X-RAY EMISSION FROM STELLAR FLARES: EXOSAT RESULTS

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ABSTRACT. We present an overview of recent observations of stellar X-ray flares obtained with the EXOSAT Observatory. We discuss a few examples of flares from M dwarf flare stars, from RS CVn and Algol-type binaries, from single late-type stars (including a G0 dwarf and an A-type visual binary), and from pre-main-sequence objects. We also draw some general conclusions from the preliminary analysis of the EXOSAT data sample.

1. INTRODUCTION

X-ray flares are a prominent feature of many stellar coronal sources, including classical M dwarf flare stars, RS CVn and Algol-type binaries, single solar-type stars, and pre-main-sequence objects. Detection of flares at X-ray wavelengths is important because it allows one to study the coronal manifestations of the process of transient magnetic energy release, and to investigate how they relate to the photospheric (optical) manifestations of flares. Unfortunately, our knowledge of X-ray flares in stellar sources has been hampered so far by the limited sensitivity of the instruments employed, by the insufficient time devoted to monitoring stellar sources, and by the sporadic and unpredictable nature of flaring events. For a summary of our knowledge about stellar X-ray flares before the launch of the EXOSAT Observatory see Haisch (1983).

With the launch of EXOSAT, our understanding of stellar X-ray flares has increased enormously. Although less sensitive than EINSTEIN, the EXOSAT Observatory was capable of performing continuous observations for periods as long as three days, without the data gaps usually associated with earth eclipses and passages through regions of high background. Moreover, the simultaneous use on board EXOSAT of different instruments covering the entire spectral range from ≈ 0.05 to ≈ 10 KeV has allowed a better determination of time variability and spectral properties of stellar flares. In this paper, we present the highlights of EXOSAT observations of stellar flares focussing on a few specific examples. A more comprehensive discussion of stellar flares as observed by EXOSAT will be given elsewhere.

The observations were obtained with the Low Energy (LE) and Medium Energy (ME) experiments aboard EXOSAT. The LE provided broad-band data in selected pass-bands over the spectral range 0.05 to 2 KeV. In order to restrict the observed spectral range, several filters were used in conjunction with a CMA detector. The ME experiment provided pulse-height spectra over the range $\approx 1 - 10$ KeV with a resolution $E/\Delta E \approx 3 - 5$. Simultaneous monitoring of the background was obtained by offsetting one half of the detector array away from the pointing direction. Since the ME experiment was less sensitive then the LE experiment, only a limited number of X-ray flares detected at low energies could also be studied spectrally at higher energies. Further details on the EXOSAT instrumentation can be found in White and Peacock (1988).

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2. FLARES FROM M DWARFS

As was expected, the largest number of X-ray flares was observed from classical M dwarf flare stars. There are about 20 such sources that were observed by EXOSAT, often for continuous periods of eight to ten hours each. A few of these sources were observed several times, thus yielding a total sample of 37 separate pointed observations, in addition to a few sources that were detected serendipitously. This is probably the largest data sample ever obtained at X-ray wavelengths on dMe flare stars. The number of flares detected was high, since typically at least one flare was observed in each $\approx$ 8 hour long observation (Pallavicini, Stella and Tagliaferri 1988).

The observed events cover a broad range of total X-ray energies (from $\approx 2 \times 10^{30}$ to $\approx 1 \times 10^{34}$ ergs) and have a variety of different time scales (from a few minutes to hours). There is evidence in the EXOSAT data for at least two different types of flares from M dwarf stars, i.e.: 1) *impulsive flares* (with rise times of a few minutes and decay times from several minutes to a few tens of minutes), which are reminiscent of *compact flares* on the Sun; 2) *long-decay flares* (with decay times of the order or $\approx$ 1 hour or longer), which are reminiscent of solar long-duration *two-ribbon flares*. Examples of the first class are the flares observed from AT Mic on 25 May 1985, Wolf 630 on 25 Aug 1985, UV Cet on 23 Dec 1985 as well as others smaller events from UV Cet, YZ CMi, BY Dra and other dMe stars. Examples of the long-decay class are the more rare large flares observed from YY Gem on 14 Nov 1984 and EQ Peg on 6 Aug 1985. As is the case for the Sun (Pallavicini, Serio and Vaiana 1977), these morphological differences may indicate real physical differences in the energy release process, as suggested by preliminary modelling attempts (Poletto, Pallavicini and Kopp 19[illegible]). It is interesting to note that different types of flares may occur on the same star. For instance, EQ Peg and YY Gem showed flares of both types. It should also be noticed that although flares from M dwarfs are strongly reminiscent of solar compact and two-ribbon flares in their temporal development, the total energies involved are orders of magnitude larger than in typical solar flares.

