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A SAX/LECS X-ray observation of the active binary Capella

F. Favata[1], R. Mewe[2], N. S. Brickhouse[3], R. Pallavicini[4], G. Micela[4], and A. K. Dupree[3]

[1] Astrophysics Division – Space Science Department of ESA, ESTEC, Postbus 299, NL-2200 AG Noordwijk, The Netherlands
[2] SRON Laboratory for Space Research, Sorbonnelaan 2, NL-3584, Utrecht, The Netherlands
[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden St., 02138 Cambridge, Mass., USA
[4] Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy

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Abstract. We present a SAX/LECS X-ray observation of the active binary Capella, the first coronal source observed in the SAX Guest Investigator program. The analysis of this observation, performed using the MEKAL plasma emission code, shows that the LECS spectrum is well fit by a two-component optically-thin plasma model. A differential emission measure (DEM) obtained by direct inversion of the X-ray spectrum shows no additional features in addition to the double-peaked structure implied by the direct two-temperature analysis. Such a simple temperature stratification is however not compatible with the EUVE emission from the same object, which is well represented by a more complex DEM, with a power-law-like tail toward the low temperatures. At the same time, the EUVE-derived DEM predicts well the softer part of the Capella LECS spectrum, but it fails to correctly reproduce the higher energy part of the Capella LECS spectrum. Possible causes for this discrepancy are discussed. The coronal metallicity derived from the SAX observation is compatible both with the EUVE-derived metallicity as well as with the photospheric metallicity of Capella, thus showing no evidence for coronal under-abundances.

Key words: Stars: individual: Capella; stars: late-type; stars: activity; X-rays: stars

1. Introduction

The thermal nature of the emission from the coronae of late-type stars as a class was established through the study of the large number of low-resolution X-ray spectra taken with the *Einstein* IPC, which were well fit by a thermal spectrum, requiring either one or two discrete temperature components (e.g. Schmitt et al. 1990). While the limited spectral resolution of the IPC did not allow to investigate the presence of a more complex temperature structure in the emitting plasma, analysis of the emission from the solar corona showed that more complex structure is likely to be present in coronal plasmas. The newer instruments available for X-ray and EUV spectroscopy, with their improved spectral resolution and energy coverage, have all added new complexity to the picture of stellar coronal emission. The data from the ASCA/SIS detector have been shown to often require deviations in the plasma metal abundance from solar values (although the issue of deviations from stellar photospheric abundances, physically more relevant, has not been thoroughly investigated), leading to a debate about supposed widespread under-abundances in coronal plasmas (the so-called Metal Abundance Deficiency syndrome, or MAD). Still, the ASCA data of coronal sources have mostly been modeled with two discrete temperature components.

The data from the EUVE spectrographs, with their much higher resolution which allows for individual lines from the various Fe ionization states to be well resolved, have been shown to require a more complex temperature structure for their modeling, with two discrete temperature components in general not supplying a satisfactory description of the data. The EUVE-derived differential emission measure (DEM) of many active binaries for example shows a characteristic feature at $\simeq 0.5$ keV often referred to as a "bump" (Dupree et al. 1996).

The Low Energy Concentrator Spectrometer (LECS, Parmar et al. 1997) on-board the SAX satellite (Boella et al. 1997) opens a new window for the study of the X-ray emission of coronal sources, thanks to its wide spectral coverage (from 0.1 to 10 keV) and good spectral resolution, in particular at the low energies, where it has a resolution comparable to CCD detectors. Energies below $\simeq 0.5$ keV are not covered by the ASCA/SIS CCD detector, yet it is precisely at these energies that typical coronal sources emit the largest photon flux. The LECS bandpass thus fills the gap between the EUVE energy coverage and the ASCA one.

Capella is a well-known nearby bright multiple system, with a slowly rotating G8 III primary and a fast rotating F8 III secondary (which has been identified as the site of strong UV

Send offprint requests to: F. Favata (fabio.favata@astro.estec.esa.nl)

chromospheric emission, Linsky et al. 1995), and a long orbital period ($\simeq$ 104 d). Its photospheric metallicity is close to solar, with some evidence for mild under-abundance, with Pilachowski & Sowell (1992) reporting a Ca abundance compatible with the solar value, and McWilliam (1990) reporting [Fe/H] = -0.37 ± 0.22 (equivalent to 0.43 times solar, with a $1\,\sigma$ range of 0.26–0.71). Thanks to its high X-ray luminosity and to its small distance from the Earth, Capella is a well studied coronal source, having been observed with essentially all the soft X-ray and UV/EUV detectors flown to date. It is also the first coronal source to have been observed in the first year of the SAX guest observing program.

