STELLAR CORONAE

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ABSTRACT

Some of the current problems in stellar coronal physics are reviewed with emphasis on the contribution given to their solution by the EXOSAT Observatory. After a brief overview of the results obtained previously with the EINSTEIN satellite, we focus on the structure and variability of the coronae of late-type stars. First, we discuss the temperature and spatial structure of coronae for both single stars and close binary systems. We then discuss the observations and modelling of flares on a variety of stars, and finally we investigate short-term variability of coronal sources during relatively quiescent periods. The latter topic is discussed in the framework of recent suggestions that coronal heating in the Sun and stars may result from continuous "microflaring" activity. We show that, in spite of the enormous progress made in the last decade, there are still a number of major problems in stellar coronal physics which remain unsolved.

1. INTRODUCTION

Twelve years ago, the Sun was the only star known to possess a high temperature corona. Of course, one could have argued -and some, in fact, did (e.g. de Jager and Neven 1961)- that other stars similar to the Sun should also possess coronae: however, with the X-ray instruments available at that time, there was no great hope of detecting them, unless they were much stronger than the solar one. As a matter of fact, it was only in 1975 that X-rays were first detected from the corona of a star other than the Sun (Catura et al. 1975). This was during a rocket flight by the Lockheed group when the instruments were pointed briefly at the bright giant Capella, a detection soon confirmed by observations with the Astronomical Netherlands Satellite (Mewe et al. 1975). In subsequent years, a few other detections followed: however, until the launch of the EINSTEIN Observatory in 1978, the number of known stellar coronal sources remained extremely limited, of the order of a dozen or so. The only stars that were established as a class of X-ray emitters were active binaries of the RS Canum Venaticorum type, of which about fifteen had been detected by the HEAO-1 satellite (Walter et al. 1980).

In order to have an idea of what the situation was just before the launch of EINSTEIN, it may be instructive to look at a diagram of observed and predicted stellar X-ray luminosities like the one prepared by R. Mewe in 1978 (see Fig.1a). The curves shown in the diagram refer to the predicted X-ray luminosities, calculated on the basis of the theory of coronal formation that was universally accepted at that time: according to this, coronal heating results from shock dissipation of acoustic waves generated in subphotospheric convective zones. Therefore, only stars in a very narrow range of spectral types were predicted to have coronae. No coronae could exist for stars earlier
Fig. 1a,b: The pre-EINSTEIN (above, from Mewe 1979) and post-EINSTEIN picture of stellar coronae. Note that some of the detections reported in Fig. 1a were not confirmed by subsequent observations.
than spectral type = F0, because these stars do not have appreciable outer convective zones. On the other hand, stars of very late spectral types (K and M) - although possessing deeper convective zones than the Sun - were not expected to be vigorous X-ray emitters because the acoustic flux depends on a very high power of the convective velocity \( f_a \sim V_{\text{conv}}^8 \), and the latter decreases steadily towards later spectral types. Finally, for the hottest stars (O and B), for which early observations by COPERNICUS had shown the existence of high temperature UV lines, the acoustic theory was somewhat modified to allow for the possible presence of radiation driven acoustic waves (Hearn 1972, 1973). At any rate, X-ray emission was not considered to be a fundamental property of stars, and it was regarded more as an exception than as the norm.

The EINSTEIN Observatory showed a completely different picture (Vaiana et al. 1981; cf. Fig. 1b and also Fig. 4a). Stars of virtually all spectral types were found to be X-ray emitters, with emission levels spanning a broad range of values \((\text{from } \approx 10^{26}\,\text{erg} \,\text{s}^{-1} \text{ to } \approx 10^{34}\,\text{erg} \,\text{s}^{-1})\). More specifically, O and B stars were found to be very strong X-ray sources, much stronger than previously predicted by even the most optimistic theories. Late-type dwarfs (F to M) were also found to be X-ray emitters, with a wide range of emission levels at each spectral type, but with very little dependence of the median X-ray luminosity on effective temperature. These observations clearly demonstrated that the acoustic theory of coronal heating was basically incorrect, thus confirming and supporting early indications from solar studies, that were all pointing at the essential role played by magnetic fields in the heating and structuring of the solar corona (Withbroe and Noyes 1977, Vaiana and Rosner 1978).

In this review, I will not attempt to discuss in detail the many fundamental results on stellar coronae obtained with the EINSTEIN Observatory. These results have been reported and discussed in a number of excellent review papers (most recently by Rosner, Golub and Vaiana 1985) and I am not going to repeat this material here, except very briefly. Instead, I would like to report on some more recent results obtained with the European satellite EXOSAT, that was launched in April 1983 and remained operational for about three years. Although less sensitive than EINSTEIN, the EXOSAT Observatory had some specific features which proved particularly useful for studying the structure and variability of stellar coronal sources, as I will illustrate in the course of this review.

2. THE "EINSTEIN" PICTURE AND THE IMPACT OF "EXOSAT"

In this section I will summarize very briefly some of the results on stellar coronae obtained with the EINSTEIN Observatory. Probably, the most fundamental one was the discovery that stars of virtually all spectral types possess X-ray emitting coronae, as mentioned above. The only exceptions are A-type dwarfs - for which there is no credible evidence of X-ray emission, except for a few Ap stars (Cash and Snow 1982, Schmitt et al. 1985a)- and late-type giants (later than \( \approx K2\) III) and supergiants (later than \( \approx G1\) Ia). This last fact is usually referred to as the existence of a coronal dividing line in the HR diagram, between stars with massive low-velocity winds and no coronal emission (above the present sensitivity levels), and stars like the Sun which have a weak high velocity wind and a hot corona (Linsky and Haisch 1979, Ayres et al. 1981). The reasons for the existence of this dividing line are as yet poorly understood (see, for instance, Haisch 1986, 1987).
Fig. 2: X-ray luminosity vs. bolometric luminosity for early-type (O to B) stars (from Pallavicini et al. 1981). Note that the detections of Sirius and Vega are now considered spurious, and that X-ray emission from Algol originates most likely from the late-type companion.

