STEELAR CORONAL PHYSICS WITH THE HIGH-THROUGHPUT X-RAY SPECTROSCOPY MISSION (XMM)*

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ABSTRACT

The High-Throughput X-Ray Spectroscopy Mission (XMM) to be flown by the end of this century is the second "cornerstone" project in the ESA Long-Term Programme for Space Science. It will consist of a high-throughput multi-mirror grazing incidence telescope coupled to dispersive and non-dispersive imaging spectrometers. With its unprecedented sensitivity over a wide band, the capability of simultaneous medium- and low-resolution spectroscopy, and the continuous-look capability, it will make possible a major advance in all fields of X-ray astronomy. This paper illustrates the capabilities of XMM for the study of stellar coronae with emphasis on the determination of the physical parameters (temperature, density, fluid motions) of coronal plasmas, the investigation of coronal heating mechanisms, the determination of the geometrical and thermal structure of coronae, and the study of variability on all time scales from seconds to days.

1. INTRODUCTION

Ten years ago the presentation of a new X-ray astronomy mission would have devoted but little attention to the coronae of normal stars. Prior to EINSTEIN there were only a handful of coronal X-ray sources known, and most of them were rather peculiar objects (e.g. close binary systems of the RS Canum Venaticorum type) which emit X-rays at levels several orders of magnitude higher than a normal star like the Sun. Actually, if the Sun were a prototype stellar X-ray emitter, it would have been quite difficult to detect coronae even with the sensitivity of the EINSTEIN Observatory: a source like the Sun, for instance, would have been detected in a typical EINSTEIN exposure only if closer than \( 10 \) pc.

The situation was not more promising on the theoretical side: there was essentially no true theoretical understanding of the origin of stellar coronal emission and of the mechanisms responsible for the heating of the coronal plasma to temperatures in excess of \( 10^6 \) K. The current ideas were based on the solar analogy and were proved to be basically wrong by both solar and stellar observations. There was little expectation to find coronae in early-type stars, or in late K and M dwarfs. No one could expect that stars with the same effective temperature and gravity may differ by orders of magnitude -as they actually do- in their X-ray luminosity.


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The EINSTEIN Observatory changed dramatically this situation and showed that the coronal phenomenon is a common property of normal stars of nearly all spectral types and luminosity classes (Vaiana et al. 1981). Fig (1) shows schematically the regions of the HR diagram were coronae have been found. X-ray emission has been detected from O and B stars of all luminosity classes as well as from dwarf stars of spectral types F to M and from yellow giants. Apparently, the only exceptions are A-type dwarfs and very late giants and supergiants for which no evidence of X-ray emission has been found at the EINSTEIN sensitivity level. These observations have given rise to a new branch of X-ray astronomy and have confronted us with an entire new series of challenging problems that we are barely starting to tackle. It is now evident that the study of stellar coronae can provide crucial information on many interesting physical processes, such as the generation of magnetic fields by dynamo action, the conversion of non-radiative energy into thermal energy and plasma heating, and the processes that cause mass and angular momentum loss in stars.

Although EINSTEIN, and later EXOSAT, have been instrumental in opening up a new field of research in X-ray astronomy, they could provide only a first glimpse at the complexity of the physical processes occurring in the coronae of stars (for recent reviews of the present status of stellar coronal research see Rosner, Golub and Vaiana 1985, Serio 1985, Vaiana and Sciortino 1987, Pallavicini 1987, 1988, Schmitt 1988). What we have now is basically a phenomenological description which relies on statistical properties and a number of correlations between various stellar parameters. An example is the dependence of X-ray luminosity upon rotation and age found for late-type stars (e.g. Pallavicini et al. 1981, cf. Fig. 2); another is the dependence of X-ray luminosity on bolometric luminosity (and hence radiation field) for early-type stars (e.g. Cassinelli 1985, cf. Fig. 3). These different correlations suggest that different mechanisms are likely to be responsible for coronal formation in early- and late-type stars; however, although interesting, these correlations can be only of limited help in understanding the microphysics of the heating mechanism. Similarly, we have learned very little so far on the structuring (in both temperature and density) of stellar coronae and on the coronal mass and energy budget for stars of different spectral types, particularly rotational velocities and ages.