The corona and transition region of Capella has been extensively studied with the EUVE spectrographs, and a detailed analysis of the EUV spectrum (Dupree et al. 1993; Brickhouse 1996) shows that the differential emission measure distribution has a "bump" around $\simeq$ 0.5 keV. The EUV spectrum, and in particular the line to continuum ratio, shows that the Fe abundance (0.88 ± 0.13 times solar) is compatible with the solar photospheric value, and and close to the upper bound of the reported photospheric abundance, as are the abundances of the other species whose lines are visible in the EUV spectrum.

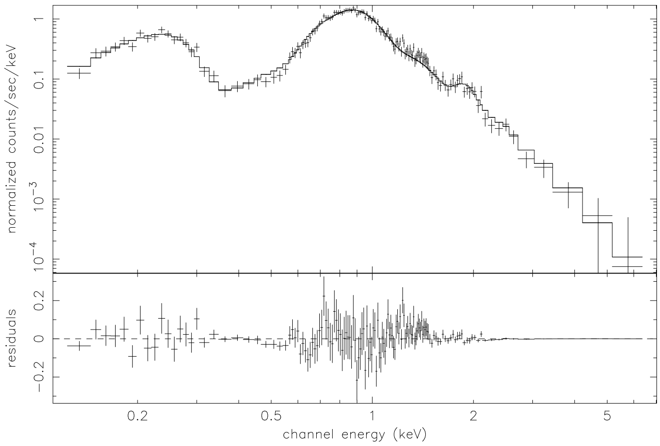

Fig. 1. The observed SAX/LECS spectrum of Capella, together with the best-fit two-temperature MEKAL spectrum and the fit residuals (expressed in terms of their contribution to the .

2. Observations and data reduction

The SAX observation of Capella took place on Oct. 4 and 5, 1996 but only 12 ks of observation were obtained with the LECS detector, rather than the 30 ks which had been allocated. The instrument performed nominally, and no evidence for flaring activity or significant time variability is present in the light curve of the source.

The data were reduced through the LECS pipeline software (SAX-LEDAS V. 1.4.0), the extraction of the source and background spectra was done within the XSELECT package, the response matrix was produced with release 3.2.0 of the LEMAT software, and the spectral analysis was done using the XSPEC V. 9.0 and SPEX V. 1.10 packages. The source spectrum was extracted from a circle 35 pixels in radius (corresponding to 8 arcmin), while the background was derived from long observations of empty fields, and extracted from the same area as the source. The extraction radius of 8 arcmin is the default in the SAX-LEDAS software pipeline, and has been chosen to allow for 95% of the source counts at 1 keV to be included. The source spectrum was re-binned so to have at least 20 counts per re-binned channel, and channels with energies below 0.1 and above 6.0 keV were discarded. The resulting source count rate is 0.78 cts s^{-1}, to be compared with a background count rate, for the same region and spectral interval, of 0.011 cts s^{-1}. The (background-subtracted) spectrum is shown in Fig. 1 (together with the best-fit two-temperature model discussed below).

3. Results

The first step in our analysis of the LECS Capella spectrum has been to fit it with an optically-thin plasma emission model with two discrete temperature components. The MEKAL plasma emission model (Mewe et al. 1995) was used throughout, as implemented in XSPEC 9.0. The column density toward the source was fixed to 1.8×10^{18} cm^{-2}, the value derived from the analysis of the HST Lyα data (Linsky et al. 1993). While (as shown by Favata et al. 1997) the LECS is rather sensitive to global abundance variations, its limited spectral resolution makes the determination of coronal abundances of individual elements much less reliable, especially at signal-to-noise ratio of the spectrum discussed here. Indeed, given the satisfactory reduced χ^2 of the fit with a model in which only the global abundance is left free to vary, the variation of individual abundances is not necessary to fit the present spectrum. Thus, in the present paper, only global abundance variations are discussed. The resulting best-fit model for a two-temperature MEKAL model is shown, together with the observed spectrum and the fit residuals, in Fig. 1. The resulting reduced χ^2 is 1.04 (with 138 degrees of freedom), resulting in a fully satisfactory fit. The best-fit temperatures are 0.66 ± 0.05 and 1.04 ± 0.2 keV, the emission measures are $5.73 \pm 1.0 \times 10^{52}$ and $1.49 \pm 1.1 \times 10^{52}$ cm^{-3} for the cool and the hot component respectively (assuming a distance of 13.4 pc; note the much larger uncertainty on the parameters of the hot component), and the best-fit coronal metallicity is 0.68 ± 0.05 times the solar photospheric value, a value compatible with the photospheric Fe abundance of McWilliam (1990).