Fig. 3: X-ray luminosity vs. rotational velocity for late-type (F6 to M5) stars (from Pallavicini et al. 1981).
Fig. 4a: Regions of the HR diagram where X-ray coronae have been observed (adapted from Rosner et al. 1985)

Fig. 4b: Schematic diagram showing which stars are probably solar-like. Also shown are the regions of the HR diagram where massive winds occur and hot coronae are apparently absent (from Linsky 1985).

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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 regards 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 \( \approx 10^{29} \text{ erg sec}^{-1} \) to \( \approx 10^{34} \text{ erg sec}^{-1} \)) depends on bolometric luminosity \( (L_x \sim L_{\text{bol}}^{-7}, \text{cf. Fig. 2}) \) and is virtually independent of rotation, the reverse occurs for late-type stars, which show no obvious dependence on the stellar radiation field, but do depend strongly on rotation \( (L_x \sim v_{\text{rot}}^2; \text{see Fig. 3}) \). 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, on the contrary, the use of such an approach is hardly justified, and is likely to lead to completely erroneous conclusions (see Fig. 4b for a schematic diagram of which stars are probably solar-like; cf. Linsky 1985). For stars of late-spectral type 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 has to be tested by future X-ray missions, has been proposed (e.g. Lucy and White 1980; see also Cassinelli 1985 for a review).

The EINSTEIN Observatory found that the X-ray luminosity of late-type dwarfs (F to M) range from \( \approx 10^{26} \text{ erg s}^{-1} \) to nearly \( \approx 10^{30} \text{ erg s}^{-1} \) (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 up to three orders of magnitude). The level of coronal emission appears to depend primarily with a few exceptions on rotation and age (Pallavicini et al. 1981 and 1982, Stern et al. 1981, Walter 1982, Micela et al. 1985 and 1987, Caillault and Helfand 1985): the latter dependence, however, is probably due to the decrease of stellar rotation rate with age, as a consequence of magnetic braking by stellar winds. There are also indications that convection is important in determining the coronal emission of 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 EINSTEIN Observatory also showed that the spectra of coronal sources were thermal and could 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 to several million degrees Kelvin, as will be discussed at some length in the next section. The EINSTEIN Observatory also showed that time variability was ubiquitous among late-type stars (Vaiana 1983, Ambruster et al. 1987) and that certain classes of objects (for instance, RS CVn binaries) were very bright in X-rays, much more than "normal" stars of comparable spectral type. Pre-main-sequence stars, when detected, were also found to be strong X-ray sources (with X-ray luminosities ranging from \( \approx 10^{29} \) to more than \( \approx 10^{31} \text{ erg sec}^{-1} \)): in addition, they display dramatic variability, which suggests that they may be in a perpetual state of flaring (see Feigelson 1984, 1985 for a review).

Although very briefly, the above summary gives us an idea of what the EINSTEIN Observatory has revealed about stellar coronae. The question we would like to address at this point is: what does EXOSAT add to this picture?
The effective area of the Low Energy (LE) experiment on EXOSAT was about one order of magnitude smaller than that of the imaging experiments on EINSTEIN, so one could not expect to obtain with EXOSAT high sensitivity surveys and/or to detect new classes of objects. On the other hand, for fairly bright sources, EXOSAT could perform 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 Taylor 1985 for a description of EXOSAT instrumentation). With the combination of these two instruments, it was possible to cover simultaneously a much larger spectral range than with EINSTEIN (more specifically, from \(\approx 0.04\) keV to more than \(\approx 10\) keV, i. e. over the entire range \(\approx 1\) to 300 Å). Secondly, EXOSAT had a very highly eccentric orbit which allowed continuous observations for periods of up to four days, without the usual data gaps due to Earth eclipses and passage through regions of high background- that were associated with previous low-orbit satellites. The importance of this fact in order to be able to study stellar variability and flares is self-evident. Finally, for stars of early-spectral types, EXOSAT suffered some UV contamination in the low-energy detectors, but was completely free of such a problem for stars later than \(\approx F0\). 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, as we shall see in a moment.

3. THE STRUCTURE OF STELLAR CORONAE

A fundamental question one would like to ask about stellar coronae is what is their spatial structure in temperature and density, as is determined by magnetic confinement and heating. To infer this spatial structure from disk integrated observations is by no means a trivial task. In this section, the contribution of recent EXOSAT observations to the solution of this problem will be discussed for both single stars and binary systems.

3a) Coronal temperatures

In order to infer the temperature structure of stellar coronae it is desirable to have moderate to high-resolution spectral observations: unfortunately, only a limited number of such observations have so far been performed, mostly with the Solid State Spectrometer (SSS) and the Objective Grating Spectrometer (OGS) on the EINSTEIN Observatory, as well as with the Medium Energy (ME) experiment and the Transmission Grating Spectrometer (TGS) on EXOSAT. 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 (IPC) on EINSTEIN (Schmitt et al. 1987), or by means of filter spectroscopy with EXOSAT (Pallavicini et al. 1987a). As an example, Fig. 5 a,b show the spectra of two bright RS CVn binaries (Capella and \(\sigma\) CrB) obtained with the EXOSAT TGS (Mewe et al. 1986; see also Schrijver 1985). Although these are among the best spectra of coronal sources so far obtained, individual lines are still not well resolved: the broad complexes of lines discernible in these spectra, however, are already sufficient to constrain quite well the range of temperatures present in the source.
Fig. 5a,b: EXOSAT TGS observations of the RS CVn stars Capella and $\sigma^2$ CrB (from Mewe et al. 1986). Two-temperature fits of the data are also shown.
It is interesting to observe that, whenever the spectral resolution and the S/N ratio are sufficiently high, one invariably finds 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 about one order of magnitude higher. This is true for the EXOSAT TGS observations of Capella and σ CrB mentioned 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 et al. 1987). 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. 1987, Schmitt et al. 1987).