The XMM mission, with its combination of high throughput, large band-width, medium spectral resolution and long continuous-look capability, will allow us to address fundamental physical questions concerning the coronae of normal stars (for a discussion of XMM instrumentation and the overall mission concept see Barr et al. 1988). For the first time it will be possible to advance from a phenomenological and largely qualitative description to the level where detailed physical models can be developed and compared quantitatively with the observations. XMM will allow us to address questions such as:

- What is the heating mechanism of stellar coronae, and how does it depend on parameters such as radiation field, mass flows, convection, rotation and age? What is the role of shocks and/or dynamo-generated magnetic fields for the heating of coronae of stars of different spectral types?

- What is the distribution of material as a function of temperature in stars of various spectral types and luminosity classes? What is the density distribution and how does it depend on other stellar parameters?

- Why and how is the plasma organized -as it seems- in spatially distinct features, presumably confined by magnetic fields? Do the coronae of close binaries differ in any fundamental way from the coronae of single stars? Do interconnecting magnetic structures exist in close binaries?
Fig. 1: Schematic HR diagram showing the regions (dotted) where X-ray coronae have been observed (from Rosner, Golub and Vaiana 1985).

(next page)

Fig. 2: The dependence of X-ray luminosity upon rotation rate for late-type stars. A best fit to the data points indicates a quadratic dependence of X-ray luminosity upon rotation rate (adapted from Pallavicini et al. 1982).

Fig. 3: The dependence of X-ray luminosity upon bolometric luminosity for early-type stars. The ratio of $L_x$ over $L_{bol}$ is approximately constant for O and B stars of all luminosity classes (adapted from Cassinelli 1985).
Fig. 2

\[ L_X = 1.9 \times 10^{27} \frac{V_{rot}^2}{L_X} \]

Fig. 3

\[ \log \frac{L_X}{L_{bol}} \]

\[ \text{Spectral Type} \]

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- What is the role of radiation, thermal conduction and mass flows in the coronal energy budget of different types of stars? What determines the disappearance of coronal emission in late-type giants and supergiants?

- How the coronae of pre-main sequence stars (PMS) differ from those of other late-type stars? Are they just scaled up versions of solar active regions, or are they fundamentally different?

- What is the variability of stellar coronal sources on a variety of different time scales (from seconds to days and years)? How can the observed temporal variations be used to infer the mechanism of coronal heating and the structuring of stellar coronae?

- What is the time evolution of the physical parameters (temperature, density, flow velocities) during transient flare-like events? Are there any physically significant differences among flares in different types of stellar sources (M dwarfs, RS CVn binaries, PMS stars)?

2. SENSITIVITY LIMITS AND LOW-RESOLUTION SPECTROSCOPY

XMM with an effective area more than one order of magnitude larger than that of EINSTEIN and more than 100 times that of EXOSAT, will increase enormously the number of stellar coronal sources accessible to detailed observations. Table 1 shows the maximum distances at which different classes of stars should be detectable with XMM in its low-resolution mode, if interstellar absorption is not excessive. We have assumed a limiting sensitivity of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$, as can be reached with the CCD array in 6 x $10^4$ sec (one full XMM orbit). For each type of source, we have assumed a "typical" X-ray luminosity, as derived from previous EINSTEIN observations. We see that relatively quiet coronae such as that of the Sun ($L_X = 10^{27}$ erg s$^{-1}$) should be detectable up to $\sim 100$ pc, while young and active late-type stars with $L_X = 10^{29}$ erg s$^{-1}$ should be detectable at distances one order of magnitude larger. RS CVn binaries and bright pre-main sequence stars ($L_X = 10^{30}-10^{31}$ erg s$^{-1}$) should be detectable up to $\sim 10$ Kpc, while early-type stars with $L_X = 10^{32}$ erg s$^{-1}$ or greater will be accessible virtually throughout the Galaxy, being limited only by confusion effects and interstellar absorption. Bright O-type supergiants (with $L_X = 10^{33}-10^{34}$ erg s$^{-1}$) could even be detected in the Magellanic Clouds ($D=50$ Kpc).

