STELLAR CORONAE: THE EXOSAT PICTURE

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ABSTRACT. The EXOSAT Observatory has allowed major progress to be made in our understanding of X-ray emission from late-type stars. This paper gives a summary of EXOSAT results on stellar coronae focussing on the following topics: a) the temperature stratification of coronae, as has been derived from low- and medium-resolution spectral data; b) the coronal spatial structure, as has been inferred from observations of eclipsing binary systems; 3) the time variability of coronal emission, as has been detected with the long, uninterrupted observations made possible by the highly eccentric orbit of EXOSAT.

1. INTRODUCTION

Until a few years ago, virtually all we knew about stellar coronae was based on observations obtained with the X-ray satellite EINSTEIN. The EINSTEIN Observatory gave us a comprehensive picture of the coronal phenomenon throughout the HR diagram and provided us with sufficiently large samples of data to allow statistical studies. With the observations from EINSTEIN we were able to study the luminosity function of X-ray emitting stars and to address fundamental questions such as the heating mechanism of coronae for stars of different spectral types and luminosity classes. In order to be able to address again similar problems for large and unbiased samples of data it will be necessary to wait until the launch of ROSAT in early 1990. Fortunately, long before that date, the EXOSAT Observatory, although much less sensitive than either EINSTEIN or ROSAT, has already provided us with many new and interesting results that have greatly increased our knowledge of coronal X-ray emission from stars.

The effective area of the Low Energy experiment on EXOSAT was about one order of magnitude smaller than that of the imaging experiments on EINSTEIN, so one could not expect to make with EXOSAT high sensitivity surveys and/or to detect new classes of objects. 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. First of all, EXOSAT had three different instruments on board, that were operated simultaneously: two of them, the Low Energy (LE) and Medium Energy (ME) experiments were particularly relevant for stellar observations (see the paper by White and Peacock elsewhere in this volume for a comprehensive description of the EXOSAT instrumentation). With the combination of these two instruments, it was possible to cover simultaneously a much larger spectral range than with EINSTEIN (from 0.04 keV to more than 10 keV, i.e. over the entire range = 1 to 300 Å). Secondly, EXOSAT had a very highly eccentric orbit which
allowed continuous observations for periods of up to three days, without the usual data
gaps -due to Earth eclipses and passages through regions of high background- that were
associated with all previous low-orbit satellites. The importance of this fact in order to
study stellar variability and flares is readily apparent. Finally, although for stars of early
spectral types EXOSAT suffered some UV contamination in the low-energy detectors, it
was free of this problem for stars later than ≈ F0. Thus, while EXOSAT could not add
much to our understanding of early-type stars (a problem that had to be postponed to
future X-ray missions), it contributed significantly to our understanding of cool stars.

In this paper, I will concentrate on three main topics for all of which the EXOSAT
Observatory has produced major advances. They are: a) the temperature stratification of
stellar coronae, both for single stars and close binaries; b) the spatial structure of
coronae, with emphasis on binary systems; c) the time variability of coronal X-ray
emission, during both quiescent periods and flares. Before discussing the new EXOSAT
results, however, it may be useful to give some background information by summarising
the main results obtained previously with the EINSTEIN Observatory.

2. A SHORT SUMMARY OF EINSTEIN RESULTS

Of the many important results on stellar coronal sources obtained with the
EINSTEIN Observatory, probably the most fundamental one was the discovery that stars
of nearly all spectral types possess X-ray emitting coronae (Vaiana et al. 1981). Apparent-
ly the only exceptions are A-type dwarfs - for which there is no unambiguous
evidence of X-ray emission, except for a few Ap stars (Cash and Snow 1982, Schmitt et
al. 1985a; see however Caillault and Zoonemat Kermani 1987)- and late-type giants and
supergiants. The available evidence indicates that there is a "dividing line" in the HR
diagram between stars with massive low-velocity winds and no measurable coronal X-
ray emission, and stars like the Sun which have a weak high-velocity wind and a hot
for the existence of this dividing line are as yet poorly understood (see, for instance,
Haisch 1986, 1987). Similarly, the reason why A-type dwarfs are weak - if at all- X-ray
emitters is also not yet clear.

Another fundamental result of the EINSTEIN Observatory was the finding that
there is an apparent dichotomy between early-type stars (O and B) and late-type stars (F
to M) with regard to the dependence of X-ray coronal emission on basic stellar
parameters (Pallavicini et al. 1981). While the X-ray luminosity of early-type stars
(which is observed to range from $10^{29}$ erg s$^{-1}$ to $10^{34}$ erg s$^{-1}$) depends on bolometric
luminosity ($L_X \sim L_{bol}^{7/2}$) and is independent of rotation, the reverse occurs for late-type
stars, which show no obvious dependence on the stellar radiation field, but depend
strongly on rotation ($L_X \sim V_{rot}^{2}$). This remarkable dichotomy suggests that, whatever the
heating mechanism of stellar coronae might be, it must be fundamentally different for early-
and late-type stars. For the latter ones, we may probably use the solar analogy as a
guide-line; for early-type stars the use of such an approach is hardly justified, and is
likely to lead to completely erroneous conclusions. For stars of late spectral types there is
indirect evidence that the heating originates from the dissipation of dynamo-generated
magnetic fields (Rosner, Golub and Vaiana 1985, Linsky 1985). For early-type stars, no
satisfactory theory exists as yet, although some plausible scenario, which needs to be
tested by future X-ray missions, has been proposed. One possibility is that X-ray
emission originates from shock heating in high density blobs in the massive radiativley-
driven winds of these stars (Lucy and White 1980, Lucy 1982, Waldron 1984; see also
Cassinelli 1985 for a review).
More specifically, the EINSTEIN Observatory showed that the X-ray luminosity of late-type dwarfs (F to M) range from $10^{26} \text{ erg s}^{-1}$ to nearly $10^{30} \text{ erg s}^{-1}$ (cf. Schmitt et al. 1985a, Bookbinder 1985, Maggio et al. 1987). It shows very little dependence on spectral type, but presents a broad range of emission levels at each spectral type (typically more than three orders of magnitude). The level of coronal emission appears to depend primarily on rotation and age (Pallavicini et al. 1981, 1982, Stern et al. 1981, Walter 1982, Micela et al. 1985 and 1987, Caillault and Helfand 1985): the latter dependence is probably simply due to the decrease of stellar rotation rate with age, as a consequence of magnetic braking by stellar winds. There are also indications that subphotospheric convective motions are important in determining the level of coronal emission in late-type stars (Schmitt et al. 1985a, Bookbinder 1985): however, the dependence on convection among late-type stars is not as well established observationally as the dependence on rotation. A dependence on both rotation and convection is what is expected - at least at a qualitative level - from coronae heated by dynamo-generated magnetic fields. The apparent dependence of chromospheric and coronal emission on the Rossby number (i.e. the ratio of rotation period to the convective overturn time) is in qualitative agreement with this concept (cf. Noyes et al. 1984, Maggio et al. 1987).

