RECENT ADVANCES IN STELLAR CORONAL PHYSICS

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ABSTRACT. A brief summary is given of recent advances in our understanding of X-ray emission from stellar coronae. Results from the European satellite EXOSAT are presented and discussed in some detail.

1. INTRODUCTION

Stars of nearly all spectral types and luminosity classes are surrounded by tenuous high-temperature coronae (with \( T = 10^6 - 10^7 \) K) which emit most of their radiation in the soft X-ray part of the spectrum. For almost thirty years the corona of the Sun has been the only one that could be studied at X-ray and UV wavelengths, because of its proximity. In 1975, however, a stellar coronal source (Capella) was detected during observations with rockets and satellites (Catura et al. 1975, Mewe et al. 1975) and a few other stellar X-ray sources were discovered in the following years (Algol, \( \alpha \) Cen, \( \eta \) Boo, \( \alpha^2 \) Eri, cf. Mewe 1979). The HEAO-1 satellite established the existence of a class of strong coronal sources which emit X-rays at levels several orders of magnitude higher than the Sun (Walter et al. 1980). These are close binaries of the RS Canum Venaticorum type. Capella is probably a long-period member of the same class.

The paucity of stellar coronal sources known in the '70s contrasts with the wealth of data on stellar coronae that were obtained with the EINSTEIN Observatory, soon after its launch in late 1978 (Vaiana et al. 1981). EINSTEIN showed that stars of nearly all spectral types and luminosity classes were X-ray emitters and that the Sun is, after all, a rather weak source, close to the bottom of the observed range of coronal X-ray levels. Nearly 2000 stellar sources have been identified in the EINSTEIN data (cf. Sciortino et al., this volume) and a comparable number is probably present among the unidentified EINSTEIN sources. This represents an increase of at least a factor 100 with respect to all previous satellites. With the ROSAT all sky survey (to be carried out in 1990), we expect to increase the number of stellar coronal sources by at least another order of magnitude. It is obvious that the study of stellar coronae has become an important and vital part of X-ray astronomy and astrophysics in general.

The study of X-ray emission from stellar coronae can help understanding a number of interesting astrophysical problems, such as, for instance, the generation of magnetic fields by dynamo action, the relationships between rotation, convection and magnetic fields, the processes that cause mass and angular momentum loss in stars, the conversion of magnetic and/or radiative energy into thermal energy and plasma heating.
By observing stellar coronae at X-ray wavelengths we can study surface activity in stars that vary widely in effective temperature, gravity, rotation and age. We can also study the details of energy release processes like flares that may be orders of magnitude more energetic than similar phenomena on the Sun. With the powerful space missions that are planned for the end of this century (AXAF and XMM) we can confidently expect that most of the above problems will receive a thorough quantitative answer.

In the talk given at the Catania meeting I tried to give the flavour of stellar X-ray astronomy as has emerged from the extensive observations carried out with the EINSTEIN and EXOSAT satellites. I focussed in particular on more recent results obtained with EXOSAT and I reviewed them in some detail. Since most of this material has already been published elsewhere (Pallavicini 1988a,b,c), only a brief summary of the talk will be presented here. For a more comprehensive discussion of X-ray emission from stellar coronae and for a more complete list of references I refer the reader to the recent review paper by Pallavicini (1989).

2. EINSTEIN OBSERVATIONS OF STELLAR CORONAE

Most of what we know about stellar coronae has been derived from the extensive observations carried out with the EINSTEIN Observatory. These observations have given us a general understanding of the behaviour of stellar X-ray emission throughout the HR diagram and have allowed us to develop some simple interpretative scenarios to account for the presence of hot plasma in stars of various spectral types and luminosity classes. The EINSTEIN results have been reviewed on several occasions, most recently by Golub, Rosner and Vaiana (1985), Serio (1985, 1987), Vaiana and Scintino (1986, 1987) and Schmitt (1988). The main results can be summarized as follows:

- Early-type stars of spectral types O and B are vigorous X-ray emitters with X-ray luminosities in the range from $10^{29}$ erg s$^{-1}$ to $10^{34}$ erg s$^{-1}$. The X-ray luminosity appears to depend on bolometric luminosity ($L_X \propto L_{bol}^{-7}$), irrespective, at least to first order, of the star luminosity class.

