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Non-thermal hard X-ray emission from stellar coronae

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Abstract. Non-thermal hard X-ray emission is a well known product of the most powerful flaring events observed in the solar corona. This emission is commonly explained with a "non-thermal thick-target model", where an electron beam generated after a magnetic reconnection event eventually hits the dense and warm plasma in the solar chromosphere. The quiescent X-ray emission level from young stellar objects or evolved active binaries can be higher than any solar flare, and these objects are also characterized by a more enhanced flaring activity. Yet, the detection of a non-thermal X-ray emission component in the stellar case remains elusive. I will show how the Simbol-X intrumentation will help us to investigate this issue, and hence to bring us unique information on the processes of energy release in stellar coronae.

Key words. Stars: X-rays – Stars: atmospheres

1. Introduction

Stellar coronae represent the largest class of X-ray sources in our Galaxy and possibly in the entire universe. The closest member of this class is our Sun, whose X-ray emission has been continuously monitored for several decades with space-borne instrumentation. Current solar observatories, like the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), allow to perform X-ray and γ-ray spectroscopy and imaging of the solar corona in the energy range from few keV up to $\sim 20\,$MeV. Such a large spectral window is motivated by the science goal of investigating particle acceleration and energy release mechanisms in the magnetized plasma of the solar corona.

On the other hand, the Sun is a low-activity coronal X-ray source if compared to the most X-ray luminous stars, typically found in young open clusters or belonging to the class of RS CVn-like binaries. Soft X-ray emission from stellar coronae has been extensively studied with a number of major space missions, starting with the *Einstein* satellite, flown in the late '70, and currently with the XMM-Newton and *Chandra* observatories. Instead, in the hard X-ray domain, the Beppo-SAX mission (1996–2002) was essentially the only one having X-ray active stars among the prime observation targets. Recent serendipitous detections of hard X-ray emission from stellar coronae with the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) and with the the *Swift* explorer (dedicated to Gamma Ray Bursts) demonstrate that nearby stars do represent feasible targets also for the forthcoming Simbol-X mission.

Coronal X-ray emission originates from hot plasma magnetically-confined in relatively compact structures in the stellar outer atmospheres. The plasma heating mechanism(s) still represents a "holy grail" in astrophysics, although a large body of circumstantial evidence indicate that magnetic reconnection events play a major role. In particular, in the solar case, a sudden reconfiguration of the magnetic field topology occurs simultaneously with impulsive energy releases observed during flares. In virtually all of these events, the clear detection of non-thermal radio and hard X-ray emission is interpreted as a direct signature of electrons and ions accelerated to mildly relativistic energies.

The above scenario suggests that (non-thermal) hard X-ray emission from stellar coronae represents the realization in stellar outer atmospheres of plasma heating and particle acceleration processes possibly similar to those at work in other more exotic astrophysical environments, and for this reason it warrants our interest.

There are at least two broad science topics related to stellar hard X-ray emission: plasma heating in a magnetized astrophysical environment, which is a quite general astrophysical phenomenon, and the influence of stellar high-energy particles and radiation on the circumstellar environment, especially in young stars with newborn planetary systems. In this paper I will focus the attention on the first topic, and more specifically on issues related to stellar flaring events, while the second topic is addressed by Sciortino elsewhere in these proceedings.

2. The solar template

Solar flares are powerful explosions releasing up to 10^{33} ergs on time scales ranging from 10 to 10^4 s. The radiation emitted during a large solar flare is visible across the entire elettromagnetic spectrum, from radio to γ-ray wavelengths but not all at the same time. In the canonical scenario, radio and hard X-ray bursts are first observed in the early phase of the flare, followed by a more gradual increase of the soft X-ray emission and finally by a slower decay phase. The time scale of the impulsive phase ranges from 1 to 100 s, while the rise phase of the soft X-ray emission follows closely the time integral of the hard X-rays (or, equivalently, of the radio emission). This is called the "Neupert effect" (Neupert, 1968) and explained in the framework of the non-thermal thick-target model (Brown, 1971; Hudson, 1972): a beam of accelerated eletrons travels along magnetic field lines from the site of the magnetic reconnection event in corona down to the dense chromospheric layers, where energy is transferred to the plasma via Coulomb collisions; in this model hard X-rays are due to non-thermal bremsstrahlung, which occurs simultaneously with the chromospheric heating, and hence they represent a proxy for the istantaneous rate of evaporating plasma; instead, the thermal soft X-ray emission increases proportionally to the total amount of evaporated plasma, and hence with the time integral of the former. The hot plasma eventually cools down via radiation and conduction on times scales of 10^3–10^4 s in the flare decay phase.