The EINSTEIN Observatory also showed that the spectra of coronal sources are thermal and can be well represented by the line + continuum emission of an optically-thin thermal plasma, as is the case for the solar corona. The temperatures found in typical coronal sources outside flares range from a few million degrees Kelvin to a few times $10^7$ K, and there are indications of a multi-temperature, possibly bimodal, structure (Swank et al. 1981, Swank 1985, Majer et al. 1986, Schmitt et al. 1988). The EINSTEIN Observatory also showed that time variability is ubiquitous among late-type stars (Vaiiana 1983, Ambruster et al. 1987) and that flares occur frequently at least in M dwarf stars (Haisch 1983). However, the many data gaps present in the EINSTEIN observations, and the short exposure times typically used with EINSTEIN, did not allow an accurate characterization of time variability and flaring properties of stellar sources. The strong X-ray emission from RS CVn binaries -first detected with HEAO-1 (Walter et al. 1980)- was confirmed by EINSTEIN, which showed that virtually all close binaries of the RS CVn type are vigorous X-ray emitters, usually much stronger than typical single stars of similar spectral type. The X-ray luminosities of RS CVn binaries are of the order of $10^{30}$ to $10^{31} \text{ erg s}^{-1}$. Although this high luminosity is consistent with the typical high rotational velocity of these binaries, there is very little dependence on rotation within the class itself (Majer et al. 1986).

Another interesting class of coronal sources discovered by the EINSTEIN Observatory are pre-main-sequence stars, of which hundreds have been detected in Orion, Taurus-Auriga, ρ Oph and other stellar associations (Feigelson 1984, 1985, Walter 1986, Walter et al. 1988 and references therein). When detected, pre-main-sequence objects have been found to be vigorous X-ray emitters with X-ray luminosities ranging from $10^{29} \text{ erg s}^{-1}$ to more than $10^{31} \text{ erg s}^{-1}$. There appears to be an inverse correlation between the level of coronal emission and the H-α emission of these stars, which suggests that the massive circumstellar envelopes of most T-Tauri stars (from which the H-α emission originates) strongly absorb X-rays (Walter and Kuhi 1981). However, the origin of X-ray emission in these objects is still poorly known and it is at all unclear whether X-rays originate by the same mechanism responsible for coronal emission in other late-type stars, or by completely different processes, possibly related to the presence of the dense circumstellar envelopes (see, e.g., Vaiiana and Scintino 1987 and references therein). Pre main sequence objects display dramatic variability at X-ray.
wavelengths (e.g. Montmerle et al. 1983) and it is possible that they may be in a perpetual state of flaring.

In brief, this is what the EINSTEIN Observatory has shown us about stellar coronae. These observations have given us a first broad overview of the coronal phenomenon for different types of stars, and have raised many important questions about the origin and properties of X-ray emission in stars. It is against this background that we should evaluate the contribution given by the EXOSAT Observatory to the clarification of some of these problems (for a more detailed discussion of EINSTEIN results on stellar coronae see Rosner, Golub and Vaiana 1985, Serio 1985, Haisch 1986, Vaiana and Sciortino 1986 and 1987, Schmitt 1988).

3. THE TEMPERATURE STRATIFICATION OF STELLAR CORONAE

Spatially-resolved observations of the Sun at X-ray wavelengths show that the solar corona is highly inhomogeneous and constituted by an ensemble of distinct magnetic structures differing one from another in both temperature and density. We may expect that something similar -although not necessarily equal- may occur for the coronae of other stars. It would be extremely important, therefore, to derive the temperature and spatial structure of stellar coronae for stars of different spectral types, luminosity classes, rotation rates and ages.

In order to infer the temperature structure of stellar coronae one needs high-resolution spectral observations: unfortunately, only a limited number of such observations were performed by the EINSTEIN Observatory, using the Solid State Spectrometer (SSS) and the Objective Grating Spectrometer (OGS) on board. In the vast majority of cases, only some coarse information on temperature could be derived from low-resolution observations obtained with the Imaging Proportional Counter (Schmitt et al. 1987b, Schmitt et al. 1988). The same is largely true also for EXOSAT, which obtained only a few high resolution coronal observations with the Transmission Grating Spectrometer (TGS), in addition to a much larger sample of spectral data obtained with the ME experiment. In all other cases, broad-band observations were performed using filters. In this section, I will discuss the spectral data obtained by EXOSAT, and their relevance for the understanding of the temperature stratification in stellar coronae. I will discuss first broad-band observations obtained with the LE telescope, and then the spectral data obtained with the TGS and the ME experiment (for a more detailed discussion of TGS observations see the contribution of Heise elsewhere in this volume).

After the failure of the Position Sensitive Detectors (PSD) early in the mission, the LE telescopes on EXOSAT were used most of the time in combination with Channel Multiplier Array (CMA) detectors, which have no intrinsic spectral resolution. In order to get some crude spectral information, the CMA can be used in conjunction with different filters and the measured count rates can be compared with those predicted on the basis of model spectra (broad-band photometry). The filters that were used most commonly for stellar observations were the Thin-Lexan (3-Lex), Thick-Lexan (4-Lex), Parylene-N + Aluminium (Al-Pa) and Boron. They have different spectral responses, and the ratio of the count rates obtained in two different filters is in principle a measure of coronal temperature, if the source can be assumed to be isothermal.