- There is no undisputed evidence for X-ray emission from single dwarf stars in the spectral range from B7 to A5. Early reports of the contrary were shown to be due to the contribution of unresolved late-type companions or to UV contamination of X-ray detectors. The available upper limits are $10^{27}$ erg s$^{-1}$.

- All late-type dwarfs of spectral type from F to M are X-ray emitters at levels ranging from less than $10^{27}$ erg s$^{-1}$ to nearly $10^{30}$ erg s$^{-1}$. There is very little dependence of the median X-ray luminosity upon spectral type. Instead, at each spectral type there is an extremely large range of observed X-ray emission levels spanning up to three orders of magnitude. The X-ray luminosity of late-type dwarfs depends primarily upon the stellar rotation rate ($L_X \propto V_{rot}^2$), and is independent of bolometric luminosity. X-ray emission depends also on age, although this is probably a consequence of the loss of angular momentum (because of the braking action of stellar winds) as stars age.

- Giants of spectral types later than early K (as well as supergiants of spectral types G to M) are not X-ray emitters at the present sensitivity levels. There is apparently a Dividing Line (DL) in the HR diagram, separating stars which have hot coronae and solar-type winds (to the left of the DL) from stars that do not show evidence for high temperature plasma and have, instead, cool massive winds (to the right of the DL).

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- Close binaries of the RS CVn, Algol and W UMa types are typically stronger X-ray sources than single stars of similar spectral types. The brightest sources are detached binaries of the RS CVn type which have X-ray luminosities in the range $10^{30}$ to several times $10^{31}$ erg s$^{-1}$.

- Pre-main sequence stars are also very vigorous X-ray emitters with emission levels ranging from less than $10^{29}$ erg s$^{-1}$ to more than $10^{31}$ erg s$^{-1}$. Hundreds of such sources have been discovered in Orion, Taurus Auriga, the $\rho$ Oph dark cloud and other star forming regions.

- The spectra of coronal sources appear to be thermal and produced by line+continuum emission from an optically-thin plasma. There is evidence for a multi-temperature structure within the X-ray emitting corona, with temperatures that may be as high as several times $10^7$ K in the most active sources.

- Active late-type stars (particularly dMe flare stars) appear to be variable on different time scales (from several minutes to hours and even months). Pre-main sequence stars are extremely variable and often characterized by the occurrence of gigantic flares. There is so far little evidence for variability in early-type stars.

There is no generally accepted theory to account for the above observational facts. An important constraint is provided by the fundamental dichotomy that appears to exist between early (O-B) and late (F to M) stars (Pallavicini et al. 1981). The X-ray luminosity of early-type stars depends on bolometric luminosity and is independent of rotation; on the contrary, late-type stars show no obvious dependence on the stellar radiation field, while their X-ray emission depends strongly upon rotation. This different behaviour is taken as evidence that coronal heating in early- and late-type stars must occur via two fundamentally different mechanisms. Coronal models for early-type stars have been developed in the context of massive radiatively-driven winds; instead, coronal theories for late-type stars have usually been based on the solar analogy and the concept that surface magnetic fields are generated by dynamo action in rotating stars possessing a subphotospheric convective zone. Dwarfs of spectral type A do not have strong winds and do not have appreciable outer convective zones: therefore, they should have no coronae. The apparent absence of X-ray emission from these stars is in qualitative agreement with this scenario.

There are basically two models that have been proposed for the coronae of early-type stars. One hypothesizes a thin high-temperature corona at the base of a massive cool wind (Cassinelli and Olson 1979, Waldron 1984). The other explains the observed X-rays as originating from shock heating in high-density blobs which form throughout the wind as a consequence of instabilities (Lucy and White 1980, Lucy 1982). The available observations, although in somewhat better agreement with the latter model, are still insufficient to discriminate between the two alternatives. Models of late-type stars, on the contrary, are largely based on the presence of a subphotospheric convective zone of increasing depth in all stars of spectral types later than F. Convective motions, by interacting with stellar rotation, are capable of generating magnetic fields which emerge at the stellar surface and dissipate energy by some (still largely unknown) mechanism (Parker 1979, 1988). The origin of strong X-ray emission from pre-main sequence (PMS) stars is still poorly understood. The available evidence suggests that X-rays originate in magnetically-confined structures by processes similar to those which are believed to occur for all other late-type stars. It may even be possible that quiescent emission of PMS stars is the result of continuous flare-like activity (Montmerle 1987, Feigelson 1987).
3. THE EXOSAT OBSERVATORY