Taken at face value, these two-temperature models suggest the co-existence on 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 of limited spectral resolution and energy dependence of detector response, if the source were characterized, as it is on the Sun, by a continuous emission measure distribution with temperature. Observations of the Sun show, in fact, that coronal emission comes predominantly from magnetically confined loop-like structures with a continuous emission measure distribution, rather than from isothermal regions. Furthermore, even considering the Sun -as we should do- as a mixture of active and quiet regions, the average temperatures of the various coronal structures do not differ by more than a factor of 2, and there is no indication on the Sun of the presence of two families of loops different in temperature by nearly one order of magnitude (Vaiana and Rosner 1978). We note in passing 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 (~ 10^-3) to the integrated X-ray flux of the Sun.

Different authors have argued convincingly for either one 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 (see Fig. 6 a, b): this suggests a dependence of the results of spectral fits on detector response. Moreover, Schmitt et al. (1987) and Pasquini et al. (1987) have shown with the help of MonteCarlo 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. As an example, Fig. 7 a,b show the results of MonteCarlo simulations of EINSTEIN IPC data and of EXOSAT LE and ME data, obtained using a continuous emission measure distribution of the form ~ (T/T_M)^α, which closely mimics the emission measure distribution in magnetically confined loops (T_M is the maximum temperature in the loop). When the simulated data are analyzed spectrally in the same way as real data, they show that the derived temperatures cluster around two well separated values.

On the other hand, Meew 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, 1987) have provided evidence, on the basis of eclipse observations, that two distinct families of loops, different in both temperature and size, may coexist in binaries. These eclipse observations, to which we will come back to in a moment, indicate that the higher temperature component most likely originates from very large structures which extend up to a few stellar radii. There is
Fig. 6a,b: Systematic differences of two-temperature fits of the same stars observed with different instruments. The upper panel shows two-temperature fits of EINSTEIN SSS observations of RS CVn binaries (Swank et al. 1981); the lower panel shows two-temperature fits of the same stars observed with the EINSTEIN IPC (Majer et al. 1986).
Fig. 7a,b: MonteCarlo simulations of EINSTEIN IPC and EXOSAT LE observations for stellar coronae characterized by a continuous emission measure distribution (from Schmitt et al. 1987). Note that a given EXOSAT LE filter ratio usually corresponds to two-temperature solutions (cf. Pallavicini et al. 1987a).

Fig. 7c: MonteCarlo simulations of EXOSAT ME observations of stellar sources characterized by a continuous emission measure distribution (from Pasquini et al. 1987).
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 et al. (1987), 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. In particular, 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: certainly, the results of eclipse observations to be discussed below seem to suggest the existence of two families of loops in close binary systems. If these eclipse observations have been correctly interpreted, it is difficult to escape the conclusion that the coronae of close binaries are fundamentally different from the solar corona.

3b) Spatial structures

Except in a few very special cases (e.g. eclipsing binary systems), it is usually not possible to obtain direct information on the spatial structure of stellar coronae. What is usually done, instead, is to assume a certain model configuration-as suggested by observations of magnetic structures on the Sun- and try to determine the physical parameters of this configuration by a $\chi^2$ fit of the 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. This is a point that needs to be kept in mind, when deriving parameters for stellar coronae.

On the Sun, virtually all of the observed X-ray emission originates from loop structures, i.e. from magnetic flux tubes, inside which high temperature, high density plasma is confined. The simplest way of modelling these structures is to assume static conditions and to impose at each point in the loop an energy balance between the heating rate $E_H$ per unit volume, the radiative losses $E_R$, and the divergence of the conductive flux $F_C$, i.e.:

$$E_H + E_R = \text{div} F_C \quad (1)$$

where $F_C = K T^{5/2} (dT/ds)$ and $s$ is a coordinate measured along the loop. The conductive flux is assumed to vanish at the loop top (for reasons of symmetry) and at the loop footpoints (assumed at chromospheric levels). With the aid of Eq. (1) it is possible to obtain simple scaling laws between global parameters of the loop. For instance, in the simplified case of constant pressure and constant heat deposition along the loop, the scaling law reads (Rosner, Tucker and Vaiana 1978):

$$T_M \sim (p L)^{1/3} \quad (2)$$

where $T_M$ is the maximum temperature (i.e. the temperature at the loop top), $L$ is the semilength of the loop and $p$ is the pressure. Similar scaling laws can be obtained for more general cases (e.g. loops larger than the pressure scale-height).
When we observe a stellar corona, all the different structural features are mixed together, and the analysis becomes much more complicated. If we assume that the corona is constituted by structures of only one type, all with the same pressure and length (i.e. that only one family of loops exists in the observed coronal source), we may expect that the integrated emission will depend on many parameters, including the number of loops, their length and pressure, their cross-sectional area, the distribution of temperature along the structure, and so on. However, as shown by the scaling law above, not all these parameters are independent. In practice, the integrated coronal emission from a star can be expressed as:

\[ F_X \sim \Psi (T_M, p, f) \]  

(3)

where \( f \) is the fraction of the stellar disk covered by X-ray emitting structures, and \( \Psi \) is a function which can be computed (in general numerically) on the basis of the energy balance equation (1).