Figure 1 shows a spatially-resolved soft X-ray image of the solar corona during a well studied event called "Masuda flare" (Masuda et al., 1994), and a zoom of the flaring regions with contour levels indicating the location of the hard (15–90 keV) X-ray emission. The figure also shows a coronal loop structrure with a cusp-like configuration of the magnetic field, and the site where energy release by magnetic reconnection and the particle acceleration process are supposed to occur.

The thick-target model explains many aspects of the flare phenomenology, including the gyrosynchrotron radio emission due to charged particles spiraling along the magnetic field lines, and the observed location of the hard X-ray and γ-ray emission near the footpoints of the magnetic loop structures, i.e. at the sites where the electron beams are stopped at chromospheric level. However, the model does not explain how the particles can be accelerated and collimated so efficiently over the observed temporal and spatial scales. The presence of a source of hard X-rays high in corona (Fig. 1) is also difficult to explain due to the low density of the plasma at that site. A number of recent observations of solar flares with

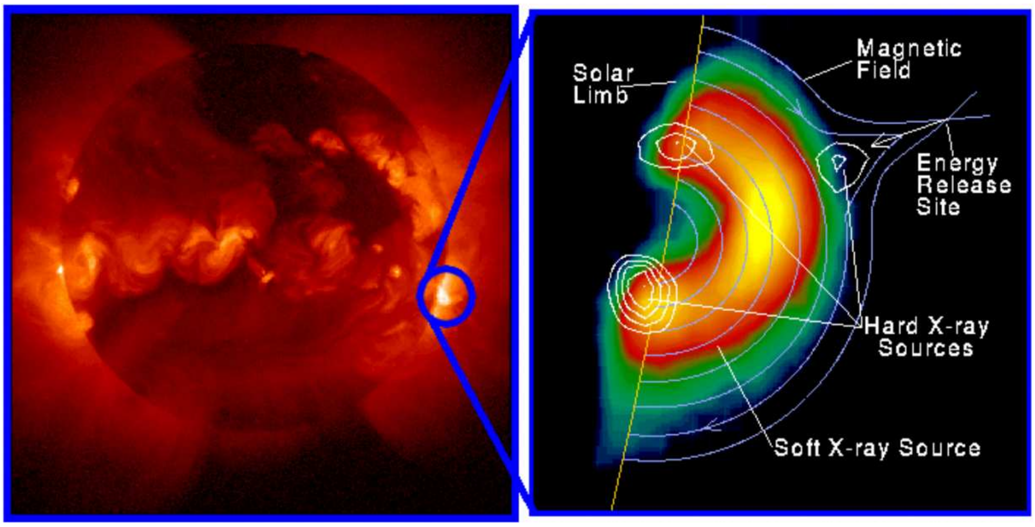

Fig. 1. Flare on the solar limb, studied by Masuda et al. (1994). *Left:* full-disk X-ray image of the Sun, taken with the Yohkoh Soft X-ray Telescope. *Right:* zoomed image of the flaring region, with sketched magnetic field lines and a contour map of the hard X-ray emission, observed with the Hard X-ray Telescope, superimposed on the soft X-ray intensity map.

RHESSI do show other non-canonical features which likely require an alternative interpretation (Hudson & Micela, 2006). In any case, the thick-target model has been widely adopted as a term of reference to test the analogy between solar and stellar flaring activity.

The complexity of the physics of solar flares is also evident from inspection of a typical high-energy spectrum. Figure 2 shows a composite spectrum over a large energy window, from X-ray to γ-ray domain, where several components are identified. The analysis of this and other similar spectra reveals the presence at low energies of thermal emission from plasma at tens of million degrees, which produces also prominent Fe and Ni K-shell emission lines from H-like and He-like ions, while the non-thermal bremsstrahlung (power-law) component becomes dominant above 20–30 keV. It is worth noting that this energy break falls nicely in the Simbol-X spectral band. Finally, at energies of 1 MeV and higher, the spectrum shows characteristic positron and nuclear γ-ray lines. Overall, the non-thermal components in solar flare spectra can be explained by populations of electrons accelerated to tens of MeV, and ions up to tens of GeV.