Unfortunately, the derivation of coronal temperatures from broad-band EXOSAT observations is by no means a trivial task. The basic difficulty is well illustrated by Fig. 1, which shows the computed ratio of count rates for various pairs of EXOSAT filters as a function of temperature and for hydrogen column densities N_H = 1 x 10^{18} cm^{-2} and N_H
Fig. 1: Computed ratio of count rates for various pairs of EXOSAT filters as a function of temperature and for two values of interstellar absorption (from Pallavicini et al. 1988a).

Fig. 2: Observed ratio of 3-Lex to IPC fluxes for stellar sources observed by both EXOSAT and EINSTEIN. The dashed area is what would be expected from the different passbands of the two satellites (from Pallavicini et al. 1988a).
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= 5 x 10^{18} \text{ cm}^{-2}, \text{respectively. For the typical filter ratios found in nearby stellar coronal sources (Al-Pa/3-Lex = 0.3-0.5), one usually gets two and even three solutions over the temperature range log T = 6.0 - 8.0 K pertinent to coronal sources. Further solutions could also formally be obtained at lower temperatures (= 5 x 10^5 K). This is an intrinsic limitation of filter spectroscopy with EXOSAT, which would persist even for a truly isothermal source. Moreover, different filter pairs usually give different temperatures. What is the physical meaning of the various temperatures derived in this way? As will be discussed later, probably none of the temperatures derived from broad-band EXOSAT observations is the correct one if the source is characterized by a continuous emission measure distribution vs. temperature. The most likely interpretation of the available data is that the source is not isothermal, and, therefore, different filters sample different plasma regions (Pallavicini et al. 1988a, Schmitt and Rosso 1988).

The conclusions above is further supported by a comparison of EXOSAT LE and EINSTEIN IPC observations of the same sources (Schmitt et al. 1987b, Pallavicini et al. 1988a). One such comparison is shown in Fig. 2. The EXOSAT fluxes appear to be systematically higher than the IPC fluxes by a factor 2 to 3. This is far in excess of what would be expected on the basis of the different spectral bands observed by the two satellites (shaded area). Since it is unlikely that almost all stars in the sample were found in a high-state by EXOSAT, a more plausible interpretation is that the EXOSAT 3-Lex and the IPC were not looking at the same plasma volume and that the effective temperatures seen by the two satellites were substantially different. The excess flux is likely provided by plasma at temperatures T \leq 3 x 10^6 K which contributes significantly to the 3-Lex flux, and little to the IPC spectral band.

Better constraints on source temperature have been provided by observations at higher resolution obtained by the Transmission Grating Spectrometer (TGS) and the ME energy experiment aboard EXOSAT. These observations, however, were possible only for very bright and/or sufficiently hard sources, mostly binaries of the RS CVn type. As an example, Fig. 3 a,b shows the spectra of two bright RS CVn binaries (Capella and \sigma CrB) obtained with the TGS (Mewe et al. 1986; see also Schrijver 1985). Although individual lines were still not well resolved, the broad line complexes discernible in these spectra are already sufficient to constrain quite well the range of temperatures present in the source. In both cases, a best fit of the data requires two components, one at \approx 5 x 10^6 K and the other at \approx 20 x 10^6 K.

The results shown in Fig. 3a,b are typical of what found by EXOSAT and EINSTEIN for bright stellar coronal sources. In all cases in which the spectral resolution and the S/N ratio were sufficiently high, it was invariably found that spectra of stellar coronae require at least two-temperatures, with one component at a temperature of a few to several million degrees, and the other one at a temperature nearly one order of magnitude higher. This is true for the EXOSAT TGS observations of Capella and \sigma CrB discussed above, as well as for the larger sample of stars (mostly RS CVn binaries and Algol-type systems) observed with the SSS experiment on EINSTEIN (Swank et al. 1981) and with the ME experiment on EXOSAT (Singh et al. 1987, Pasquini, Schmitt and Pallavicini 1988). This is also true for the lower resolution observations of both RS CVn and single active stars obtained with the IPC on EINSTEIN (Majer et al. 1986, Schmitt et al. 1987b, Schmitt et al. 1988).

Taken at face value, these two-temperature models suggest the co-existence in stars of separate regions in two distinct temperature regimes. More physically, these two regions could be constituted by two different families of loops, characterized by different physical conditions. Alternatively, the two temperature solutions could be a consequence

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Fig. 3a,b: EXOSAT TGS observations of the RS CVn stars Capella and \( \sigma \) CrB (from Mewe et al. 1986). Two-temperature fits of the data are also shown.
of limited spectral resolution and energy dependence of detector response, if the sources were characterized, as it is for the Sun and probably also for other single stars, by a continuous emission measure distribution with temperature. Observations of the Sun show that coronal emission comes predominantly from magnetically confined loop-like structures with a continuous emission measure distribution, rather than from isothermal regions. Furthermore, on the Sun, temperatures in excess of \( T = 10^7 \) K are usually found only during transient flare-like events (Vaiana and Rosner 1978). We note that the steady high-temperature component (at \( T = 10^7 \) K) seen outside flares by the HXIS experiment on the Solar Maximum Mission (Schaade et al. 1983) contributes negligibly (\( \approx 10^{-3} \)) to the integrated X-ray flux of the Sun.

Different authors have argued in favor of one or the other of the above alternatives. For instance, Schmitt (1984) and Majer et al. (1986) have pointed out the existence of systematic differences in the temperatures derived by observing the same sources with different instruments: this suggests a dependence of the results of spectral fits on detector response. Moreover, Schmitt et al. (1987b) and Pasquini, Schmitt and Pallavicini (1988) have shown with the help of Monte Carlo simulations that two temperature fits can be obtained also for a continuous emission measure distribution and, therefore, two temperature fits do not necessarily imply physically distinct regions. More specifically, the above authors have made Monte Carlo simulations of EINSTEIN IPC data and of EXOSAT LE and ME data, using a continuous emission measure distribution of the form \( EM \sim (T/T_M)^\alpha \), which closely mimics the emission measure distribution in magnetically confined loops in energy balance and static conditions (see, e.g., Antiochos and Noci 1986; \( T_M \) is the maximum temperature in the loop). When the simulated data are analyzed spectrally in the same way as real data, it is found that the derived temperatures cluster around two well separated values, as observed.