Detectability, however, is just one part of the story. More importantly, for a substantial fraction of these stars (say up to distances a factor $\sim 3$ smaller than those given in Table 1) we will be able to obtain reasonably good broad-band spectra with a resolution $E/\Delta E = 6-50$, far better than that obtained with the EINSTEIN IPC ($E/\Delta E = 1$) and even better than that of the EINSTEIN SSS and EXOSAT ME ($E/\Delta E = 5-10$). Thousands of such high quality spectra will be obtained for stars covering a wide range of different physical conditions and located in different regions of the Galaxy (e.g., in clusters of different ages), thus allowing us to explore how the coronal temperature changes in response to a variety of different stellar parameters. The XMM low-resolution data thus represent already a major improvement with respect to existing data. The H-like and He-like lines of O, Ne, Mg, Si, S, Ca and Fe will be prominent in these spectra and can be used to derive the distribution of coronal material as a function of temperature (differential emission measure analysis). The expected long duration of the mission will allow us to obtain large and complete samples of stars and to investigate how the
TABLE 1

XMM DETECTION LIMITS FOR STARS

$= 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ in } = 10^5 \text{ sec}$

($= 10 \text{ times EINSTEIN, } =100 \text{ times EXOSAT}$)

<table>
<thead>
<tr>
<th>Star class ($L_X$)</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar-type star ($= 10^{27} \text{ erg s}^{-1}$)</td>
<td>$\approx 100 \text{ pc}$</td>
</tr>
<tr>
<td>Active late-type star ($= 10^{29}$)</td>
<td>$\approx 1 \text{ Kpc}$</td>
</tr>
<tr>
<td>RS CVn binary ($= 10^{30} - 10^{31}$)</td>
<td>$\approx 3-10 \text{ Kpc}$</td>
</tr>
<tr>
<td>Bright T-Tauri star ($= 10^{30} - 10^{31}$)</td>
<td>$\approx 3-10 \text{ Kpc}$</td>
</tr>
<tr>
<td>Average early-type star ($= 10^{32}$)</td>
<td>$\approx 30 \text{ Kpc}$</td>
</tr>
<tr>
<td>Bright O supergiant ($= 10^{34}$)</td>
<td>$\approx 300 \text{ Kpc}$</td>
</tr>
</tbody>
</table>

Fig. 4 : EXOSAT Transmission Grating spectrum of Capella. The most prominent line complexes are indicated. Also shown is the spectral range that will be covered by the Reflection Grating on XMM (courtesy of ESA).

Fig. 5 : Simulated spectrum of Capella as will be obtained with the Reflection Grating on XMM in an exposure time of $5 \times 10^4 \text{ sec}$. A two-temperature source spectrum has been assumed. The $\text{O VII}$ triplet is shown at the lower left on an expanded scale. The inset at the upper right shows a simulated CCD spectrum as will be obtained in an exposure time of $1.5 \times 10^3 \text{ sec}$ (courtesy of ESA).
Fig. 4

Fig. 5

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observed spectral properties change with effective temperature, gravity, radiation field, mass loss, rotation and age.