In principle, one might expect to determine the three parameters \( T_M \), \( p \) and \( f \) (as well as other parameters, such as the loop semilength \( L \) and the heating rate \( E_H \), which are related to the ones above by scaling laws) by fitting the observed data with model computations of the type described by Eq. (3). This has been done by a number of authors, with various degrees of success (Schmitt et al. 1985b, Giampapa et al. 1985, Landini et al. 1985a,b, Stern, Antiochos and Harnden 1986). For instance, Stern et al. (1986) have shown that one family of loops in energy balance is capable of fitting in a satisfactory way IPC spectra of active F and G stars in the Hyades cluster, while Landini et al. (1985a,b) and Giampapa et al. (1985) have tried to find consistent solutions for both X-ray and UV observations (the latter observed by IUE). A loop model, in fact, should be able to simultaneously reproduce the coronal portion of the loop, as well as the transition region and chromospheric sections at the base of the same structure. On the other hand, Mewe et al. (1986) and Schrijver (1987) were unable to fit TGS spectra of RS CVn binaries with the simple loop model of Rosner et al. (1978): not only two families of loops, with different maximum temperatures, were required, but they also found it necessary to postulate a large increase of loop cross-section with height in order to find an acceptable fit.

A fundamental limitation of the above approach is that it is usually not possible to derive separately the three parameters \( T_M \), \( p \) and \( f \), unless other, independent constraints are imposed. In fact, while the maximum temperature in the loop can be uniquely determined, it is usually impossible to separate the area filling factor \( f \) from the pressure \( p \) : only a combination of these two quantities can be obtained. As is easily understood, the observed X-ray emission can result from either large regions at low pressure, or from more localized high pressure structures. This in turn affects the determination of the loop length, which could be uniquely determined only if both maximum temperature and pressure were known (cf. the scaling law (2) above). In other words, the spatial structure of stellar coronae inferred by loop model calculations is only a convenient, although not necessarily correct, way of describing the available observational data: one should be aware of the fact that the values of loop length and pressure for stellar coronal sources often quoted in the literature were determined in most cases by arbitrarily imposing additional conditions (for instance, that the loop length is equal to the pressure scale height, or that the pressure decreases by a certain amount from the base to the top; cf. Golub et al. 1982, Landini et al. 1985a).

Fortunately, there is at least one class of objects (the eclipsing binary systems) for which direct information on coronal structures can in principle be obtained. This is an
Fig. 8a: EINSTEIN IPC observation of AR Lac during one orbital cycle (from Walter et al. 1983). Note the many data gaps.

Fig. 8b: The coronal structure of AR Lac as inferred by Walter et al. (1983) on the basis of the EINSTEIN observation shown above.
Fig. 9: EXOSAT LE and ME observation of Algol centered on the secondary eclipse. No evidence of an X-ray eclipse is apparent (from White et al. 1986).

Fig. 10: EXOSAT LE and ME observation of 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. 1987).
area in which the EXOSAT contribution has been particularly important. If one has 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 high S/N ratio data which should 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 have tried to infer the properties
of photospheric starspots from the observed light curves of BY Dra and RS CVn stars.

The technique of using eclipse observations to infer the structure of stellar
coronae was first applied by Swank and White (1980) and by Walter et al. (1983), using
the EINSTEIN Observatory. They observed the RS CVn binary AR Lac, which is
formed by a G2 IV primary (with $R=1.52\ R_\odot$) and a KO IV secondary (with $R=2.77$
$R_\odot$), separated by $9.1\ R_\odot$. In spite of the many gaps present in the data owing to the low
orbit of the satellite (see Fig. 8a), 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 secondary
eclipse (when the K star is behind the G star). From this they concluded (see Fig. 8b)
that compact coronal structures existed on both stars and, in addition, that an extended
corona, highly inhomogeneous in longitude, was around the KO 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: this identification, however,
could only be considered hypothetical at that time.

As a matter of fact, it has only been 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, 1987; see also the contribution of
N. White in these Proceedings). 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. The observation of Algol (White et al. 1986) failed to reveal any eclipse
when the KO IV X-ray bright component was behind the X-ray dark B8 V primary (see
Fig. 9; note that the two components have about the same radius). From this it was
inferred that an extended high temperature corona with a scale-height of at least $=1\ R_*$
was around the K star. The observation of AR Lac is even more interesting (White et al.
1987; see Fig. 10). 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 indicated that the extended corona was at a higher temperature than the
more compact structures close to the surface of the stars.

The picture which emerges from these eclipse observations indicates that
structures of different sizes, temperatures and pressures are likely to coexist in close
binaries. The more compact structures close to the star surface are apparently at a lower
temperature and higher density than the more extended structures whose size are
comparable and even larger than the stellar radius. We do not know what these extended
components are. They might be associated with loops connecting the two stars, as has
been suggested by extrapolations of photospheric magnetic fields (Uchida and Sakurai
1983). Direct evidence for the existence of extended magnetospheres embracing the entire
binary system has been recently provided by VLBI radio observations (Mutel et al. 1985,
Massi et al. 1987). Alternatively, the extended components may represent the upper end
of a range of 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. If
so, the two-temperature components found in spectral fits of SSS and EXOSAT TGS
data (Swank et al. 1981, Mewe et al. 1986) may really refer to spatially distinct regions. At any rate, the ensemble of available data suggests that the coronae of RS CVn and other close binary systems may be quite different from the solar corona. This possibility has to be taken seriously into account when trying to extend to binary systems the same type of concepts usually adopted for the solar case.

4. THE VARIABILITY OF CORONAL EMISSION

Surprisingly enough, very little was known until quite recently 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 high background regions. Furthermore, systematic effects and the poor knowledge of source temperature make 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. 1987a). The most comprehensive study of stellar X-ray variability before the advent of EXOSAT is probably that of Ambruster et al. (1987). They have analyzed a sample of active late-type stars (mostly flare stars), using a new and substantially improved version of the classical $\chi^2$ test (Collura et al. 1987b). 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. Haisch et al. 1983).