On the other hand, Mewe et al. (1986) and Schrijver (1987) have found it difficult to explain with a single family of loops EXOSAT TGS observations of RS CVn binaries. The differential emission measure distribution they derive from the data has two well separated peaks, centered at the two temperatures found by fitting the data with the usual two-temperature isothermal models. White et al. (1986, 1987b, 1988) have provided evidence, on the basis of eclipse observations, that two distinct families of loops, different in both temperature and size, coexist in binaries. These eclipse observations, to which we will come back in the next section, indicate that the higher temperature component most likely originates from very large structures which extend up to more than one stellar radius. There is no evidence on the Sun that large structures of this type - if they exist - contribute significantly to the total coronal X-ray emission.

At present, the situation appears by and large unclear. Pasquini, Schmitt and Pallavicini (1988), while analyzing a sample of EXOSAT ME observations of RS CVn binaries, found it possible to fit some, but not all of them, with a continuous emission measure distribution. Whereas they were able to fit with a continuous distribution the LE and ME observations of UX Ari and other sources, they were unable to do so for ME observations of Capella obtained simultaneously with the TGS data discussed by Mewe et al. (1986) and Schrijver (1987). It is possible that different situations (one or two families of loops) may hold for single and binaries systems, or even for different stars within the same class. At any rate, the results of eclipse observations to be discussed below strongly suggest the presence of two families of loops in close binary systems as well as the existence of fundamental differences between the coronae of single stars and the coronae of close binaries. Clearly, there is a need of further high-resolution spectral observations to resolve the temperature structure of stellar coronae: such observations will hopefully be obtained by the next generations of X-ray Observatories, including NASA's AXAF and ESA's XMM.
4. THE SPATIAL STRUCTURE OF CLOSE BINARY SYSTEMS

Except in a few very special cases (e.g. eclipsing binary systems), it is usually not possible to obtain information on the spatial structure of stellar coronae. An X-ray observation of a stellar source will provide a disk-integrated flux, from which we can infer indirectly some limited, and model-dependent, information about spatial structures. What is usually done is to assume a certain model configuration - for instance an ensemble of loops, as suggested by observations of magnetic structures on the Sun - and try to determine the physical parameters of this configuration by $\chi^2$ fit of disk-integrated data. This approach is not without pitfalls and, what is even more important, it does not guarantee that an acceptable solution (in a purely statistical sense) is also a physically appropriate description of the coronal source (see, for instance, Schmitt et al. 1985b, Giampapa et al. 1985, Landini et al. 1985a,b, Stern et al. 1986).

Fortunately, there is at least one class of objects (the eclipsing binary systems) for which somewhat more direct information on coronal structures can in principle be obtained. This is an area in which the EXOSAT contribution has been particularly important. In the case of an eclipsing binary, one can use the periodic eclipses of one star by the other to roughly infer the location and size of coronal structures. For the technique to be effective, one needs data with high S/N ratio and which extend continuously over long periods of time: in addition, several consecutive cycles should be observed, in order to separate the modulation due to the eclipse from possible intrinsic changes in the emission of the component stars. Even with the best available data, there is always the problem of the uniqueness of the solution, as well known to those who attempt to infer the properties of photospheric stars from the observed light curves of BY Dra and RS CVn stars (e.g. Rodonò et al. 1986).

The technique of using eclipse observations to infer the structure of stellar coronae was first applied by Swank and White (1980) and by Walter, Gibson and Basri (1983), using the EINSTEIN Observatory. They observed the RS CVn binary AR Lac, which is formed by a G2 IV primary (with $R=1.5 \ R_\odot$) and a KO IV secondary (with $R=2.8 \ R_\odot$), separated by 9.1 $R_\odot$. In spite of the many gaps present in the data owing to the low orbit of the satellite, Walter et al. (1983) were able to observe a deep primary eclipse (when the G star is occulted by the K star) and a shallow minimum preceding secondary eclipse (when the K star is behind the G star). From this they concluded that compact coronal structures were present on both stars and, in addition, that an extended corona, highly inhomogeneous in longitude, was around the K0 IV component. They also tentatively identified the extended component with the high temperature solution found by Swank et al. (1981) from spectral fits of SSS data: the identification, however, could only be considered hypothetical at that time.

However, it has been only with the long, uninterrupted observations provided by the EXOSAT Observatory that it has become possible to fully exploit the technique of eclipse observations (White et al. 1986, 1987a,b, 1988). EXOSAT has obtained observations of several systems, including a 35 hour continuous 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). Unfortunately, no source has been observed so far for more than one orbital cycle (except ER Vul, which, however, is only a partially eclipsing system; cf. White et al. 1987a). The observation of Algol (White et al. 1986) failed to reveal any eclipse when the K0 IV X-ray bright component was behind the X-ray dark B8 V primary (see Fig. 4; note that the two components have about the same radius). From this it was inferred that an extended high temperature corona with a
Fig. 4: EXOSAT LE and ME observations of Algol centered on the secondary eclipse. No evidence of an X-ray eclipse is apparent (from White et al. 1986).

Fig. 5: EXOSAT LE and ME observations of the eclipsing binary AR Lac throughout a full orbital cycle. The primary eclipse is seen in the LE data, but not in the ME data (from White et al. 1987b).
scale-height of $\approx 1 R_\star$ was around the K star. The observation of AR Lac is even more interesting (White et al. 1987b, 1988; see Fig. 5). The primary eclipse was observed in the Low Energy detector (as it was with the IPC on EINSTEIN), but there was no obvious eclipse in the Medium Energy 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 at least one of the component stars.

White et al. (1987b, 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. An early modelling attempt (White et al. 1987a) showed that the deep primary eclipse in the LE data could be reproduced by assuming an X-ray emitting structure on the G star on the side facing the K0 IV component. This structure had an angular half-width of $\approx 27^\circ$. The shallow secondary eclipse required in addition a much larger structure (with a height of $\approx 1 R_\star$) above the K star which extended for $\approx 90^\circ$. Extending the fit to include the whole light curve showed that there must be also a third X-ray structure on the rear face of the G star to account for the large uneclipsed excess flux around secondary eclipse. The height of both structures on the G star is small ($< 0.1 R_\star$). Subsequent more refined simulations (White et al. 1988) showed that it is not possible to constraint the model to be unique, but that in all cases one needs large high-temperature structures in addition to compact ones. It is not possible, however, to determine precisely on which star the various components are, and there are also uncertainties about the longitude and latitude distributions of the various components.