The EINSTEIN Observatory remained operational for about two and half years from late 1978 to middle 1981. On 26 May 1983 ESA launched the EXOSAT satellite which remained operational for about three years and which also contributed substantially to our knowledge of stellar coronal sources. The imaging experiments on EXOSAT were about one order of magnitude less sensitive than those of EINSTEIN. On the other hand, for fairly bright sources, EXOSAT could make types of observations that were not possible with EINSTEIN, thus complementing in a very effective way the more sensitive EINSTEIN observations. A detailed description of the EXOSAT satellite and of the overall EXOSAT mission can be found in White and Peacock (1988). Here I will first summarise key features of EXOSAT that are relevant for stellar observations and then, in the next section, I will discuss some of the stellar results obtained during the mission. For a more comprehensive summary of EXOSAT results on stellar coronae see Pallavicini (1988c).

EXOSAT had three different instruments on board that were operated simultaneously. Two of them, the Low Energy (LE) and the Medium Energy (ME) experiments, were sufficiently sensitive for observing nearby coronal sources. The LE consisted of two identical grazing incidence telescopes, each of them equipped with two different types of detectors, a Position Sensitive Detector (PSD) and a Channel Multiplier Array (CMA). Transmission Gratings could be inserted into the optical path to obtain high resolution spectra. Unfortunately, a series of malfunctions reduced the capabilities of the LE experiment with respect to the original design. The two PSD’s (which were capable of obtaining low resolution spectra) ceased functioning from the very beginning of the mission; one of the two CMA’s (that on the LE telescope n. 2) failed after about five months, making this telescope completely blind. The mechanism for inserting the grating behind telescope n. 1 started to have problems when only a limited number of high resolution spectral observations had been obtained; further use of the mechanism was judged too risky. In brief, most EXOSAT low energy observations were obtained using only one of the two LE telescopes and with only one type of focal plane detector (the CMA). Only a few observations could be obtained with the Transmission Grating.

In spite of the many problems experienced during the early phases of the mission, the LE on EXOSAT provided many valuable observations of stellar coronal sources. The CMA detector had no intrinsic spectral resolution, but some crude information on source temperature could be obtained by inserting different filters. The filters most commonly used were the Thin-Lexan (3-Lex), the Thick-Lexan (4-Lex), the Aluminium Parylene (Al/Pa) and the Boron. The ratio of count rates in different filters is a function of the temperature in the corona (assumed to be isothermal) and of the interstellar hydrogen column density. Unfortunately, in most cases this ratio is not a one-value function of temperature, even for a truly isothermal source. The EXOSAT CMA data, therefore, can give some indication on the temperature structure in the source (especially if more filters were used), but cannot determine precisely the coronal temperature (cf. Pallavicini et al. 1988). An important feature of the CMA is its imaging capability and relatively high spatial resolution (≈ 20 arc sec) which allows separation of nearby sources. The spectral range covered by the CMA was from 0.05 keV to 2 keV.

The ME experiment on EXOSAT consisted in an array of eight proportional counters sensitive over the spectral range from 1 keV to 50 keV. The intrinsic weakness of stellar coronal sources effectively limited the useful spectral range covered by the ME to = 1-10 keV. Over this range, the ME obtained spectra with a resolution E/ΔE = 2-6.
The instrument had virtually no spatial resolution (0.75°x0.75°). Half of the array was usually offset from the pointing direction to monitor the background. The ME was less sensitive than the LE and provided useful data only for the brightest coronal sources. In particular, it obtained spectra of quiescent and flaring emission from RS CVn binaries and from Algol as well as spectra of a few other very active stars. Observations of dMe flare stars with the the EXOSAT ME were limited almost exclusively to the strongest flares.