3. HIGH RESOLUTION SPECTROSCOPY

The major step forward that XMM will produce in stellar coronal physics can be appreciated only if we consider the full spectral capabilities of the mission. X-rays from stellar coronae originate from optically-thin thermal plasmas in statistical equilibrium. Since the relevant temperatures are in the range from $10^6$ K to several times $10^7$ K, the spectrum is rich in emission lines produced by the most abundant elements (Raymond 1988; see also the calculations of Mewe, Gronenschild and van den Oord 1985, which have been assumed as input spectrum in all the following simulations). If suitably resolved, these lines are powerful diagnostics of temperature, density, ionization equilibrium, mass motions and elemental abundances. The instruments flown on previous missions had in general insufficient spectral resolution to take full advantage of the wealth of information contained in X-ray spectral lines. Even in the best cases, only a crude estimate of the relevant parameters could be obtained. As an example, Fig. 4 shows an observation of the bright giant Capella obtained with the Transmission Grating Spectrometer on EXOSAT (with E/ΔE = 50). Although this is probably one of the best stellar X-ray spectra ever obtained, individual lines could not be resolved; however, the complexes of lines revealed by the EXOSAT instrument were already sufficient to show that plasma of at least two temperatures (one of a few million degrees and the other at a temperature nearly one order of magnitude higher) were necessary to fit the data in a satisfactory way (Schrijver 1985, Mewe et al. 1986). While a low temperature plasma is needed to reproduce the complexes of O VIII + Fe XVII-XVIII at = 10-20 Å, as well as the lines of Fe XVIII at = 90-100 Å, a higher temperature component is needed to reproduce the higher ionization lines of Fe XXII-XXIII at = 120-140 Å.

With the improved resolution of the Reflection Grating Spectrometer on XMM (E/ΔE ≥ 250) it will be possible to resolve individual lines and to determine the temperature structure of stellar coronae far more accurately and for far more distant objects than has been possible previously. In addition, the simultaneous operation of both the Reflection Grating Spectrometer and the CCD camera will allow a broad spectral interval (from ~0.1 to 10 KeV) to be covered, thus extending the temperature range that can be usefully explored. Fig. 5 shows a simulated spectrum of Capella as seen by the Reflection Grating on two XMM telescopes in an exposure time of 5 x 10^4 sec (i.e. a factor 1.7 shorter than the lower resolution EXOSAT observation shown in Fig. 4). Individual lines of ions formed at different temperatures are clearly resolved, including the He-like triplets of abundant ions such as O VII and Ne IX. An expanded view of the region of the He-like triplet of O VII is also shown. The resonance, intercombination and forbidden lines are clearly resolved. This is very important since the ratio of the latter two lines is a diagnostic of coronal density for sufficiently high densities ($\geq 10^{11}$ cm$^{-3}$, cf. Gabriel and Jordan 1972, Bely-Dubau and Gabriel 1984)). There are indications that such high densities, which in the Sun occur normally only in flares, might indeed be present in the coronae of many active late-type stars: these stars have been inferred to be covered by high-temperature, high-density active regions whose physical conditions approach those of the flaring Sun. The determination of density, in conjunction with that of the emission measure $J n^2 dV$, will allow a better determination of the emitting volume.

The inset in Fig. 5 shows the simulated spectrum of the same source as would be obtained with the CCD camera in only 1.5 x 10^3 sec. H-like and He-like lines are

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prominent up to the Fe XXV line at 6.7 KeV. By combining the CCD and Grating spectra we can simultaneously cover the entire range of temperatures from $\approx 1 \times 10^6$ K to several times $10^7$ K, i.e. precisely the range of temperatures expected to occur in stellar coronal sources. Notice that the spectral range covered by the Gratings alone, although somewhat limited ($\Delta \lambda \approx 5-50 \ \text{Å}$), is already sufficient to cover the temperature interval from $\approx 2 \times 10^6$ K (O VII) up to $\approx 1 \times 10^7$ K (Fe XXI), thus encompassing a substantial fraction of the temperature range found in stellar coronal sources.