A direct inversion performed using the "multi-temperature" algorithm contained in the SRON SPEX package yields a two-component DEM (shown in Fig. 2 by the dashed line) very similar to the one implied by the two-temperature analysis, with two peaks and very little if any additional structure. To produce this DEM, the global metallicity was fixed to the best-fit value derived from the two-temperature analysis.

3.1. Comparison with the EUVE-derived DEM

The EUVE spectrum of Capella has been discussed by Dupree et al. (1993), Schrijver et al. (1995) and Brickhouse (1996). Their analysis shows the presence of a complex structure in the DEM, with a minimum around 0.1 keV, rising toward higher temperatures, and with a fairly narrow feature (the "bump") around 0.4–0.5 keV. Substantial emission measure appears to be present up to $\simeq$ 1.5 keV. Schrijver et al. (1995) and Mewe et al. (1996) have compared and discussed in detail the results for the DEM derived from different EUVE analyses and from observations with various other instruments. The EUVE-derived DEM of Brickhouse (1996) is shown in Fig. 2 by the continuous line histogram (note the logarithmic scale).

A synthetic spectrum computed using the EUVE-derived DEM produces a very good fit to the soft component ($E \lesssim$ 0.5 keV) of the LECS spectrum, both for the spectral shape and for the normalization, with an acceptable resulting χ^2. However, the same DEM does not do a good job at reproducing the $\simeq$ 1 keV peak of the spectrum and the hard tail. The fit improves if the relative normalization of the hotter "plateau" of the EUVE-derived DEM is left free to vary. The normalization of the high-T plateau becomes in this case much higher, requiring values which are incompatible with the EUVE line fluxes. In particular, several lines from Fe XVIII, Fe XIX and Fe XX become over-predicted when the additional high-temperature emission measure is included, since their emissivity curves peak in the range between $\simeq$ 0.5 and $\simeq$ 1 keV (Brickhouse et al. 1995) and their intensity results from both from the "bump" in the DEM ($\simeq 0.5$ keV) as well as from the $\simeq$ 1 keV component. Thus, the presence of a large emission measure at $\simeq$ 1 keV, required by the LECS data, produces large imbalances in the predicted EUVE line flux.

A better fit to the LECS spectrum can be achieved by leaving all the hotter components of the EUVE-derived DEM free to vary. In this case the fitting process "collapses" the flat high-temperature distribution resulting from the analysis of the EUVE line fluxes onto a single component, whose normalization again needs, to properly fit the LECS spectrum, to be much higher than allowed by the EUVE line fluxes. While the presence of a sharp (and with higher normalization) high-temperature feature in the DEM improves the fit to the LECS data, it is again not compatible with the EUVE spectrum. Thus, it appears that a single DEM cannot satisfactorily fit both the EUVE spectrum as analyzed by Brickhouse (1996) and the LECS spectrum.

Given that the LECS and EUVE observations are not simultaneous, intrinsic source variability may play a role. The EUVE spectrum from which the DEM used here has been derived is actually the sum of a number of individual spectra taken at different times, ensuring maximal signal to noise. Analysis of the DEM derived from individual spectra shows that while the variability of the "bump" component is limited (i.e. $\lesssim$ 30%), the higher-temperature emission components tend to show a much higher variability, up to a factor of 4 (Dupree & Brickhouse 1996). Higher variability for the hotter component was seen in many active binaries, using *Einstein* SSS data, by Swank et al. (1981), although Capella was the only object, in their data, showing *no* variability in its hot component. Thus, part of the discrepancy between the ratio of high- and low-temperature emission measure necessary to fit the EUVE and SAX spectra could be due to intrinsic variability of the emission from the higher-temperature plasma. Simultaneous observations will be needed to ascertain whether source variability alone can explain the observed discrepancy.