The ME spectral data show that the plasma is first heating and then cooling during the evolution of the flare. The temperatures observed are in the range from $\approx 2 \times 10^7$ K to $\approx 4 \times 10^7$ K, similar to the typical temperatures found for X-ray flares from the Sun. One of the best cases for time-resolved spectral studies is the long decay flare from EQ Peg observed on 6 Aug 1985. Only the peak and the decay were observed, from $\approx$ 06:30 UT, when the flare reached its maximum intensity, to $\approx$ 09:00 UT, when the emission returned to the stellar quiescent level. Over this time interval, five different spectra could be accumulated that were fitted with a simple bremsstrahlung spectrum + an Fe line at 6.7 KeV. The Fe line appears to be necessary to obtain a satisfactory fit. The temperature was found to decrease from $(4.4 \pm 0.4) \times 10^7$ K to $(1.7 \pm 0.4) \times 10^7$ K and the volume emission measure decreased over the same time interval from 2.1×10^{53} cm^{-3} to 3.0×10^{52} cm^{-3}. The total energy released by the flare during the observed period over the spectral band 0.1 - 10 KeV was $\approx 5 \times 10^{33}$ ergs.

3. FLARES FROM RS CVN AND ALGOL-TYPE BINARIES

The second class of stellar objects for which EXOSAT obtained a substantial number of flare observations is constituted by the RS CVn binaries, of which about 15 were observed by EXOSAT. Some of them were pointed several times, thus almost doubling the total number of observations available for these systems. The same class of objects also comprises the triple system Algol, which appears undistinguishable from the RS CVn stars in both its quiescent and flaring X-ray emission. Several of these sources (in particular, the eclipsing systems) were observed continuously for periods of many hours with the purpose of detecting light variations produced by orbital and/or rotational motions. However, in addition to orbital modulations (White et al. 1986, 1988), several flares were also observed by the LE and ME experiments aboard EXOSAT.

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In contrast to the case of M dwarfs, there has been no systematic study so far of X-ray flares from RS CVn and Algol-type binaries. Hence, only tentative conclusions can be drawn from the preliminary inspection of the EXOSAT data sample. The first impression one gets when looking at the ensemble of the data is that X-ray flares from RS CVn binaries may be substantially different from flares from M dwarfs. Usually they involve longer time scales and larger energies than typical flares on M dwarfs. The derived temperatures, however, are not too much different, and, again, there is evidence that the plasma is heating to temperatures of several 10^7 K during the rise phase and then cooling during the decay phase. X-ray flares observed from the RS CVn binaries AR Lac, TY Pyx and II Peg typically lasted for several hours and involved energies as high as $\approx 10^{35}$ ergs, i.e. time scales and total energies substantially larger than typically observed in flares from M dwarf stars. However, a flare observed from the RS CVn binary σ CrB on 29 Sept 1983 had a rise time of only 5 minutes, with an exponential decay of $\approx$ 30 min and a total duration of two and a half hour (van den Oord, Mewe and Brinkman 1988). The total energy of this flare over the spectral range 0.1 - 10 KeV was $\approx 2 \times 10^{34}$ ergs.

Probably the best example of flares from this class of objects is the five-hours long event observed from Algol on 19 Aug 1983. This flare was first studied by White et al. (1983). The flare started at $\approx$ 10:00 UT, peaked at $\approx$ 11:00 UT and then decayed steadily until $\approx$ 15:00 UT. We have reanalyzed the data by subdividing the flare into five time intervals, one during the rise phase (from 10:00 to 11:00 UT), and the other four during the decay. ME spectra were accumulated over these five time intervals, after subtraction of a preflare quiescent spectrum. The emissivity model assumed was that of an optically-thin line+continuum thermal plasma as computed by Mewe, Gronenschild and van den Oord (1985). We find that the temperature was decreasing from a peak value of $(6.1 \pm 0.8) \times 10^7$ K to $(2.3 \pm 0.6) \times 10^7$ K in the late decay. During the same time interval the volume emission measure decreased from 6.7×10^{53} cm^{-3} to 1.1×10^{53} cm^{-3}. The average temperature during the rise phase (from 10:00 to 11:00 UT) was $(5.2 \pm 0.8) \times 10^7$ K and the emission measure was 3.0×10^{53} cm^{-3}. Although the count rate was not sufficiently high to resolve the temperature variations during the rise phase, these data clearly indicate that the plasma, after an initial rapid heating, was slowly cooling during the decay of the flare. The total energy released over the spectral band 0.1 - 10 KeV was 1.1×10^{35} ergs.