Capella is an intrinsically bright ($L_x = 2 \times 10^{30}$ erg s$^{-1}$) and nearby ($D = 14$ pc) source, so it may not appear particularly suitable for illustrating the ultimate possibilities of XMM. Nevertheless, the observation of this and other bright sources is important, since in this case we can get Grating and CCD spectra of extremely high S/N ratio, which are particularly useful for coronal modelling and the application of diagnostic techniques for temperature and density such as those already discussed. We note, however, that good quality spectra could be obtained with the Grating in $10^5$ sec for sources that are over three orders of magnitude weaker than Capella. There are thousands of such sources (either weaker or at greater distances than Capella) that could be observed with XMM. Table 2 summarizes the spectral capabilities of XMM for different classes of stars. Weak sources with X-ray luminosities comparable to that of the solar corona ($L_x = 10^{27}$ erg s$^{-1}$) should be observable with the Grating up to $\approx 10$ pc, a distance at which a typical EINSTEIN exposure could have just detected the same source with only very limited spectral resolution ($E/\Delta E \approx 1$). Young and active late-type stars ($L_x = 10^{29}$ erg s$^{-1}$) should be studied easily with the Grating up to $\approx 100$ pc, while very bright RS CVn and Algol-type binaries could be explored up to $\approx 1$ Kpc. Early-type stars are also within the reach of the XMM Gratings and this promises to provide essential clues for understanding the nature of coronal emission in early-type stars, as we will discuss further later on.

With the CCD camera on XMM we should be able to reach typically a factor of $\approx 3$ greater distances than with the Gratings, thus further increasing the accessible volume by a factor $= 30$. In order to appreciate the tremendous impact that these spectroscopic capabilities will have on stellar coronal studies, it may suffice to recall that the Solid State Spectrometer (SSS) on EINSTEIN was able to acquire only 19 spectra of stellar sources (Swank 1985), and a comparable number was obtained with the ME experiment on EXOSAT (Pallavicini 1988). Even lower is the number of high-resolution spectra of coronal sources obtained so far. The Objective Grating Spectrometer (OGS) on EINSTEIN observed Capella (Mewe et al. 1982), and four stellar coronal spectra were obtained with the Transmission Grating Spectrometer (TGS) on EXOSAT (Heise 1988). The only large samples of spectral data obtained so far remain, therefore, the low-resolution observations ($E/\Delta E \approx 1$) obtained with the Imaging Proportional Counter (IPC) on EINSTEIN (Majer et al. 1986, Schmitt 1988). The IPC spectra were clearly not sufficient to determine the detailed physical properties of stellar coronae.

The present model payload does not implement very high spectral resolution ($E/\Delta E \geq 1000$) on XMM, although there is some possibility that an Objective Bragg Crystal Spectrometer working at the Fe K-lines may eventually be accommodated. In principle, with such an extremely high resolution it should be possible to resolve both the He-like lines and the associated satellite lines, thus allowing the application of sophisticated plasma diagnostics techniques (to determine the electron temperature, departure from ionization equilibrium, plasma flows, etc.), which so far have been successfully applied only in the case of solar and laboratory plasmas (Bely-Dubau and Gabriel 1984, Bely-Dubau 1988). However, the small anticipated efficiency of the Bragg
TABLE 2

XMM SPECTRAL CAPABILITIES FOR STARS

a) With the reflection grating in $10^5$ sec

<table>
<thead>
<tr>
<th>Description</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar-type star ($10^{27}$ erg s$^{-1}$)</td>
<td>10 pc</td>
</tr>
<tr>
<td>Active late-type star ($10^{29}$)</td>
<td>100 pc</td>
</tr>
<tr>
<td>RS CVn binary ($10^{30}-10^{31}$)</td>
<td>300-900 pc</td>
</tr>
<tr>
<td>Average early-type star ($10^{32}$)</td>
<td>3 Kpc</td>
</tr>
</tbody>
</table>

b) A factor = 30 larger volume accessible to broadband CCD spectra

c) Longer exposures needed for Bragg spectra:

<table>
<thead>
<tr>
<th>Description</th>
<th>Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flares in nearby stars (D ≤ 10 pc)</td>
<td>$t_{exp} = 10^4$ sec</td>
</tr>
<tr>
<td>Bright RS CVn star (D ≤ 100 pc)</td>
<td>$t_{exp} = 10^5$ sec</td>
</tr>
<tr>
<td>Bright early-type star (D ≤ 1 Kpc)</td>
<td>$t_{exp} = 10^5$ sec</td>
</tr>
</tbody>
</table>

Fig. 6: Comparison of the EINSTEIN SSS spectrum of ε Ori with the slab model of Cassinelli and Olson (1979). The large absorption edge at 0.6 KeV predicted by the model as a consequence of strong absorption by the massive stellar wind is apparently not observed (from Cassinelli and Swank 1983).