The EXOSAT satellite has dramatically increased our knowledge of time variability of stellar coronal sources. This is vividly illustrated in Fig. 11 a,b, where we compare an EINSTEIN IPC and an EXOSAT LE observation of the same source (UV Cet) over a period of 8 to 10 hours. The EINSTEIN observation (Fig. 11a) is made up of six separate pieces, each lasting about 20 minutes. Although strong variability is obviously present (and is confirmed by the statistical analysis of Ambruster et al.), it is not clear whether it is due to a single long-enduring event, or to a succession of several short-lived flares. By contrast, Fig. 11b shows how the same source was observed by EXOSAT. There are no data gaps in this case, and we can study accurately both the entire evolution of the strong flare and the more subtle variations during the quiescent period of several hours that preceded it. In this section, I will discuss some of the EXOSAT results on time variability: I will first discuss flares, and then more gradual and/or smaller amplitude variations observed during relatively quiescent conditions. 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 is such as to allow for the first time realistic modelling of the observed emission and the derivation of meaningful physical parameters.
Fig. 11a,b,c: X-ray variability observed in UV Cet with EINSTEIN (upper panel, from Ambruster et al. 1987) and with EXOSAT (middle panel, from Pallavicini and Stella 1987) over periods of several hours. Note the many data gaps in the EINSTEIN data. The large flare seen by EXOSAT is plotted at higher time resolution in the lower panel to the left.
Fig. 12: EXOSAT LE observation of AT Mic showing the occurrence of a large flare (from Pallavicini and Stella 1987, see also Nelson et al. 1987).

Fig. 13: EXOSAT LE and ME observation of a flare on Gl 644 AB (Wolf 630 AB). Also shown are the simultaneous Hα observations (from Tagliaferri et al. 1987).
4a) Flares

Flares have been observed by EXOSAT on a variety of stars (Brinkman et al. 1984, de Jager et al. 1986, Landini et al. 1986, Pallavicini et al. 1986, White et al. 1986, Nelson et al. 1987, Haisch et al. 1987, Butler et al. 1987, Kundu et al. 1987, Pallavicini 1987a and b, Doyle et al. 1987, Tagliaferri et al. 1987). They have been observed from classical dMe flare stars (UV Cet, AT Mic, YZ CMi, EQ Peg, YY Gem, Wolf 630 etc; see Figs. 11c, 12 and 13), on RS CVn and Algol-type systems (σ CrB, Algol, II Peg, TY Pyx etc; see Fig. 9) and even on a single solar-type G star (π1 UMa, cf. Landini et al. 1986). The latter observations may not appear as particularly surprising, since variability and flares are commonly observed in integrated X-ray observations of the Sun. What is surprising, however, is that the flare on π1 UMa was seen against a background quiescent emission that was two orders of magnitude higher than the quiescent X-ray luminosity of the Sun. This implies that the π1 UMa flare released, in the X-ray band alone, at least a factor of \( \approx 10 \) more energy than the total energy released by the largest solar flares over the entire electromagnetic spectrum (the total energy released in the X-ray band was \( \approx 10^{33} \) erg). This indicates that activity on young rapidly-rotating solar-type stars (such as π1 UMa) does not result simply from larger areas of the star covered by magnetic regions: it must also be intrinsically more powerful. An even more interesting observation is that shown in Fig. 14. It is a 3-Lex observation of the bright star Castor (α Gem), which is constituted by two (unresolved in X-rays) A-type stars (A1V + A2Vn, both spectroscopic binaries, with components of similar spectral types). Since, as shown by the EINSTEIN Observatory, A-type dwarfs are not strong X-ray emitters (if at all, cf. Schmitt et al. 1985a), the observed EXOSAT emission during the quiescent phase is mostly due to contamination of the EXOSAT LE detector by the ultraviolet radiation from the photosphere and the chromosphere of the stars. The data in Fig. 14 show the occurrence of a flare (Pallavicini 1987a), whose time behavior closely resembles that of flares observed on the Sun and dMe stars. It is difficult to separate a possible X-ray contribution during the flare from UV contamination: Schmitt (1987, private communication) has found evidence from summed signal histograms that the flare may be a genuine X-ray event, with a total energy of at least \( 10^{33} \) ergs above the background quiescent emission. At any rate, even if the flare was mainly due to UV contamination, it indicates the occurrence of magnetic activity on an A star: it is thought that these stars do not possess a subphotospheric convection zone and, hence, are not expected to have the high level of turbulent surface motions that is required to stress surface magnetic fields. The observation of a flare on Castor indicates, therefore, that some of our current expectations are probably oversimplified. It would be interesting to search for similar transient events in the hundreds of early-type stars observed serendipitously by the EXOSAT Observatory: those sources were dominated by UV contamination and for this reason have not yet been adequately studied.

The largest number of flares observed by EXOSAT occurred on dMe stars. These flares 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). There is clear evidence in the data of different types of flares on dMe stars, as also observed on the Sun. More specifically, the EXOSAT Observatory has shown the existence of at least three types of stellar events (Pallavicini 1987b):

a) impulsive 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 on UV Cet, AT Mic and Wolf 630 shown above in Figs.11c, 12 and 13.
Fig. 14: EXOSAT LE observation of a flare on the A-type star Castor. The quiescent emission is almost entirely UV radiation from the photosphere and chromosphere of the star. Some UV contamination is likely to be present also during the flare (from Pallavicini 1987a).

Fig. 15: EXOSAT LE observation of the eclipsing binary flare star YY Gem throughout a full orbital cycle. Note the large long-decay flare (from Pallavicini and Stella 1987).
Fig. 16: EXOSAT ME observation of a long-decay flare from the star EQ Peg. The time intervals used for spectral fits of the data are also shown (from Poletto et al. 1987; see also Fig. 18 for comparison with model calculations).