The major advantages offered by EXOSAT with respect to EINSTEIN for the study of coronal sources are the larger spectral range covered simultaneously (from 0.05 to ≈ 10 KeV) and the possibility of performing continuous observations for long periods of time. The highly eccentric orbit of EXOSAT allowed, in fact, continuous observations for time intervals as long as three days without the usual data gaps, due to Earth eclipses and passages through high background regions, that are associated with low-orbit satellites like EINSTEIN. Another point that is worth mentioning is the partial transparency of the CMA detector to UV photons. The UV contamination was severe in the case of early-type stars and this explains why EXOSAT did not contribute significantly to our understanding of coronal emission from O and B stars. On the other hand, the degree of UV contamination was negligible for stars of spectral type later than F even for observations with the 3-Lex filter. EXOSAT was in fact capable of obtaining extremely good data for late-type stars.

4. EXOSAT OBSERVATIONS OF STELLAR CORONAE

a) Spectroscopy

The high-resolution spectra (E/ΔE ≈ 50) obtained with the Transmission Grating Spectrometer (TGS), though few in number, are among the most significant results on stellar coronae obtained with EXOSAT. The TGS obtained spectra for only three coronal sources, i.e. the two RS CVn binaries Capella and σ CrB and the F5 IV-V star Procyon (Mewe et al. 1986, Heise 1988). These data, which cover the spectral range from 10 to 200 Å are probably the best X-ray spectra ever obtained of a stellar corona (except, of course, for the Sun). Individual lines are still not resolved, but the broad line complexes visible in these spectra are already sufficient to constrain quite well the range of temperatures present in the source. For the two RS CVn stars, best fits of the spectra require a two-temperature model with one component at a temperature of ≈ 5 x 10⁶ K and the other one at ≈ 20 x 10⁶ K. The data on Procyon indicate much lower temperatures, with one component at ≈ 0.6 x 10⁶ K and the other one at ≈ 3 x 10⁶ K. The finding that high-resolution spectra of RS CVn stars require a two-temperature model is consistent with similar results obtained previously with the EINSTEIN SSS (Swank et al. 1981). It is unclear at present whether the two temperature structure found from spectral fits of RS CVn systems refers to two physically separate coronal regions (e.g. two distinct families of loops in different temperature regimes) or whether it results from a continuous emission measure distribution of coronal plasma in an ensemble of loop-like structures. It is also unclear whether this two-temperature structure is a distinctive feature of close binary systems or apply to coronal sources in general. The data from EINSTEIN and EXOSAT do not yet allow answering these questions in a definite way.

Lemen et al. (1988) have used the EXOSAT TGS spectra of Capella and σ CrB to derive the differential emission measure distribution within the source. The distribution

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they obtain presents two broad peaks around the same two temperatures obtained with the usual two-temperature fits of the spectra. There is apparently no way of reproducing the observed differential emission measure distribution with a single family of magnetically confined loops. Rather, two families of loops are needed, characterized by different maximum temperatures. Schrijver et al. (1988) have further demonstrated that, even assuming two distinct families of loops, these are not consistent with the simple loop model of Rosner, Tucker and Vaiana (1978), i.e. with loops of constant cross-section, pressure and energy deposition. The TGS data require a very large expansion (of the order of a factor of 10) of the loop cross section towards the apex. This is because there is a deficit of low-temperature material (around a few million degrees) with respect to the high temperature material. Unfortunately, it is difficult to generalize these conclusions to all coronal sources and more high-resolution spectra need to be obtained. The much lower temperatures found for Procyon, as well as the absence of a high-temperature component in the corona of the Sun except during flares, argue against a direct extrapolation of the Capella and σ CrB results to all coronal sources. From an analysis of low-resolution (E/ΔE = 1) EINSTEIN IPC data, Schmitt et al. (1988) have inferred that most F and G dwarfs have, like the Sun, little high-temperature coronal material. On the contrary, single giants of spectral type G have hotter coronae (≈ 10^7 K) than single stars of similar spectral type and apparently lack a low-temperature component. Active M dwarfs also show evidence for high temperature plasma, while RS CVn binaries show definite evidence of very high temperature components. The reasons of these differences in the temperature structure of stellar coronae are not understood.