Fig. 7: Comparison of the EINSTEIN SSS spectrum of ε Ori with the shock model of Lucy (1982). A best fit to the observed spectrum requires strong, but rather infrequent shocks (from Cassinelli and Swank 1983).
Spectrometer (effective area = 30 cm²) and the need to observe the lines at a very high S/N ratio, greatly restrict the range of suitable targets while requiring in any case very long exposures. For instance, the observation of a strong stellar flare ($L_X \sim 10^{31}$ erg s⁻¹) in a nearby M dwarf (D ≤ 10 pc) in search of plasma flows with velocities of the order of ≈ 300 Km s⁻¹ or less -as typically observed in solar flares- requires an exposure time of at least ≈ $10^4$ sec, which is comparable to or longer than the total duration of the flare. More suitable targets might be bright RS CVn binaries at D ≤ 100 pc (for instance to separate the two components by Doppler shift of the lines due to orbital motion), and early-type stars at D ≤ 1 Kpc (to determine the outflowing wind speed at the location where X-rays are produced). Even in these cases one would need exposures longer than one full XMM orbit (6 x $10^4$ sec). Observations of stars with the Bragg spectrometer may, therefore, be difficult even with the large throughput of XMM.

An area in which XMM spectral data can contribute significantly to our understanding of stellar sources is in elucidating the structure and heating mechanism of the corona of early-type stars. As already mentioned, there are clear indications from previous EINSTEIN observations that the corona of O and B stars is fundamentally different from those of late-type stars. While for the latter the dependence on rotation ($L_X \sim V_{\text{rot}}^2$) is a strong, although indirect, evidence for the action of dynamo-generated magnetic fields -as observed for the Sun- there is no consensus at present on the physical processes responsible for the corona of early-type stars. Early models hypothesized a thin high-temperature corona at the base of a cool wind (the so-called "slab model", Cassinelli and Olson 1979). This model predicts a strong absorption in the coronal spectrum at the oxygen K-edge at ≈ 0.6 KeV, which was not observed in the EINSTEIN IPC and SSS spectra (cf. Fig. 6). Further refinements of the model, taking into account the increased ionization and reduced opacity of the wind caused by the hot corona, have strongly reduced the predicted absorption feature, without however eliminating it (Waldron 1984). Alternatively, the hot plasma could originate from shock-heated high-density blobs which are expected to form as a consequence of instabilities in the radiatively-driven winds of early-type stars (Lucy and White 1980, Lucy 1982). These blobs might be distributed throughout the wind, thus reducing drastically the amount of absorption of coronal X-rays by the cooler wind material (cf. Fig. 7). Preliminary comparison of model predictions with EINSTEIN observations suggests that the heating is produced by rare and strong shocks, rather than by a continuous sequence of weak shocks (Lucy 1982, Cassinelli and Swank 1983). If this model is correct, one would expect rapid time variability (on time scales of hours) in the X-ray emission of early-type stars as well as Doppler broadening of the spectral lines caused by shock-associated turbulent motions (with $V_{\text{tur}} = 1000-3000$ Km s⁻¹). On the other hand, if the coronal plasma possesses a high temperature component (T > $10^7$ K) -as suggested by some EINSTEIN SSS observations (Cassinelli and Swank 1983)- which is magnetically confined at the base of the wind, one would expect high temperature lines, a more gradual (or absent) time variability, and the presence of more-or-less pronounced absorption edges at low energies.