Fig. 17: EXOSAT LE observation of a flare on EQ Peg characterized by a slow rise and a more rapid decay (from Pallavicini and Stella 1987; see also Haisch et al. 1987).
b) **long-decay flares** (with decay times of the order of \( \approx 1 \) hour or longer), which are reminiscent of solar long-duration 2-ribbon flares. Examples are the flares on YY Gem and EQ Peg shown in Figs. 15 and 16.

c) **flares with a gradual rise and a more rapid decay**, which have apparently no solar analogy. The best example of this class is the flare on EQ Peg shown in Fig. 17 (see also Haisch et al. 1987)

As we shall discuss below, these morphological differences probably indicate real physical differences in the energy release process, as is also true for solar compact and 2-ribbon flares. It is interesting to note that different types of flares may occur on the same star. For instance, EQ Peg showed flares of all three types. We also note in passing that although stellar flares are strongly reminiscent of solar compact and 2-ribbon flares in their time behaviour, the total energies involved are often orders of magnitude higher than in typical solar flares.

The simplest way of modelling flaring events is to assume a single magnetically-confined loop, which remains unchanged throughout the flare evolution. We 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. Under these assumptions, the flare will decay through radiative and conductive losses whose characteristic times are given by:

\[
\tau_R = 3 k_B T / n P(T) \quad (4)
\]

and

\[
\tau_C = 4.8 \times 10^{-10} n L_C^2 T^{-5/2} \quad \text{sec} \quad (5)
\]

In the Eqs. above, \( T \) is the temperature of the flaring coronal plasma (assumed isothermal), \( n \) is the density, \( k_B \) is the Boltzmann constant, \( P(T) \) is the emissivity function for an optically-thin plasma, and \( L_C \) is a characteristic length for the temperature gradient.

From Eqs. (4) and (5), and the temperature and emission measure derived from X-ray data, we can estimate the physical parameters of the flare region (density, volume, characteristic length \( L_C \), etc.). In order to do so, 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 (see, for instance, Landini et al. 1986). This approach, as crude as it might be, gives reasonable numbers when applied to flares on dMe stars. Densities, temperatures and volumes derived in this way (\( T \approx 2-3 \times 10^7 \) K, \( n \approx 10^{11}-10^{12} \) cm\(^{-3} \), \( V \approx 10^{27.10^{28}} \) cm\(^3 \)) are not very different from those of flares on the Sun. However, as mentioned above, the total energy released may be much larger than in compact flares on the Sun (most typically, on the order of \( 10^{31}-10^{33} \) erg, as compared to \( \approx 10^{29}-10^{31} \) erg in compact solar flares). Note that the flare on Algol shown in Fig. 9 released a much larger energy (\( \approx 10^{35} \) erg, White et al. 1986) and involved a larger volume (\( \approx 10^{31} \) cm\(^3 \)) than typical flares on dMe stars. It also had a higher temperature (\( T \approx 6 \times 10^7 \) K) and a longer decay time (\( \approx 7 \times 10^3 \) sec) than most flares on the Sun and on dMe flare stars. Apparently, this flare on Algol had more in common with large long-decay events than with compact impulsive events. It is still unclear, however, whether
flares on RS CVn and Algol-type binaries bear a real physical relationship with flares on dMe stars.

Are the above order of magnitude estimates realistic? Recently, Schmitt, Harnden and Fink (1987) 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 good agreement with those derived directly from spatially resolved solar observations, thus supporting the basic correctness of the method, at least to a first approximation. Of course, the physics involved in real flares is much more complex than the simple order of magnitude estimates discussed above. 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 already been made by Reale et al. (1987) for a flare observed on Prox Cen by the EINSTEIN Observatory: the many high quality observations of stellar flares obtained with EXOSAT provide an ideal sample for further pursuing this modelling effort.

All the above considerations apply to flares which occur in magnetically closed structures which remain unchanged throughout the event. This, however, is completely different from what occurs in long-duration solar two-ribbon flares (Priest 1981). These flares are believed to occur as a consequence of a disruptive phenomenon which suddenly opens a magnetic field structure (Kopp and Pneuman 1976, Kopp and Poletto 1984). The open field lines, under the action of an unbalanced Lorentz force, relax back to a closed lower-energy configuration and energy is released gradually by magnetic reconnection as the field lines reconnect at progressively higher altitudes during the flare decay. An interesting question is whether the same physical processes are also responsible for the large long-decay flares observed by EXOSAT from some dMe stars (see above).

In order to address this question, Poletto et al. (1986, 1987) and Pallavicini et al. (1987) have applied the reconnection model developed by Kopp and Poletto (1984) for solar two-ribbon flares to two long-duration flares observed on the stars EQ Peg and Prox Cen. The first of these events was observed by EXOSAT and is shown in Fig.16; the other one was observed by Haisch et al. (1983) with the EINSTEIN Observatory, and is one of the very few relatively long (= 5 hours) uninterrupted observations that was possible to obtain with EINSTEIN (owing to the favorable position of the source in the sky). Incidentally, we note that this EINSTEIN flare is the same modelled by Reale et al. (1987) as a compact event, in spite of its long duration and the early suggestion by Haisch et al. (1983) that it might be the stellar analog of a solar two-ribbon flare. We emphasize once again that a formal fitting of the data, without taking into account all available information, does not necessarily guarantee that a given model is also a correct physical description of the observed phenomenon. Unfortunately, in most cases, the available observational constraints are insufficient to discriminate between various models.
With these caveats in mind, we show in Fig. 18 the results of Poletto et al. (1987) for the flare on EQ Peg: the energy release rate predicted by the model is compared with the observed energy release, after allowing for the energy losses outside the observed spectral band. As shown by the figure, the model is capable of reproducing the main characteristics of the decay phase of the observed flare, thus supporting the identification of this event as a stellar analog of solar two-ribbon flares. Similar results have been obtained for the flare on Prox Cen observed with EINSTEIN (see Poletto et al. 1987 for details). An important by-product of this modelling exercise is the possibility of deriving constraints on the physical parameters of the emitting region: we derived that 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 \( \approx 3600 \) G. The flaring loops reached a height of \( \approx 40,000 \) Km, with an initial upward velocity of \( \approx 5 \) Km sec\(^{-1}\). The average density at the beginning of the decay phase was \( \approx 6 \times 10^{12} \) cm\(^{-3}\). On the contrary, the flare on Prox Cen may have involved lower magnetic fields (\( \approx 1000 \) G) and a lower density (\( \approx 1 \times 10^{12} \) cm\(^{-3}\)). The smaller magnetic field strength derived for the Prox Cen flare is consistent with the fact that this flare had a peak X-ray luminosity a factor \( \approx 150 \) lower than the flare on EQ Peg, and the quiescent X-ray luminosity of Prox Cen is more than 2 orders of magnitude smaller than the quiescent X-ray luminosity of EQ Peg.