Pasquini et al. (1988) have carried out a comprehensive investigation of EXOSAT ME spectra of RS CVn stars during quiescent conditions (i.e. after excluding all flares). They have fitted the ME spectra and simultaneous LE data with one-temperature and two-temperature models as well as with a continuous emission measure distribution of the simple form (T/T_M)^{2\alpha}. This form (with \alpha \leq 1) is similar to what expected for a magnetically-confined loop structure with constant cross-section, heating and energy deposition. They found substantial differences among different RS CVn stars. Two-temperature models were all able to fit all data (except in the case of low S/N observations for which one-temperature models were already sufficient). A continuous emission measure model was able to fit part of the data, but not all of them. Moreover, for those cases when the continuous emission measure distribution was capable of fitting the observed spectra, the parameter \alpha came out to be > 1, indicating an excess of high-temperature material with respect to the simple emission measure distribution assumed. It is perhaps premature to use this results to speculate about the structure of stellar coronae; however, they clearly indicate that substantial differences must exist from one star to the other and that the coronae of RS CVn binaries are likely to be different from those of single solar-type stars.

b) Eclipsing binaries

Another area in which the EXOSAT Observatory has allowed major advances to be made is in the study of eclipsing binary systems. By using eclipses we can try to infer, at least approximately, the location and size of X-ray emitting structures in stellar coronae. The long continuous observations of EXOSAT are ideally suited for this type of studies. EXOSAT has obtained observations of several systems, including a 35 hours observation of Algol, centered on the secondary eclipse, and complete coverage of a full orbital period for AR Lac (P=1.98 days) and TY Pyx (P=3.20 days). Observations where also made of the partially eclipsing system ER Vul (over 1.5 orbital cycles) and of the short-period eclipsing system XY UMa (over 1.25 cycles). All these systems, except
Algol, belong to the class of RS CVn-type binaries. A continuous observation over one orbital cycle was made also of the eclipsing M dwarf binary YY Gem. Unfortunately, in this case a strong long-duration flare occurred just in the middle of the observation, thus making the interpretation of the light curve much more difficult.

Only part of the eclipse observations carried out by EXOSAT have so far been thoroughly analyzed. The observation of Algol (White et al. 1986) failed to reveal any eclipse when the K0IV X-ray bright component was behind the X-ray dark B8V primary (the two components have about the same radius). From this, it was inferred that an extended high-temperature corona with a scale-height of about one stellar radius, was around the K star. The observation of AR Lac was even more interesting (White et al. 1988). The primary eclipse was observed in the LE detector, but there was no obvious eclipse in the ME data. This indicates that there must be a high-temperature component sufficiently extended to avoid eclipses by the two stars, while at the same time compact structures must also exist close to the surface of one, or both, of the component stars.

White et al. (1988) have carried out extensive model simulations of the EXOSAT light curve of AR Lac, using $\chi^2$ fitting as well as maximum entropy techniques. Although it is not possible to constrain the model in a unique way, one needs in all cases large high-temperature structures (with a height $\geq R_*$) together with more compact structures whose sizes are much smaller than the stellar radius. Unfortunately, it is not possible to determine precisely on which star these various components are, and there are also ambiguities about the longitude and latitude distribution of the various components.

The interpretation of the light curves of eclipsing binary systems in not a trivial task. Apart from the intrinsic limitations of the method (first of all, lack of uniqueness of the derived solution), it requires data with very high S/N ratio and possibly extended over many orbital cycles. Under this respect, the EXOSAT data are far better than anything else obtained in the past (see, e.g., Walter et al. 1983), but, nonetheless, they are only a first attempt to disentangle the spatial structure of stellar coronae. At any rate, the picture that is consistently emerging from these observations suggests that structures of different sizes, temperatures and pressures coexist in close binaries. The more compact structures close to the stellar surface are apparently at a lower temperature and higher density than the more extended structures whose sizes are comparable and even larger than the stellar radius. The results of eclipse observations strongly suggest that the two temperature solutions found from spectral fits of the TGS data (see above) refer to spatially separated coronal regions, at least in the case of RS CVn binaries. This picture contrasts with what we know from the Sun, where more compact structures are hotter than larger structures (cf. Vaiana and Rosner 1978). Moreover, on the Sun, there is no obvious counterpart of the large ($\geq R_*$) high-temperature ($> 10^7$ K) components found in RS CVn binaries. This is another indication that the coronae of close binaries are likely to be fundamentally different from the corona of the Sun and of other single late-type stars.

c) Flare activity

The continuous look capability of EXOSAT has also been crucial for making major progress in our understanding of short-term variability and flares in the coronae of late-type stars. Flares have been observed by EXOSAT from many different types of stars, including classical dMe flare stars (UV Ceti, AT Mic, YZ CMi, EQ Peg, YY Gem, Wolf 630, etc.), RS CVn and Algol-type binaries (Algol, $\sigma$ CrB, II Peg, AR Lac, etc.), pre-main sequence objects (HD 560B and AB Dor), and even from a single solar-type star ($\pi^1$ UMa) and from an A-type binary (Castor). Many of these EXOSAT observations
were carried out simultaneously with UV, optical and radio observations, thus allowing a much better understanding of the complex flare phenomenon.

