LECS nor the ASCA SIS X-ray spectra of β Cet appear to support the classification of this star among the so-called Metal Abundance Deficiency syndrome stars (see (Drake, 1996) for a review about this issue).

However, a note of caution is in order: we stress that the determination of element abundances is closely coupled with that of the coronal thermal structure, when a parametric spectral fitting approach is adopted. We cannot exclude that a better fit to the SIS data could be obtained with a model less simplistic than the two-temperature one, adopted in any analysis of the β Cet emission so far, such as a coronal loop model or a model with a continuous emission measure distribution. The resulting

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3 The Ancillary Response File (ARF) was created with the routine ASCAARF V2.72, and the Response Matrix File (RMF) with SISRMG V1.10, as implemented in the package FTOOLS V4.0, including up to date (APR 97) ASCA calibration data

4 This χ^2 value was obtained adopting for the count errors the approximation of (1986), appropriate for data following Poisson statistics. If the Gaussian approximation is adopted, the reduced χ^2 is $\simeq$ 1.7.

individual abundances may then be different, as suggested by the simulations performed by Favata et al. (1997a).

An additional caveat is motivated by the lack of many weak lines in the current versions of the available plasma emissivity codes: their individual contribution is small, but their global effect may be significant and hard to disentangle with moderate spectral resolution instruments, such as ASCA SIS and SAX LECS. Finally, calibration errors in the instrument response, especially possible near the several absorption edges of the instrument effective area, may introduce systematic errors in the fitted abundances of individual elements. In fact, the calibration measurements of the energy response of the SAX LECS (Parmar et al., 1997), and of instruments designed for the future missions AXAF and JET-X (Barbera et al., 1996; Owens et al., 1997), performed at synchrotron-beam facilities, have revealed the existence of fine structures at every absorption edge (due to mirrors, detectors or filters), which cannot be properly modelled if the edge shapes are calculated from standard absorption cross sections. In the latter case, the χ^2 fitting results, and especially the abundances of elements with emission lines near the instrument absorption edges, like N and O, may be affected by significant systematic errors. Therefore, we conclude that the uncertainties on the parameter values, reported in Tab. 1, may be significantly larger than the quoted statistical errors, and there is room for improvement in the abundance determination.

It is instructive to compare our observation with those of other coronal sources observed so far with the LECS. β Cet appears to be significantly softer than the active binary VY Ari (Favata et al., 1997c), and shows a slightly larger coronal metallicity. This is in line with the already known difference between active giants and active binaries, as obtained by previous X-ray data. Instead, the β Cet LECS spectrum shows a striking similarity with Capella's one (Favata et al., 1997b): temperatures, emission measures as well as metallicities appear to be almost identical. Given the new Hipparcos distance[5] of β Cet, D = 29.4 pc, also the X-ray luminosities turn out to be very similar: log $L_{\rm x}$ = 30.2 erg s^{-1} for β Cet, at the time of the SAX observation.

The similar X-ray emission characteristics of β Cet, Capella, and few other late G or early K giants, like the Hyades members θ^1 Tau and γ Tau, challenge our understanding of coronal activity in evolved late-type stars. In fact, all these giants have X-ray emission levels higher than those of the numerous low-activity giants located in the same region of the H-R diagram, and it is not clear whether these strong X-ray sources have some other feature in common which may explain their peculiarity.