As mentioned above, the flare on Prox Cen, modelled by us as a two-ribbon flare, has been modelled by Reale et al. (1987) -only for the rise and early decay phases- as a compact flare. Although both models can fit the observations reasonably well, they differ in their predictions of important flare parameters. The major difference is with regard to the size of the loop, which in the model of Reale et al. results to be much larger than in our case. Whereas we inferred that the loops were rising to a height of less than \( \approx 0.1 \) R\(_*\), the confined loop of Reale et al. had a height of \( \approx 0.4 \) R\(_*\): this is much larger than the pressure scale-height of the preflare coronal atmosphere (\( \approx 0.1 \) R\(_*\)), and sharply contrasts with what observed for compact flares on the Sun.

4b) Quiescent Emission

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 magnetic flux at the stellar surface, as observed in the case of the Sun. Moreover, long term variations of the integrated X-ray emission from a star could result from the existence of activity cycles similar to the 11-year sunspot cycle. 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 the footpoints, reconnect and dissipate their 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.

Before we discuss this important topic, it is useful to stress the similarities and differences between the solar and stellar case. The concept of "microflares" was first introduced in the solar case by Lin et al. (1984), on the basis of high-sensitivity hard X-ray observations of the integrated solar disk. During a balloon flight, they found that small amplitude hard X-ray (\( > 22 \) KeV) bursts, with an intensity 10 to 100 times smaller than all previously detected hard X-ray bursts, occur frequently on the Sun (typically, one every five minutes). These events, which are usually observed during the rise phase.
Fig. 18: Comparison of model calculations and observations for the long-decay flare on EQ Peg shown in Fig. 16. The model is an extension of the reconnection theory for solar 2-ribbon flares (from Poletto et al. 1987).

Fig. 19: EXOSAT LE and simultaneous optical Hα observations of UV Cet showing rapid time variability (from Butler et al. 1986).
of associated soft X-ray flares, are indicative of the frequent occurrence on the Sun of electron acceleration to supra-thermal energies. The average rate of energy deposition by greater than 20 KeV electrons is quite small (= 10^{24} \text{ erg sec}^{-1}), much smaller than what is needed to heat the corona (= 10^{27} \text{ erg sec}^{-1}). However, the available energy may be substantially higher if the spectrum of the accelerated electrons extends to energies as low as 10 or 5 KeV. Since the rate of occurrence of these "microflares" continues to increase as a power law as the detection threshold decreases, without any indication of flattening, there is the possibility that the energy deposited by non thermal electrons may indeed be sufficient to heat the corona.

As discussed by E. Parker in these Proceedings, there are good theoretical and observational reasons to believe that the heating of the solar corona occurs in discrete events, rather than continuously (see also Parker 1983, 1986). Recent high resolution observations of the Sun at UV wavelengths (Porter et al. 1987) have shown the occurrence of many small UV brightenings, which occur at random over the solar disk. The energy of each individual event is rather small (= 10^{23} - 10^{24} \text{ erg}), but the average rate of energy deposition by these events may be comparable to the energy flux required to heat the quiet solar corona. There are many other observational indications (mainly at UV wavelengths) of the occurrence of small discrete events in the solar atmosphere (cf. Bruekner and Bartoe 1983, Habbal et al. 1984, Porter et al. 1984). It is unclear, however, whether these events, which are localized in small areas and which individually involve only small energies, could be detectable at all in disk integrated observations.

The concept that coronal heating may result from continuous flaring activity has been proposed also in the stellar context. This suggestion is based on two main arguments. First, it has been found by several authors (Doyle and Butler 1985, Skumanich 1985, Whitehouse 1985) that there is a statistical correlation between the time averaged rate of energy release in optical U-band flares, and the quiescent X-ray luminosity of dMe stars. What is even more important, there appears to be an approximate equality between the total energy released by flares (averaged over time) and the X-ray quiescent luminosity of dMe stars (Doyle and Butler 1985). Note that a relationship between quiescent and flaring activity is not unexpected if both originate from the same basic physical mechanisms, such as stressing and dissipation of dynamo generated magnetic fields. However, in order to conclude that flares do energize stellar coronae it is also necessary to postulate that flares deposit in the atmosphere (for instance by mass motions, cf. Butler and Rodonò 1985) an equal amount of energy to that emitted by them in electromagnetic radiation. How this non-radiative energy could be stored and subsequently reabsorbed by the stellar atmosphere is not explained.

The second argument is more direct. Butler et al. (1986, see also Butler and Rodonò 1985, 1986) have compared EXOSAT observations of flare stars with spectroscopic observations obtained simultaneously in the \text{H}\gamma line. They have 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 \text{H}\gamma peaks, which led them to suggest that most fluctuations seen in X-rays might be statistically significant. This was particularly true for an observations of UV Cet obtained in December 1984. Fig. 19 shows a comparison of the EXOSAT LE data with simultaneous \text{H}\gamma data obtained at ESO (Butler et al. 1986). Some of the main peaks are clearly associated at the two wavelengths, although this is not obvious for all of them. From this observation they 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} \text{ erg}. In a subsequent observation of YZ CMi,
however, there was little, if any, correlation between X-ray and optical fluctuations (Doyle et al. 1987). 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.