XMM will be able to address these questions by observing early-type stars with a spectral resolution and a S/N ratio much higher than obtained in all previous missions. Both the Reflection Grating spectrometer and the CCD camera will be able to obtain valuable observations for a large number of stars, up to distances of a few Kpc. With the Reflection Grating it will be possible to carry out critical tests on existing models, thus discriminating between alternative scenarios. More specifically, it will be possible to search for absorption edges produced by overlying massive winds in the case of the thin base coronal model, or to search for Doppler broadening of the emission lines by turbulent motions, if shocks are indeed generated far out into the stellar wind.
4. TIME RESOLVED SPECTROSCOPY AND VARIABILITY

The high throughput of XMM will allow time-resolved spectroscopy during transient flare-like events. Fig. 8 shows a simulated CCD spectrum of a large flare observed by EXOSAT on Algol (see also Fig. 9 for the EXOSAT ME observation; cf. White et al. 1986). In the simulation, the temperature has been assumed to increase from $30 \times 10^6$ K to $55 \times 10^6$ K during the rise phase of the flare. The H-like and He-like lines of the most abundant elements are clearly resolved and they can be used as a good temperature diagnostic during the evolution of the flare. The higher quality of the CCD spectrum with respect to the ME spectrum is apparent. Notice that the flare lasted for almost 5 hours, and during that time EXOSAT could accumulate only a few time-resolved ME spectra with sufficiently high statistics to allow reliable spectral fits to be made (White et al. 1986). With XMM it will also be possible to obtain time-resolved Grating spectra of large flares ($L_x \approx 10^{31}$ erg s$^{-1}$) on Algol and nearby dMe flare stars with exposure times as short as $10^3$ sec. With the CCD we will get good quality spectra even in exposures as short as $10^2$ sec. With these data it will be possible to follow the time evolution of the temperature during both the rise and decay phases of transient events, thus allowing constraints to be put on the heating and cooling processes of the flare plasma. Data of this type are essential for comparison with model predictions which describe the hydrodynamic response of magnetically confined plasmas to various heating processes (Pallavicini et al. 1983, Reale et al. 1988).

An important diagnostic of stellar coronal emission is time variability. As mentioned above, observations of time variations are crucial for understanding the instabilities that may occur in the winds of early-type stars (Cassinelli and Swank 1983). Variability studies allow also investigation of the stochastic nature of magnetic activity in late-type stars. The detection of variability on short time-scales is expected to give insights into the heating mechanism of stellar coronae, especially if, as recently suggested (Butler et al. 1986), "quiescent" coronal emission in late-type stars results from the superposition of a large number of small-amplitude flare-like events ("microflares"). The monitoring of temporal variations is also crucial in order to resolve the spatial structure of eclipsing binary systems (Walter, Gibson and Basri 1983, White et al. 1986, 1987) or to infer the inhomogeneous distribution of surface activity in single, rapidly rotating stars (Collier Cameron et al. 1988). EXOSAT has already demonstrated the importance of time variability as a diagnostic tool of stellar coronal emission (e.g. Pallavicini 1988). However, the small collecting area of EXOSAT greatly limited the number of coronal sources that could be studied with sufficient counting statistics.

The high throughput and continuous-look capability of XMM are ideally suited for the study of time variations in stellar coronal sources. More importantly, the capability of XMM for time-resolved spectroscopy will greatly increase the value of such studies by allowing us to disentangle both the geometrical and thermal structure of stellar coronae. A specific example may help to illustrate this point. The EXOSAT Observatory monitored the RS CVn eclipsing binary AR Lac throughout a full orbital period (White et al. 1987). By studying the eclipses with the LE and ME experiments, it was possible to infer that compact low-temperature structures (at a temperature of a few million degrees) exist on the surface of the primary star, while far more extended ($\geq 1R_\star$) high-temperature structures ($T \geq 10^7$ K) are associated with the secondary star. These large structures (inferred also for a few other binaries observed by EXOSAT) have no solar analog and their physical nature remains unknown. It is unclear whether these are persistent structures or only transient features associated with flaring events. They may also be magnetically confined loops that interconnect the two components of the binary, as