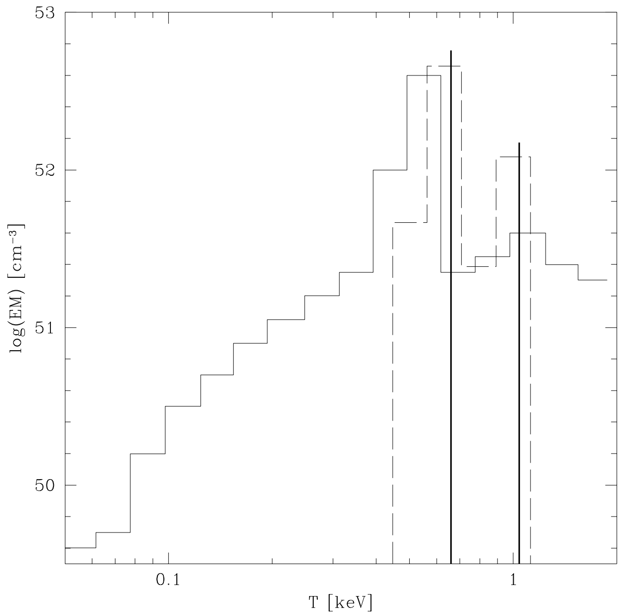

Fig. 2. The DEM implied by the two-temperature analysis is plotted (two thick vertical lines) together with the DEM obtained by direct inversion of the LECS spectrum (dashed-line histogram) and the EUVE-derived DEM of Brickhouse (1996) (continuous-line histogram).

3.2. Comparison with other previous observations

A review of the existing X-ray data on Capella shows a rather puzzling variety of results. While most of the spectra have been fit with two-temperature models, the best-fit parameters vary widely with regard to both temperatures and emission measure ratios. Two-temperature and DEM fitting of the spectra taken with the various spectrometers on board *Einstein* (transmission grating and solid state, Mewe et al. 1982, Swank et al. 1981) and on the EXOSAT transmission grating (Lemen et al. 1989) have revealed a structure with two temperature maxima, concentrated around 0.3–0.5 and 1–3 keV, respectively.

The *Einstein* IPC spectrum of Capella, when fit with a 2-temperature model yielded best-fit temperatures of 0.21 and 0.69 keV and a ratio between the cool and hot emission measure of 0.15. The χ^2 of the fit was, at 2.3, rather poor (Schmitt et al. 1990). The ROSAT PSPC data yielded best-fit temperatures of 0.2 and 1.0 keV and an emission-measure ratio of 0.33, with an acceptable χ^2 (Dempsey et al. 1993). The EXOSAT TGS data yelded a rather hot spectrum, with temperatures of 0.43 and 2.16 keV, and an emission-meaure ratio of 0.34 (Lemen et al. 1989). A re-analysis of the EXOSAT ME data (Ortolani et al. 1997) also shows similar temperatures, at 0.56 and 2.2 keV, and an inversion of the emission-measure ratio, at 3.2. Finally, Bauer & Bregman (1996) report a 2-T fit with variable abundance to the PSPC data, with temperatures of 0.13 and 0.68 keV, a very low emission-measure ratio of 0.026 and a range of acceptable metallicities of 0.15–0.3 times solar. The χ^2 is however, at 3.4, rather poor.

These fits are not necessarily directly comparable since they are based on different plasma emission codes, use different fit acceptance criteria, and make different assumptions about the model metallicity (either kept fixed to the solar value or left free to vary). Moreover, temporal variability between the various observations is also likely to play a role.

The only published results on the ASCA SIS data of Capella are the preliminary 2-T fits of Drake (1996) and White (1996), which were made will all the individual abundances left free to vary, and apparently did not converge to a satisfactory fit so that their best-fit parameters (which would imply a factor 0.2-0.3 under-abundance of metals with the respect to the solar values) cannot directly compared with the results of our fits to the LECS spectra (which were made with only the global metallicity left as a free parameter and which did converge to a satisfactory fit). A comparison of the LECS data with the ASCA SIS data, using both available and still to be released ASCA archival data, is deferred to a future paper.