The picture emerging from these eclipse observations, although somewhat model dependent, suggests that structures of different sizes, temperatures and pressures may 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. We do not know what these extended components are. They might be related to large-scale magnetic fields connecting the two stars, as has been suggested by extrapolations of photospheric fields (Uchida and Sakurai 1983). Direct evidence for the existence of extended magnetospheres embracing the entire binary system has been provided by VLBI radio observations (Mutel et al. 1985, Massi et al. 1988).

Recently, White et al. (1988) have suggested that the large high-temperature X-ray emitting regions may be the long-lasting remnants of material heated and released during flares. The large regions, in fact, are at much lower density than the more compact structures close to the stellar surface, and their radiative cooling time may be as long as several days. Alternatively, the extended components may represent the upper end of a range of more persistent solar-like loops whose larger dimensions are allowed by the lower gravity and higher temperature (and hence larger pressure scale-height) of RS CVn binaries. In either case, the bimodal temperature distribution found by spectral fitting of SSS and EXOSAT TGS data (Swank et al. 1981, Mewe et al. 1986) seems to be confirmed by these eclipse observations and to really indicate physically distinct regions. If so, the coronae of RS CVn and other close binary systems should be quite different from the solar corona, whose structures typically have heights $\leq 0.1$ of the solar radius. This possibility of the existence of a fundamental difference between single and binary stars should be taken into account when trying to extend to binary systems the same type of concepts usually adopted for the solar case.
5. THE TIME VARIABILITY OF STELLAR CORONAL EMISSION

Prior to EXOSAT very little was known on time variability of coronal X-ray sources. The observations from the EINSTEIN Observatory were usually quite short (= a few thousands seconds) and longer observations - when available - were interrupted by Earth eclipses and passages through regions of high background. Furthermore, systematic effects and the poor knowledge of source temperature made it difficult to compare observations obtained with different satellites in search of long-term variations (as could be expected from stellar activity cycles). For instance, fluxes measured with the EINSTEIN IPC and the EXOSAT LE may have systematic differences of up to a factor of ≈ 2, owing to the different spectral bands and to the temperature dependence of the detector response (Pallavicini et al. 1988a). The most comprehensive study of stellar X-ray variability before the advent of EXOSAT was probably that of Ambruster et al. (1987). They analyzed a sample of active late-type stars (mostly flare stars), using an improved version of the classical χ² test (Collura et al. 1987). They found that variability is ubiquitous in their sample of K and M stars, with a typical amplitude of ≈ 30% and time scales ranging from a few hundred seconds to more than 1000 sec. However, the presence of many data gaps, typical of EINSTEIN observations, makes the physical nature of the observed variability rather unclear. In addition, long time scales (including the entire evolution of long-lived transient events) could not be adequately studied with EINSTEIN (except in a few very special cases, cf. Haish et al. 1983).

The EXOSAT satellite has dramatically increased our knowledge of time variability of stellar coronal sources. With the new EXOSAT observations we are starting to become aware of the rich variety of transient phenomena observed on X-ray stars, and we are now in a better position to make comparisons with similar phenomena observed on the Sun. The quality of the data allows for the first time realistic modelling of the observed emission and the derivation of meaningful physical parameters. In this section, I will discuss both flares and the more subtle variations which may occur during relatively quiescent periods.

a) Stellar flares

Flares have been observed by EXOSAT on many different types of stars (Brinkman et al. 1984, Barstow 1985, de Jager et al. 1986 and 1988, Landini et al. 1986, White et al. 1986, Smale et al. 1986, Nelson et al. 1987, Haish et al. 1987, Butler et al. 1987, Kundu et al. 1988, Pallavicini 1988, Pallavicini and Tagliaferri 1988, Doyle et al. 1988a and b, Tagliaferri et al. 1987 and 1988, van den Oord, Mewe and Brinkman 1988, Collier Cameron et al. 1988, Pallavicini, Stella and Tagliaferri 1988). They have been observed from classical DMe flare stars (UV Cet, AT Mic, YZ CMi, EQ Peg, YY Gem, Wolf 630 etc., cf. Figs. 6, 7 and 8), on RS CVn and Algol-type binaries (σ CrB, Algol, II Peg, TY Pyx etc., cf. Figs. 4 and 5), in pre-main sequence objects (HD 560B and AB Dor, cf. Tagliaferri et al. 1988 and Collier Cameron et al. 1988) and even from a single solar-type G star (π¹ UMa, cf. Landini et al. 1986). The flare on Algol (see Fig. 4) and most flares on RS CVn binaries typically lasted for several hours and involved energies as large as ≈ 10^{35} ergs in the X-ray band. Flares on M dwarf stars, on the contrary, are usually less powerful and may last as short as a few minutes. The flare on the young solar-type star π¹ UMA released ≈ 10^{33} erg in the X-ray band, i.e. a factor = 10 more than the total energy released in the most powerful solar flares. Flares observed from the post-T Tauri star candidates HD 560B and AB Dor had a total energy of ≈ 10^{35} erg, indicating an enormous degree of magnetic activity in these stars.

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Fig. 6: EXOSAT LE observation of UV Ceti showing the occurrence of a flare and more gradual variations during the preflare phase (from Pallavicini 1987). The observation covers continuously a period of nearly 10 hours.

Fig. 7: EXOSAT LE observation of AT Mic showing the occurrence of a large flare and steady emission during the five hours preceding it (from Pallavicini 1987). Notice the enhanced emission in the late flare phases.