A large flare from Algol was observed by White et al. (1986). As most flares on RS CVn binaries, it was of large intensity and long duration. It lasted for about 5 hours and released \( \approx 1 \times 10^{35} \) erg in the spectral band 0.1-10 KeV (this is a factor 10\(^3\) higher than the total energy released by the largest solar flares over the entire electromagnetic spectrum!). Analysis of ME spectral data shows that the temperature decreased from a peak value of \( \approx 6 \times 10^7 \) K to \( \approx 2 \times 10^7 \) K in the late decay. Similar large X-ray energies and long durations (\( \approx \) hours) were also exhibited by flares observed by EXOSAT from the post-T Tauri star candidates HD560B and AB Dor (Tagliaferri et al. 1988, Collier Cameron et al. 1988). The first of these sources was discovered serendipitously by EXOSAT while pointing at the Seyfert galaxy III Zw 2. The simultaneous occurrence of the flare in the LE and ME, together with the imaging capability of the LE, allows an unambiguous identification of the flaring source with the star HD 560, which is formed by a B9V primary and a G0Ve secondary. Since late B and early A-type stars are not known to be X-ray emitters (see section 2 above), the most likely source is HD 560 B, which is a very young star still contracting towards the main-sequence. HD 560 B has been in fact identified as a post-T Tauri star, i.e. a star intermediate between classical T Tauri stars and zero-age main-sequence stars. Post-T Tauri's, although expected to be much more numerous than classical T Tauri stars, are extremely difficult to identify at optical wavelengths. X-ray observations may be the best way to find them. AB Dor (HD 38705) is also believed to be a very young object, probably a post-T Tauri star.

Pallavicini et al. (1988b) have carried out a comprehensive analysis of EXOSAT observations of solar neighbourhood flare stars using the entire EXOSAT sample (see also Pallavicini 1988d). Flares from dMe stars appear to cover a broad range of total X-ray energies (from \( \approx 2 \times 10^{30} \) erg to \( \approx 1 \times 10^{34} \) erg) and have a variety of different time scales (from a few minutes to hours). Analysis of spectral data from the EXOSAT ME shows that the observed temperatures are in the range \( \approx 2 \times 10^7 \) K to \( \approx 4 \times 10^7 \) K. Typically, the high-energy (ME) flux peaks earlier and decay faster than the low energy (LE) flux, similarly to what is observed in solar flares. There is evidence from the ME data that the plasma is cooling during the flare decay. There is usually a good temporal correspondence between X-ray flares and optical flares, although in one case a strong optical flare was observed with no accompanying X-ray flare (Butler et al. 1988). There appears to be very little correlation between X-ray and microwave flares at 6 cm and 20 cm (Kundu et al. 1988).

An interesting result that may be relevant for modelling stellar flares is the finding from EXOSAT data (Pallavicini 1988d) that two different types of flares may exist on dMe stars, i.e.: 1) impulsive flares (with rise times of a few minutes and decay times from several minutes to a few tens of minutes), which are reminiscent of compact flares on the Sun; 2) long-decay flares (with decay times of the order of \( \approx 1 \) hour or longer), which are reminiscent of solar long-duration two-ribbon flares. These morphological differences suggest the existence of real physical differences in the energy release process, as believed to occur for solar compact and two-ribbon flares (Pallavicini et al. 1977). Preliminary models of stellar X-ray flares are taking this classification into account, by either assuming a compact closed magnetic structure which remains unchanged throughout the hydrodynamic and thermodynamic evolution of the flare (Reale et al. 1988) or by assuming a large scale restructuring of the magnetic topology from an open configuration to a closed one (Poletto et al. 1988).