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, we have undertaken an extensive analysis of all flare stars observations obtained with EXOSAT (Pallavicini 1987b, Pallavicini and Stella 1987). In total, there are 36 separate observations in the EXOSAT archives, pertaining to 21 different stars. About 20 out of 36 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 on more than one occasion, often at time intervals several months apart. This allows us to study variability on time scales longer than those typically observable in the course of one 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. 1987).

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 analysis of EINSTEIN data and which is basically a modified χ² test (Collura et al. 1987b; see also Collura et al. 1987a). It is important, therefore, to briefly outline the main features of our method.

We have used binned data, with no phase average, and we have run all variability tests for a number of different bin sizes (Δt = 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 cannot 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 5σ; 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 $\text{rms} = (\sigma_{\text{obs}}^2 - \sigma_{\text{exp}}^2)^{1/2} / \langle c \rangle$, where $\sigma_{\text{obs}}^2$ is the observed variance, $\sigma_{\text{exp}}^2$ is the expected variance for a constant source and $\langle c \rangle$ 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 3σ). 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).
Fig. 20a: EXOSAT LE observation of UV Cet on December 6, 1984 (from Pallavicini and Stella 1987). The time interval 02:00 to 05:00 UT is the same plotted with a shorter time binning in Fig. 19. Note the absence of significant variability during the last three hours of the observation.

Fig. 20b: EXOSAT LE observation of UV Cet on August 4, 1985 (from Pallavicini and Stella 1987; see also Kundu et al. 1987). Note the similarity of this observation and the one shown in Fig. 20a with regard to rapid time variability. By contrast, the same source observed on December 22-23, 1985 showed more gradual variations, in addition to a major flare (cf. Fig. 11b).
The results of our study for the flare stars observed with EXOSAT can be summarized as follows:

1) We find substantial variability for most flare stars over a variety of time scales (from a few minutes to hours).

2) The observed variability is in the form of both individual _usually sporadic_ flares and of more gradual variations (on timescales of tens of minutes to hours), and appears to be stochastic. Flares show a wide range of amplitudes (up to a factor of ≈ 10), while the more gradual variations on timescales of hours do not exceed amplitudes of 50% and are usually substantially less than that.

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

4) 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. The available data suggests, however, that these variations, if they occur, are probably small.

5) In contrast with previous claims by others, 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).

6) 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.

7) For those stars which have been observed simultaneously at X-ray and radio wavelengths (Kundu et al. 1987), 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. 20a,b two observations of UV Cet, including the one previously analyzed by Butler et al. (1986) and reported (partially) in Fig. 19. In both cases, the source appeared quite variable (at significance levels exceeding 7σ and 5σ, respectively). However, the observed variability could be interpreted in both cases as due to individual flares with durations of ≈ 10 to 20 min each and total energies on the order of ≈ 5×10^{30} to ≈ 1×10^{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. 20a,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, as shown in Figs. 11b and 12. We also note in passing 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 impulsive, localized phenomena on the Sun and possible, short-term variability observed in disk-integrated stellar observations.

To summarize, we conclude that, in our opinion, there is no observational basis in the EXOSAT data to support the view that quiescent emission of dMe (and possibly other) stars may originate from continuous low-amplitude flaring activity. This is not to say that "microflaring" activity of the type observed on the Sun may not be relevant for heating stellar coronae: we simply say that soft X-ray disk-integrated observations have not yet been able to give us an unquestionable observational indication that this is actually true. We also note that if continuous rapid microflaring activity were a general property of flare stars, and if an observable signature of it were present in disk-integrated soft X-ray observations, it could have been detected much more easily with the EINSTEIN Observatory, whose higher sensitivity would have allowed variability to be studied on time scales as short as \( \approx 10 \) sec for most of our sources. There is no indication of the existence of this type of variability in the data reported by Ambruster et al. (1987).

5. CONCLUSIONS

As shown above, the EXOSAT Observatory has contributed substantially to our understanding of stellar coronal emission. In the decade that has elapsed since the launch of the EINSTEIN Observatory in 1978, the field of stellar X-ray astronomy has undergone enormous progress which has established it as a major branch of modern astrophysics. However, in spite of the progress made, there are a number of fundamental problems which remain as yet poorly understood. These include:

- What is the mechanism of coronal formation for early-type stars? Do the coronae of these stars result from shock-dissipation in radiatively-driven winds (Lucy and White 1980, Lucy 1982) or rather from a thin corona at the base of an ionized wind (Cassinelli and Olson 1979, Waldron 1984)? What is the role, if any, of magnetic fields in these stars?

- Are A-type dwarfs really devoid of any coronal emission, or are they simply too weak to be detected at the present sensitivity levels?

- What is the role of rotation, convection and age in establishing the level of coronal emission among late-type stars? How is it related to magnetic fields? How can we convert the qualitative picture available at present into a sound quantitative theory?

- How are coronae structured in temperature and density? To what extent can we apply the solar analogy to other stars?

- Are the coronae of close binaries fundamentally different from the corona of the Sun and other single late-type stars? If so, which parameters are responsible for the differences?

- What determines the disappearance of coronal emission among late-type giants and supergiants? How is this related to the onset of massive low-velocity winds? What is
the upper limit that should be assigned to coronal emission from late-type giants and supergiants? Are hybrid stars (cf. Haisch 1987) different from other giants with respect to coronal emission?

- What determines vigorous X-ray emission in pre-main-sequence stars? What is the role of flares and/or absorbing circumstellar envelopes in determining the observed X-ray luminosity?

- What mechanisms are responsible for stellar flares? Are they similar to those operating in solar flares? Are flares on RS CVn binaries and/or pre-main-sequence stars produced by the same, or different, mechanisms as flares on dMe stars?

- What is the variability of coronal X-ray emission for different stars in the HR diagram? How can we use the information on stellar variability to put constraints on coronal heating processes?

We hope that these and other questions will be largely solved by the next generation of X-ray satellites, including the coming ROSAT and the far more remote AXAF and XMM missions.

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