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TABLE 3

XMM CAPABILITIES FOR TIME-RESOLVED OBSERVATIONS OF STARS

a) large flares on Algol and nearby flare stars
   grating spectra in $10^3$ sec
   CCD spectra in $10^2$ sec

b) eclipses in RS CVn binaries at $D \leq 100$ pc
   CCD light curves with $\Delta t \approx 10$ sec
   grating spectra in $10^4$ sec
   CCD spectra in $10^3$ sec

c) short-term variability in M dwarfs
   time scale $\Delta t \approx 1$ sec for $D \leq 10$ pc

d) variability in early-type stars
   time scale $\Delta t \approx 10$-100 sec for $D \leq 1$ kpc

Fig. 8: Simulated CCD spectra of a flare on Algol at two different times as will be observed with the CCD camera on XMM in $10^3$ sec (courtesy of ESA).

Fig. 9: EXOSAT ME light curve and spectrum (inset) of a large flare on Algol.

Fig. 10: EXOSAT LE observation of the eclipsing binary AR Lac compared with simulated XMM observations of the same source. The simulated XMM light curves are shown for both the CCD camera and the Reflection Grating. All data are binned over time intervals of 10 min. The light curves cover one orbital period of AR Lac (courtesy of ESA).

Fig. 11: Simulated spectrum of AR Lac as will be obtained by the Reflection Grating on XMM in a 40 min exposure (courtesy of ESA).
suggested by theoretical arguments (Uchida and Sakurai 1983) and by VLBI radio
observations (Mutel et al. 1985).

Fig. 10 compares the EXOSAT LE observation of AR Lac to simulated XMM
observations with both the CCD camera and the Reflection Grating. The tremendous
improvement in the S/N ratio for the same time binning is apparent (for instance, the
count rate in the CCD camera is increased by a factor 300 with respect to the EXOSAT
LE). Fig. 11 shows a simulated Grating spectrum as it would be obtained in a 40 min
exposure. Notice that 40 minutes represents only 1.5% of the entire orbital cycle (P =
1.98 d). Hence, even if XMM, with its useful orbit of 16.7 hours, will not be able to
cover continuously -as EXOSAT did- the entire orbital cycle of AR Lac, it will be able to
obtain spectrally resolved data at all important phases including primary and secondary
eclipses. In addition, the high throughput will allow the observation of objects located at
far greater distances than AR Lac, thus vastly increasing the number of interesting
systems that it will be possible to study in this way. The Optical Monitor on board XMM
will automatically ensure simultaneous coverage at UV and optical wavelengths, making
it possible to relate the observed variations of coronal emission to the photospheric
structure of the star.

Table 3 summarizes the capabilities of XMM for time-resolved observations of
stars. In its photometric mode, XMM will be able to study variability of nearby stars on
all temporal scales from seconds to days. Note in particular that nearby (D ≤ 10 pc) M
dwarfs could be searched for time variations on time scales as short as ≈ 1 sec, a factor
100 improvement with respect to what was typically possible with EXOSAT (Pallavicini
1987, 1988). If "microflares" do exist -in the sense that they have a signature in the
integrated emission of a stars- and if they represent the principal heating mechanism, they
should hardly escape detection: the high throughput of XMM at energies as high as 6
KeV, in conjunction with the simultaneous operation of the Optical Monitor, will make it
easy to detect rapid brightenings of possible non-thermal origin.

6. CONCLUSION

XMM will represent a major leap forward in the study of stellar coronal emission
and will allow us to tackle the physics, rather than the phenomenology, of stellar coronal
sources. XMM will contribute to all aspects of coronal studies, from the determination of
the physical conditions (temperature, density, fluid motions) of coronal sources, to time-
resolved spectroscopy of flares and close binary systems, to the study of rapid time
variations in different classes of stars. Two decades after the birth of stellar X-ray
astronomy, XMM, in conjunction with AXAF (cf. Linsky 1987), will provide us with
the essential tools for understanding those fascinating coronal phenomena of which the
EINSTEIN and EXOSAT Observatories could give us only a first glimpse.

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