4. FLARES FROM OTHER STELLAR SOURCES.

The EXOSAT data base comprises a few other coronal sources from which flares were observed. One of the most interesting observation is that of a flare from the A-type visual binary Castor (Pallavicini et al. 1988). This source has a nearby M dwarf flare star companion (YY Gem) and the two sources cannot be spatially resolved by the ME experiment. However, by comparing the ME light curve with the separate light curves of YY Gem and Castor obtained simultaneously by the LE experiment, it is possible to attribute unambiguously the observed flare events to either YY Gem or Castor. A flare from the latter source was detected on 14 Nov 1984 at 03:40 UT. Spectral analysis of the flare was made over three distinct time intervals throughout the flare evolution (peak, early decay, late decay). The results of the spectral fits, made using the optically-thin line+continuum thermal model of Mewe, Gronenschild and van den Oord (1985), shows that the temperature decreased from $\approx 5 \times 10^7$ K at the flare peak to $\approx 3 \times 10^7$ K in the late decay, while the emission measure decreased from 5.0×10^{53} cm^{-3} to 1.2×10^{53} cm^{-3}. The total energy released by the flare over the spectral band 0.1 - 10 KeV was 4.3×10^{33} ergs. The time scales and energy involved as well as the values of the derived parameters are similar to those typically observed from M dwarf flare stars. As discussed by Pallavicini et al. (1988) this suggests the possibility that the flare did not originate from the A-type primary components of the Castor system, but rather from an unseen low-mass companion.

Another interesting case is a flare observed from the single G0V star π^1 UMa on 31 Jan 1984 (Landini et al. 1986). To our knowledge, this is the only X-ray flare observed so far from a normal solar-type star, which is not a classical flare star, is not a pre-main-sequence object and is not a member of the binary system. Since X-ray flares are frequently observed from the Sun, the rarity of similar events from other solar-type stars is likely due to a selection effect, since little time has been devoted in the past to systematic monitoring of X-ray emission from normal stars. At any rate, the detected flare was much stronger that typical X-ray flares from the Sun. It released in the X-ray band $\approx 10^{33}$ ergs, i.e. a factor $\approx$ 10 more than the *total* energy released by the largest solar flares. The large energy of this flare made it possible to detect the transient event against the strong quiescent X-ray emission level ($\approx 10^{29}$ erg s^{-1}) of this young rapidly rotating star. The flare had a temperature of $\approx 3 \times 10^7$ K, a volume emission measure of 7.3×10^{52} cm^{-3} and a total duration of $\approx$ 20 min. The LE soft X-ray flux peaked a few minutes later than the ME hard X-ray flux, as typically observed in solar and stellar flares.

Another class of sources observed to flare at X-ray wavelengths are pre-main-sequence stars. During an EXOSAT observation of the Seyfert galaxy III ZW 2 a serendipitous source in the same field was observed to flare both in the LE and ME detectors (Tagliaferri et al. 1988; see also elsewhere in this volume). The flare had an average temperature of $\approx 4.5 \times 10^7$ K and an emission measure of 1.8×10^{54} cm^{-3}. The total duration was about two hours and the X-ray energy released over this period was $\approx 1.9 \times 10^{35}$ ergs. The serendipitous source has been identified with the visual binary HD 560 which is formed by a B9V primary and a G0Ve secondary. Tagliaferri et al. (1988) have argued that the flare likely originated from the secondary component of the system, which has been classified on the basis of optical studies as a post-T Tauri star. The optical identification is consistent with the quiescent X-ray luminosity ($\sim 10^{30}$ erg s^{-1}) and strong flaring activity observed from this source. Another similar source is probably AB Dor = HD 36705, which was observed by EXOSAT both as a quiescent and as a flaring source (Collier Cameron et al. 1988). The quiescent X-ray luminosity of AB Dor ($\approx 2 \times 10^{30}$ erg s^{-1}), the time scales of the observed flare ($\approx$ hours) and the total energy released in the flare ($\sim 10^{35}$ ergs) are very similar to those observed from HD 560B and are larger than those typically observed in flares from M dwarfs and other single late-type stars. Thus, even if the sample is quite limited, the available data suggest that flares from pre-main-sequence stars may be more similar to flares from RS CVn and Algol-type binaries than to flares on M dwarf stars.

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