Another quite puzzling discovery made by EXOSAT is the detection of a flare from the A-type star Castor (Pallavicini et al. 1988c). This source is a visual binary (not
resolved by EXOSAT), formed by two A-type dwarfs (A1V + A2Vm), both spectroscopic binaries. Since we know from EINSTEIN observations (see section 2 above) that A-type dwarfs are not X-ray emitters, it is important to determine whether the flare originated from one of the A-type primaries of the system or from an unseen late-type companion. Unfortunately, it is not easy to answer this question. Spectral analysis of the flare shows that the temperature decreased from $\approx 5 \times 10^7$ K at the flare peak to $\approx 3 \times 10^7$ K in the late decay. The total energy released by the flare in the spectral band 0.1-10 keV was $\approx 4 \times 10^{33}$ ergs. These values, as well as the time scales involved, are very similar to those typically observed in flares from M dwarf stars. This suggests the possibility that the flare originated from a late-type companion, rather than from the A-type primaries of Castor (notice that the nearby companion Castor C = YY Gem is well resolved from Castor A+B in the LE data).

d) Microflares

Over the past few years considerable attention has been devoted to the possibility that coronal heating in the Sun and other late-type stars may result from continuous low level activity, produced by a large number of small flare-like events (e.g. Parker 1983, 1988). In the case of the Sun, evidence for this "microflaring" activity has been found in hard X-rays and in spatially resolved UV observations. EXOSAT data can provide information of the existence of "microflaring" activity in the coronae of other stars. Unfortunately, this is a topic that has given rise to some controversy and different authors have reached quite different conclusions. For instance, Butler et al. (1986) have suggested that quiescent emission from M dwarf stars results from a continuous succession of "microflares" lasting from tens of seconds to several minutes and with characteristic energies of $\approx 2 \times 10^{30}$ erg. They claim to have detected a signature of this "microflaring" activity in EXOSAT observations of flare stars and in the close temporal association found between X-ray events and simultaneously observed Hz events.

In order to test the above suggestion, Pallavicini (1987, 1988d) and Collura et al. (1988) have carried out a detailed investigation of the time variability of X-ray emission of M dwarf stars by applying two different statistical methods. In particular, they have searched for frequently occurring impulsive events with energies of $\approx 2 \times 10^{30}$ erg or less on time scales of a few hundred seconds (i.e. energies and time scales similar to those reported by Butler et al. for "microflares", but smaller than those typically observed in stellar flares). The first method (Pallavicini 1988d) compares the observed variance with the expected variance for a constant source and uses autocorrelation techniques to estimate the relevant time scales of the observed variability. The second method (Collura et al. 1988) is a modification of the classical $\chi^2$ test optimized for detecting stochastic variability in low count rate sources. It also allows determination of the amplitude and time scale of the variability, if the latter is present.

When applied to the same data sets, the two methods give consistently the same results. In no case evidence was found for continuous low-amplitude short-term variations in the quiescent emission of M dwarf stars, i.e. in periods during which no obvious large flare occurred. In all cases in which substantial variability was detected, it appeared in the form of either individual sporadic flares or as gradual variations. In contrast with the results of Butler et al. (1986), the observed variability appears to be confined to well defined periods of time, rather than being continuous. These statistical studies indicate that stellar "microflares", if they exist, must have an amplitude at X-ray wavelengths well below the sensitivity level of EXOSAT observations.
5. CONCLUDING REMARK

As shown above, the EXOSAT data have produced major advances in our understanding of the structuring and variability of stellar coronal sources. They have complemented in a very effective way the more sensitive EINSTEIN observations and have allowed us to obtain a better knowledge of the physical processes occurring in the coronae of stars. However, much work remains to be done before we can start having a detailed theoretical understanding of stellar coronae. Major progress is expected from the coming ROSAT mission and substantial advances should also be produced by several other X-ray missions that are now planned or under development (SAX, SPECTROSAT, ASTRO-D, JET-X, SPECTRUM-X). However, a major breakthrough in stellar coronal physics will occur only towards the end of this century with the launch of powerful spectroscopic missions such as AXAF and XMM. As discussed by Linsky (1987) for AXAF and by Pallavicini (1988e) for XMM, these missions will allow us to advance from the phenomenological and largely qualitative picture available at present to the stage where sound quantitative theories can be developed and confronted with the observational data.

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