3. The stellar case

While on the quiet Sun the X-ray to bolometric luminosity ratio is $L_x/L_{bol} \approx 10^{-6}$, in very active stars this value can reach $\approx 10^{-3}$. Moreover, during large flares the solar bolometric luminosity may increase by no more than $\sim$ 0.01%, while at the peak of extreme stellar flares L_x up to 10–30% of L_{bol} has been observed in red dwarfs. The flare frequency is also higher, with a few large flares per day in active stars, compared to one large flare every ten days in the Sun at the maximum of the solar magnetic cycle. Finally, stellar flares can be characterized by very long time scales, up to a few days, including both rise and decay phases. If X-ray spectra are interpreted purely with thermal models (see below), peak temperatures up to 10^8 K are inferred.

The above comparison shows how the solar activity is a relatively modest phenomenon with respect to active stars. On the other hand, stellar flares show characteristics similar to those of solar flares, and hence they appear to work with similar physical mechanisms (Favata & Micela, 2003). In fact, the evolution of the soft X-ray emission and of the plasma

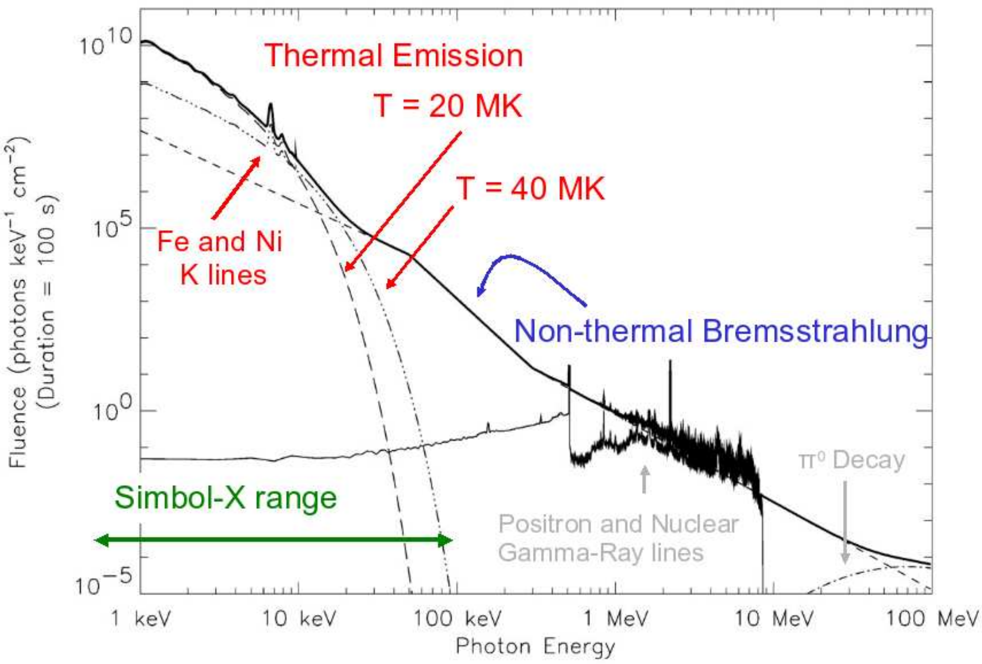

Fig. 2. Composite X-ray and γ-ray solar spectrum near the peak of a large flare (Courtesy H. Hudson). Several emission components are identified (see text), and the spectral window of Simbol-X is also shown.

temperature and density, as derived from time-resolved spectral analysis, can be explained within the same "impulsive heating and chromospheric evaporation" framework developed for the solar case. Soft X-ray emission during stellar flares has been also shown to follow, in several cases, a "Neupert effect" behavior when compared with the time profile of the non-thermal gyrosynchrotron radio emission. Hence, it is natural to expect that signatures of particle acceleration could be easily derived from the analysis of hard X-ray spectra. Unfortunately, no compelling evidence has been reported for non-thermal components in stellar X-ray spectra during flares, up to the present day.

Several large stellar flares have been observed with the *Beppo*SAX satellite, whose payload included four different detectors with a total spectral bandpass from 0.1 to over 200 keV. Hard X-ray emission up to 50 keV was indeed detected with the Phoswich Detector System (PDS) in the early phase of a few flaring events, while the soft X-ray emission followed a time evolution quite typical of compact solar flares, although much longer (Güdel, 2004). The spectral analysis yielded ambiguous results however: in fact, the spectra could be fitted equally well with pure thermal models, including a component at temperature of $\approx 10^8$ K, or with hybrid models comprising a thermal component and a power-law high-energy tail (Pallavicini et al., 2000).