4. Conclusions

The SAX LECS spectrum of Capella is well fit by a simple two-temperature spectral model using the MEKAL plasma emission code. A DEM derived by inversion of the LECS spectrum yields a similar temperature structure. Such a simple 2-T model however does not provide a good fit to a (non-simultaneous) observation by EUVE, and thus is likely not a good description of the full temperature structure of the corona of Capella. The LECS spectrum is compatible with the broad low-temperature peak present in the EUVE-derived DEM, but indicates a much larger emission measure at a temperature greater than 10^7 K. The ratio between the emission measures of the cool and of the hot component required to fit the LECS spectrum is incompatible with the ratio of the emission measure at the same temperatures required to fit the EUVE spectrum. The coronal metallicity derived from our fits to the LECS spectrum is compatible both with the EUVE-derived data as well as with the published values of photospheric abundance. Capella therefore (similarly to β Cet, Maggio et al. 1997) show no evidence for a significant "Metal Abundance Deficiency", contrary to early reports based on both ROSAT PSPC data (Bauer & Bregman 1996) and a preliminary analysis of ASCA SIS spectra (Drake 1996; White 1996).

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References

Bauer F., Bregman J. N. 1996, ApJ, 457, 382
Boella G., Butler R. C., Perola G. C. et al. 1997, A&AS, 122, 299
Brickhouse N. S. 1996, in S. Bowyer, R. F. Malina (eds.), Astrophysics in the extreme ultraviolet, IAU Colloquium 152, Kluwer, Dordrecht, 105
Brickhouse N. S., Raymond J. C., Smith B. W. 1995, ApJS, 97, 551
Dempsey R., Linsky J. L., Fleming T. A., Schmitt J. H. M. M. 1993, ApJ, 413, 333
Drake S. A. 1996, in S. S. Holt, G. Sonneborn (eds.), Maryland conference on Cosmic Abundances, ASP, San Francisco, 215
Dupree A. K., Brickhouse N. S. 1996, in K. Strassmeier (ed.), Stellar surface structure, IAU Symposium 176, Institut für Astronomie, Wien, Universität Wien, 184
Dupree A. K., Brickhouse N. S., Doschek G. A., Green J. C., Raymond J. C. 1993, ApJ, 418, L41
Dupree A. K., Brickhouse N. S., Hanson G. J. 1996, in S. Bowyer, R. F. Malina (eds.), Astrophysics in the extreme ultraviolet, IAU Colloquium 152, Kluwer, Dordrecht, 141
Favata F., Maggio A., Peres G., Sciortino S. 1997, A&A, submitted
Lemen J. R., Mewe R., Schrijver C. J., Fludra A. 1989, ApJ, 341, 474
Linsky J. L., Brown A., Gayley K. et al. 1993, ApJ, 402, 694
Linsky J. L., Wood B. E., Judge P. et al. 1995, ApJ, 422, 381
Maggio A., Favata F., Peres G., Sciortino S. 1997, A&A, submitted
McWilliam A. 1990, ApJS, 74, 1075
Mewe R., Gronenschild E. H. B. M., Westergaard N. J. et al. 1982, ApJ, 260, 233
Mewe R., Kaastra J. S., Liedahl D. A. 1995, Legacy, 6, 16
Mewe R., van den Oord G. H. J., Schrijver C. J., Kaastra J. S. 1996, in S. Bowyer, R. F. Malina (eds.), Astrophysics in the extreme ultraviolet, IAU Colloquium 152, Kluwer, Dordrecht, 553
Ortolani R., Pallavicini R., Tagliaferri G. 1997, in preparation
Parmar A. N., Martin D. D. E., Bavdaz M. et al. 1997, A&AS, 122, 309
Pilachowski C. A., Sowell J. R. 1992, AJ, 103, 1668
Schmitt J. H. M. M., Collura A., Sciortino S. et al. 1990, ApJ, 365, 704
Schrijver C. J., Mewe R., van den Oord G. H. J., Kaastra J. S. 1995, A&A, 302, 438
Swank J. H., White N. E., Holt S. S., Becker R. H. 1981, ApJ, 246, 208
White N. E. 1996, in R. Pallavicini, A. K. Dupree (eds.), 9th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, Vol. 109 of *ASP Conf. Series*, ASP, San Francisco, p. 193

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