While Capella is classified as a long-period RS CVn-type active binary, β Cet is a hitherto single giant star. The early G-type component (Ab) of the Capella system is a fast rotating star ($v \sin i$ = 36 km s^{-1}) probably in the phase of crossing the Hertzsprung gap for the first time, while the G8 III component (Aa) rotates more slowly ($v \sin i$ = 3 km s^{-1}), and it is more likely an He-burning clump giant, as inferred from the difference in mass ($M_{\rm Aa}$ = 2.69 ± 0.06, $M_{\rm Ab}$ = 2.56 ± 0.04; (Hummell et al., 1994)) and in Li abundance (log ε(Li) = 0.8 and 3.0, for Capella Aa and Ab, respectively; (Pilachowski & Sowell, 1992)). β Cet shares with the Capella's Aa component the slow rotational velocity (see Sect. 1), and its "clump giant" classification is strongly suggested by the low Li abundance, log ε(Li) = 0.01, and by the low abundance ratios C/N = 1.38 and ^{12}C/^{13}C = 19 (Luck & Challener, 1995; Tomkin et al., 1975), interpreted as evidence of deep convective mixing (first dredge-up) during the ascent of the giant branch and before helium ignition. It's worth noting that, while the C/N and ^{12}C/^{13}C ratios can be accounted for by standard evolutionary models (e.g. (Schaller et al., 1992)), no reliable prediction of Li abundance for evolved stars is available (Brown et al., 1989). Using the evolutionary tracks of Shaller et al. (1992), together with the new Hipparcos parallax, we have estimated that β Cet is a $\simeq 3 M_\odot$ star, i.e. slightly more massive than the Capella components, but they all should have started as A-type stars on the main-sequence.

A high activity level is expected for "first-crossing" giant stars, which have spent most of their main-sequence life as rapidly rotating, inactive A-type stars, and have only recently developed a deep convection zone and hence an efficient magnetic dynamo (Maggio et al., 1990; Rosner et al., 1995). For more evolved stars (later than about G5, or redder than B-V $\simeq$ 0.8) there is evidence of a large spread in X-ray emission levels, even for stars selected in the restricted mass range between 1.5 and 3 $M_\odot$ (Pizzolato et al., 1997). According to this scenario, one is tempted to assign the X-ray bright G and early-K giants to the class of stars at the exit of the Hertzsprung gap, and the lower activity giants of similar spectral type to the population of the clump giants. However, the evidences to the contrary, based on the surface abundance measurements reported above, are difficult to overcome.

On the other hand, well studied cases, suggest that *a large spread in X-ray activity level may be intrinsic to stars of similar mass and evolutionary stage.* Let us take as an example the Hyades cluster giants: there are only four of them, and in spite of their being coeval, there is a factor $\simeq$ 40 difference in X-ray luminosity between the least and the most luminous, a spread which still escapes any simple explanation (Collura et al., 1993). Most recently, Hipparcos observations provided us with very precise values of their individual parallaxes, with only a 5% error, thus removing the uncertainty due to distance determination. Two of these giants, including the brightest one, θ^1 Tau, are indeed known to be spectroscopic binaries, but the multiplicity of these stars seems not to be a viable explanation of the large spread in X-ray luminosity.

Finally, even the contribution from each Capella component to the observed UV and X-ray emission is less clear than intuition may suggest: the UV chromospheric and transition region emission of the Capella system is dominated by the contribution of the secondary component (Linsky et al., 1995), which accounts for about 90% of the total emission in the Si III, Si IV, and C IV lines formed in the transition region at temperatures

[5] Note that the Hipparcos parallax of Capella is π = 77.29 ± 0.89 mas, very similar to the previously known value π = 76 ± 3 mas (Heintz, 1975), but the goodness of fit parameter, F2 = 3.79, indicates a bad fit to the Hipparcos data

near 10^5 K. The same behavior is expected for the X-ray emission, but Linsky et al. (1997) have recently obtained 15 km/s resolution spectra of the Capella Fe XXI 1354 Å coronal line with the Goddard High Resolution Spectrometer (GHRS), and find that the contribution of the two components is about the same.

We conclude that the evidence accumulated so far points toward some yet unrecognized ingredient which is critical to determine the X-ray emission level of evolved late-type stars. One such ingredient may be differential rotation within the star, a crucial parameter in magnetic dynamo models. Recent studies (Pinsonneault et al., 1991) suggest that substantial radial differential rotation is required to explain the relatively rapid rotation of evolved horizontal-branch stars. Similar conclusions are reached by other studies, including the recent work of Donati et al. (1995) on activity, rotation and evolution of the RS CVn system λ And.

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