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One of the best examples of flares observed with EXOSAT is the five hours long event which occurred on Algol on 19 Aug 1983 (see Fig. 4). The flare started at = 10:00 UT, peaked at = 11:00 UT and then decayed steadily until = 15:00 UT. This flare was first studied by White et al (1983) and later by van den Oord and Mewe (1988) and Pallavicini and Tagliaferri (1988). The latter authors have subdivided the flare into five time intervals, one during the rise phase (from 10:00 to 11:00 UT) and the other four during the decay. ME spectra were accumulated over these five time intervals, after subtraction of a preflare quiescent spectrum. It was found that the temperature was decreasing from a peak value of (6.1 ± 0.8) x 10^7 K to (2.3 ± 0.6) x 10^7 K in the late decay. During the same time interval the volume emission measure decreased from 6.7 x 10^{53} cm^-3 to 1.1 x 10^{53} cm^-3. The average temperature during the rise phase (from 10:00 to 11:00 UT) was (5.2 ± 0.8) x 10^7 K and the emission measure was 3.0 x 10^{53} cm^{-3}. Although the count rates were not sufficiently high to resolve the temperature variations during the rise phase, these data clearly indicate that the plasma, after an initial rapid heating, was slowly cooling during the decay of the flare. The total energy released over the spectral band 0.1 - 10 KeV was 1.1 x 10^{35} erg.

The largest number of flares observed by EXOSAT occurred on dMe stars. A systematic analysis of the EXOSAT data sample (Pallavicini, Stella and Tagliaferri 1988) shows that these flares cover a broad range of total X-ray energies (from ≈ 2 x 10^{35} erg to = 1 x 10^{34} erg) and have a variety of different time scales (from a few minutes to hours). There is evidence in the EXOSAT data for at least two different types of flares on M dwarf stars, i.e.:

a) impulsively flares (with rise times of a few minutes and decay times of tens of minutes), which are reminiscent of compact flares on the Sun. Examples are the events observed on AT Mic: 25 May 1985, Wolf 630: 25 Aug 1985, UV Cet: 23 Dec 1985, and others (cf. Figs. 6 and 7).

b) long-decay flares (with decay times of the order of = 1 hour or longer), which are reminiscent of solar long-duration 2-ribbon flares. Examples are the flares observed on YY Gem: 14 Nov 1984 and EQ Peg: 6 Aug 1985 (cf. Fig. 8).

As we shall discuss in a moment, these morphological differences probably indicate real physical differences in the energy release process, as it appears to be true also for solar compact and 2-ribbon flares (Pallavicini, Serio and Vaiana 1977). It is interesting to note that different types of flares may occur on the same star. For instance, EQ Peg and YY Gem showed flares of both types. Analysis of spectral data from the ME experiment on EXOSAT (Pallavicini and Tagliaferri 1988) shows that the observed temperatures are in the range = 2 x 10^7 to = 4 x 10^7 K, independently of the type of flares (at least within the small available data sample). There is evidence from the ME data that the plasma is cooling during the flare decay. Typically, the high energy (ME) flux peaks earlier and decay faster than the low energy (LE) flux, similarly to what observed for solar flares.

In order to model the observed flares we may assume a single magnetically-confined loop, which remains unchanged throughout the flare evolution. We may also assume that energy is released impulsively close to the top of the loop, and that there is no energy input during the decay phase. These assumptions are the same as those believed to be valid for compact flares on the Sun (Moore et al. 1980). Under these assumptions, the flare will decay through radiative and conductive losses whose characteristic times depend on temperature, density and loop length (or, more correctly, on a characteristic length-scale for the temperature gradient at the footpoints of the coronal loop, cf. Landini et al. 1986). In order to estimate the physical parameters of the flaring
Fig. 8: EXOSAT LE observation of the eclipsing binary flare star YY Gem throughout a full orbital cycle. Note the large long-decay flare (from Pallavicini 1987).

Fig. 9: EXOSAT ME observation of a flare from the A-type visual binary Castor A+B (from Pallavicini et al. 1988b). Comparison with simultaneous observations by the EXOSAT LE shows that the flare originated entirely from Castor, and not from the M dwarf companion YY Gem (Castor C).
region, the observed decay time is usually equated to the radiative time, and the further assumption is made that conductive and radiative times are approximately equal. This approach, although quite crude, gives reasonable numbers when applied to flares on dMe stars. Densities, temperatures and volumes derived in this way (\(T = 2-4 \times 10^7\) K, \(n = 10^{11-10^{12}}\) cm\(^{-3}\), \(V = 10^{27-10^{28}}\) cm\(^3\)) are not very different from those typically observed in solar flares, except for the total energy release which may be several orders of magnitude higher.

Are the above order of magnitude estimates realistic? Recently, Schmitt et al. (1987a) have tested this question by applying the above formalism to solar flares observed with the EINSTEIN Observatory by looking at the X-ray radiation scattered by the Sun-lit Earth. The parameters derived for these flares were in agreement with those derived directly from spatially resolved solar observations, thus supporting the basic correctness of the method, at least to a first approximation.

A more sophisticated approach for modelling compact flares involves the use of hydrodynamic codes which describe the response of the stellar atmosphere to various heating depositions under prescribed geometric conditions. A flaring loop is not an isolated system: it is rooted in the dense chromospheric and photospheric layers, and the flare evolution will depend on the complex hydrodynamic phenomena which result from this coupling. More specifically, if energy is deposited at the loop top, it will be transferred to lower levels either by accelerated particles or by heat conduction. When the chromosphere receives more energy than can be radiated away, it expands upwards (chromospheric evaporation) filling the loop with high density plasma. This in turn will profoundly affect the subsequent evolution of the flare. Full hydrodynamic calculations of this type have been carried out for the Sun and have been successfully applied to flares observed from the Solar Maximum Mission (Pallavicini et al. 1983, Cheng et al. 1983, Peres et al. 1987). In principle the same type of modelling can be applied to stellar flares as well: this should allow us to get a better insight into the physics of the flare phenomenon. A first attempt in this direction has recently been made by Reale et al. (1988) for a flare observed on Prox Cen by the EINSTEIN Observatory. The EXOSAT observations, with their continuous coverage and ME spectral information, provide an ideal sample for further pursuing this modelling effort.

A completely different model is required for long-duration stellar flares, if they are indeed the stellar analogs of solar two-ribbon flares. These flares are believed to occur under the action of an unbalanced Lorentz force, relax back to a closed field configuration of lower energy: the excess energy is released gradually by magnetic reconnection as the field lines reconnect at progressively higher altitudes during the flare decay. Comparison of model calculations with observations have shown that the model is capable of reproducing the main characteristics of solar two-ribbon flares. The same model has been applied by Poletto et al. (1988) to two long-duration stellar flares. The first one was observed by EXOSAT from the star EQ Peg, while the second one is the long-decay flare from Prox Cen that was modelled by Reale et al. (1988) as a compact flare. The comparison of model predictions and observations show that the reconnection model is indeed capable of reproducing the main characteristics of the decay phase of the observed flares, thus supporting the identification of these long-duration events as stellar analogs of solar two-ribbon flares. Although the model is not capable of determining the physical parameters of the flaring regions in a unique way, it is possible to derive some useful constraints on their values. For instance, the flare on EQ Peg probably occurred in a small localized region, covering \(\approx 1\%\) of the stellar surface, where the photospheric magnetic field was on the order of \(\approx 3600\) Gauss. The rising flaring arches reached a height of \(\approx 40,000\) Km, with an initial upward velocity of \(\approx 5\) Km s\(^{-1}\).
Before leaving the subject of stellar flares I would like to mention the unexpected
discovery by EXOSAT of a flare from the early-type star α Gem=Castor (Pallavicini
1987, Pallavicini et al. 1988b). This source is a visual binary (not resolved by
EXOSAT), which is formed by two A-type dwarfs (A1V + A2Vm), both spectroscopic
binaries. Since we know from previous EINSTEIN observations that A-type dwarfs are
not strong X-ray emitters (if at all, cf. Schmitt et al. 1985a), it is important to ascertain
whether the flare originated from one of the A-type primaries in the system, or rather
from an unseen late-type companion. Unfortunately, it is not easy to answer this question
since the source was strongly contaminated by UV radiation in the EXOSAT 3-Lex data
and was confused with the nearby strong source YY Gem (Castor C) in all previous
EINSTEIN’s IPC observations. However, the flare was seen both by the LE and ME
experiments on EXOSAT (see Fig. 9) and there is no doubt that it was a genuine X-ray
flare. Spectral analysis of the flare shows that the temperature decreased from \(5 \times 10^7\)
K at the flare peak to \(3 \times 10^7\) K in the late decay, while the volume emission measure
decreased from \(5.0 \times 10^{53}\) cm\(^{-3}\) to \(1.2 \times 10^{53}\) cm\(^{-3}\). The total energy released by the flare
over the spectral band 0.1 - 10 KeV was \(4.3 \times 10^{33}\) ergs. The time scales and energy
involved as well as the values of the derived parameters are similar to those typically
observed from M dwarf flare stars. As discussed by Pallavicini et al. (1988b) this
suggests the possibility that the flare did not originate from one of the A-type primaries,
but rather from a low-mass companion.

b) Quiescent emission and microflares

In addition to flares, the EXOSAT satellite has given us the opportunity to study
lower amplitude fluctuations which may occur during relatively quiescent periods. Such
fluctuations are expected from the emergence of new magnetic flux at the stellar surface
or from the decay of preexisting active regions. Recently, it has also been suggested that
the heating of solar and stellar coronae may result from continuous low-amplitude
"microflaring" activity, produced by a large number of discrete events when magnetic
fields lines, shuffled around by random fluid motions at their footpoints, reconnect and
dissipate energy. Some authors (Butler and Rodonò 1985, 1986, Butler et al. 1986) have
claimed to have detected a signature of this microflaring activity in observations of flare
stars obtained with EXOSAT.

More specifically, Butler et al. (1986) have compared EXOSAT observations of
flare stars with spectroscopic observations obtained simultaneously in the H\(_\alpha\) line. They
noticed that some of the peaks observed in the X-ray light curve -when binned at very
short time intervals (= 30 to 60 sec)- were correlated with simultaneous H\(_\alpha\) peaks, which
led them to suggest that most fluctuations seen in X-rays might be statistically significant.
This was true in particular for an observations of UV Cet obtained on 1984 Dec 6. A
comparison of the EXOSAT LE data with simultaneous H\(_\alpha\) data obtained at ESO (Butler
et al. 1986) showed that some of the main peaks were indeed associated at the two
wavelengths, although this was not obvious for all of them. From this observation the
authors concluded that the quiescent corona of dMe stars likely originates 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. In a subsequent observation of YZ CMi,
however, there was little, if any, correlation between X-ray and optical fluctuations
(Doyle et al. 1988a). At any rate, the energy involved in these soft X-ray "microflares" is
orders of magnitude larger than typically observed in solar hard-ray and UV microflares
(the latter is on the order of \(\approx 10^{24}\) erg sec\(^{-1}\), cf. Lin et al. 1984, Porter et al. 1987).

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In order to test the above suggestion for a much larger sample of data, and with the aim of getting a better idea of time variability in coronal X-ray sources, I have undertaken an extensive analysis of all flare star observations obtained with EXOSAT (Pallavicini 1988, Pallavicini and Tagliaferri 1988, Pallavicini, Stella and Tagliaferri 1988). In total, there are 37 separate pointed observations in the EXOSAT archives, pertaining to 22 different stars. About 20 out of 37 are long continuous observations lasting from 5 hours to 1 day. A number of objects (UV Cet, YY Gem, YZ CMi, AD Leo, CM Dra, Wolf 630, BY Dra, EV Lac, EQ Peg) were observed repeatedly, often at time intervals several months apart. This allows the study of variability on time scales longer than those typically observable in the course of a single observation. One source (YY Gem) is an eclipsing binary that was monitored throughout a full rotational period. In addition, four sources (UV Cet, EQ Peg, YZ CMi and AD Leo) were observed simultaneously at the Very Large Array for continuous periods of 8 to 10 hours (Kundu et al. 1988).

In order to study the short-term variability expected from "microflaring" activity, we have applied to the data a rms variability analysis particularly appropriate for the study of continuous EXOSAT data (Stella 1985). This technique is substantially different from that used previously by Ambruster et al. (1987) for the time-analysis of EINSTEIN data and which is basically a modified $\chi^2$ test (Collura et al. 1987). It is important, therefore, to briefly outline the main features of the method.

We have used binned data, with no phase average, and we have run all variability tests for a number of different bin sizes ($\Delta t = 60, 120, 180, 240, 300$ and 600 sec). For the flare stars observed by EXOSAT, the source count rates during quiescent conditions were in the range $0.05 - 0.2$ counts/sec, so bin sizes shorter than 60 sec could not reliably be used. We have used background subtracted data, with the background taken by averaging over a much larger area than the source cell. When scaled to the source cell, the background amounted at most to $30\% - 40\%$ of the source count rate. We have initially excluded the most obvious flares detected at a significance level greater than 5$\sigma$; however, in order to test the method, we have also run the variability analysis including all flares. In every case, the variability analysis was done separately for the background subtracted source count rate and for the background alone.

We define a rms variability (expressed as percentage variability of the average source count rate) as $rms = (\sigma_{obs}^2 - \sigma_{exp}^2)^{1/2} / <c>$, where $\sigma_{obs}^2$ is the observed variance, $\sigma_{exp}^2$ is the expected variance for a constant source and $<c>$ is the background subtracted average source count rate. We have computed the rms and the associated error for all our data and we have established the significance of the measured variability in terms of the number of standard deviations (we have taken the variability as detected when the significance level exceeded 3$\sigma$). For the cases when significant variability was detected, we have computed the autocorrelation function (ACF) for both the background subtracted source count rate and for the background alone, and we have further computed the cross-correlation function (CCF) between the two. If, based on the CCF, no clear correlation was found between the source and background variations, the relevant time scale of the detected variability was determined from the exponential decay time of the ACF, assuming that the variability was due to random shot noise (see Stella et al. 1984 for details on the method).

The results of this study for the flare stars observed with EXOSAT can be summarized as follows:
Fig. 10a: EXOSAT LE observation of UV Ceti on December 6, 1984 (from Pallavicini 1987; see also Butler et al. 1986 for a comparison of the X-ray data with simultaneous optical Hγ observations during the first three hours). Note the occurrence of several individual flares during the time interval from 02:00 to 07:00 UT, and the absence of significant variability during the last three hours of observation.

Fig. 10b: EXOSAT LE observation of UV Ceti on August 4, 1985 (from Pallavicini 1987; see also Kundu et al. 1988 for simultaneous VLA radio observations). Note the similarity between this observation and the one shown in Fig. 10a with regard to rapid time variability. By contrast, the same source observed on December 22-23, 1985 showed only gradual variations, in addition to a major flare (cf. Fig. 6).
- We find substantial variability for most flare stars over a variety of time scales (from a few minutes to hours).

- The observed variability is in the form of both individual usually sporadic flares and of more gradual variations (on times scales of tens of minutes to hours), and appears to be stochastic. Flares show a wide range of amplitudes with respect to the quiescent emission level (up to a factor of \( \approx 10 \)), while the more gradual variations on times scales of hours do not exceed amplitudes of 50% and are usually substantially less.

- For those stars observed by EXOSAT on several times, we did not see any large variation of the quiescent X-ray flux. The observed variations were always less than a factor of \( \approx 2 \) over periods of several months, and more typically did not exceed amplitudes of \( \approx 20\%-30\% \).

- The small data sample available from EINSTEIN and EXOSAT, and the uncertainty inherent in the comparison of fluxes from different instruments, do not allow the determination of possible long-term variations on time scales of years (as might result from activity cycles). The available data suggest, however, that these variations, if they occur, are probably small.

- In contrast with previous claims, we do not find evidence in the EXOSAT data for continuous low-amplitude short-time scale variability as might be expected from "microflaring" activity. More specifically, we do not confirm the continuous low-level rapid variability reported by Butler and Rodonò (1985, 1986) and Butler et al. (1986).

- For all stars in our sample, continuous periods of several hours were observed with no significant variability, in contrast to what could be expected from an interpretation of the quiescent emission of dMe flare stars as the superposition of many discrete events. If these events occur, they must be washed out in disk-integrated soft X-ray observations.

- For those stars which have been observed simultaneously at X-ray and radio wavelengths (Kundu et al. 1988), there was very little correlation between the variability observed in the two wavelength domains.

As an example of the high variability observed occasionally with EXOSAT, we show in Fig. 10a,b two observations of UV Cet, including the one previously analyzed by Butler et al. (1986). In both cases, the source appeared quite variable (at significance levels exceeding 7\( \sigma \) and 5\( \sigma \), respectively). However, the observed variability could be interpreted in both cases as due to individual flares with durations of \( \approx 10 \) to 20 min each and total energies of the order of \( \approx 5\times10^{30} \) to \( \approx 1\times10^{31} \) erg. The time scales of these events and the energy involved were both substantially larger than those reported by Butler et al. (1986) for their "microflares". In addition, there was no evidence of continuous lower amplitude variations outside these relatively major events. For instance, the last three hours of the observation of UV Cet on Dec 6, 1984 were completely free of significant variability.

The variability observed in all other cases was substantially less than that shown in Fig. 10a,b. More typically, individual events were separated by relatively long periods (several hours) with no obvious variability or with only gradual fluctuations on time scales of tens of minutes to hours (see, for instance, Fig. 6). We also note that in order to observe fluctuations in disk integrated soft X-ray observations, the rate of energy release in these fluctuations must be comparable to, or greater than, the total X-ray luminosity of the star, i.e. much larger than the typical energies associated with solar "microflares". It is not clear, therefore, whether there should be any relationship between the impulsive,
localized phenomena that have been observed on the Sun and any possible, short-term variability to be detected in disk-integrated stellar observations.

To summarize, our analysis has shown that there is no evidence in the EXOSAT data that quiescent emission of dMe (and possibly other) stars may originate from continuous low-amplitude flaring activity. Identical conclusions have been reached independently by Collura, Pasquini and Schmitt (1988) who have recently analyzed a subset of the same EXOSAT observations using the optimized \( \chi^2 \)-test previously employed by Ambruster et al. (1987) in the analysis of EINSTEIN data. The results of both studies do not necessarily imply that “microflaring” activity of the type observed on the Sun may not be relevant for heating stellar coronae: they indicate, however, that stellar microflares - if they exist - must have an amplitude well below the sensitivity level of EXOSAT observations.

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