Most recently, an extreme stellar flare from the active binary star II Peg was caugth by the Burst Alert Telescope of the *Swift* satellite, and then followed with the Soft X-ray Telescope (Fig. 3). Hard X-ray emission up to ~ 100 keV was detected for about 2 hours. Again, two alternative models were considered to fit the observed spectra: thermal emission from a plasma with an high-temperature component at ~ 300 MK, or a thermal component plus thick-target bremsstrahlung emission. The authors have eventually rejected the first hypothesis arguing that the high-temperature compo-

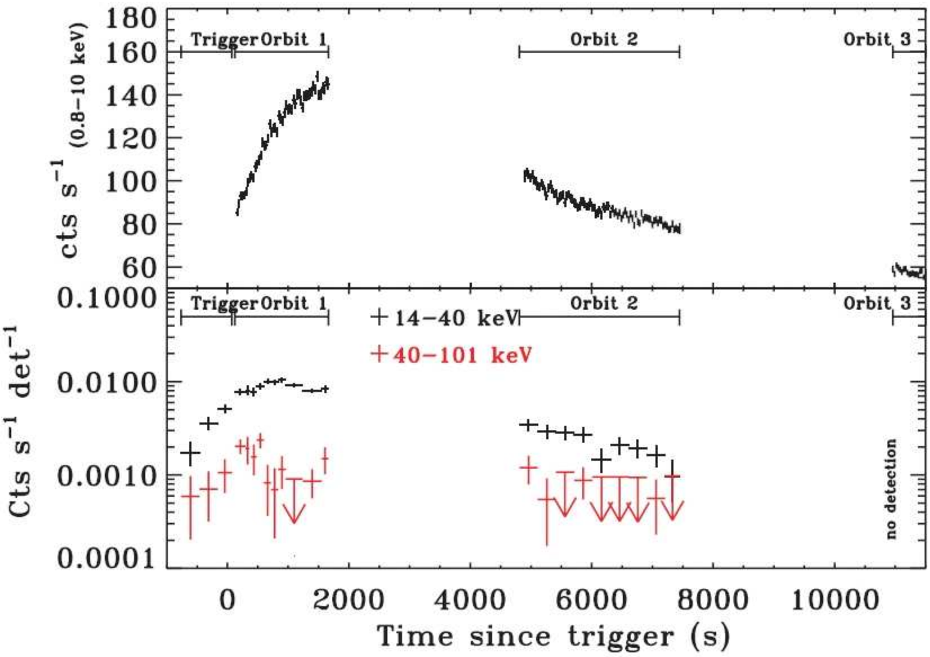

Fig. 3. X-ray light curves of the flare observed from the binary star II Peg with XRT (0.8–10 keV, top panel), and the BAT (two hard X-ray bands, lower panel) on board the *Swift* satellite (Osten et al., 2007).

nent is unphysically high, based on estimates of the size of the flaring region and of the magnetic field required to confine the plasma. The non-thermal interpretation was also supported indirectly by the detection of Fe K 6.4 keV line emission, attributed to collisional ionization from a beam of accelerated electrons.

Although the non-thermal X-ray emission from stellar coronae has eluded a firm demostration up to now, there are clear observational evidences in the radio domain of non-thermal processes in active stars. In fact, typical stellar radio spectra *in quiescent state* are rather flat between 1 and 20 GHz, and they have been interpreted as due to non-thermal gyrosynchrotron emission from mildly relativistic electrons in magnetic fields of a $few \times 10^2$ G (Güdel, 2002). Since this appears to be quiescent emission the open question is whether there is continuous acceleration of particles or rather a mechanism for trapping them in stellar magnetospheres for very long times. Finally, there is a rather tight linear correlation between the stellar microwave (5–8 GeV) and soft X-ray emission, which extends over 8 dex, including the full range of solar flares (Benz & Guedel, 1994). This correlation suggests that thermal and non-thermal emission in active stars are linked, and naturally leads to the issue whether stellar coronae are heated by continuous flaring activity.

Similar conclusion can be derived from the recent work by Isola et al. (2007), who have studied the correlation between the soft (1.6–12.4 keV) and hard (20–40 and 60–80 keV) X-ray emission in solar flares, establishing a general scaling law which can be extrapolated to the most intense stellar events observed to date. This result suggests again that the hard X-ray emission observed in extreme stellar flares is indeed non-thermal in origin, and it also allows us to study the feasibility of hard X-ray observations of stellar coronae with Simbol-X.

4. Science prospects with Simbol-X

The detection of non-thermal hard X-ray emission from stellar coronae during flares represents a test for the particle acceleration scenario and the thick-target emission model. More in general, the interpretation of the stellar hard X-ray emission is key to understand the mechanism(s) of energy release in magnetized coronal plasmas.

Past instrumentation allowed us to detect hard X-ray emission from stellar coronae only during extreme stellar flares. Thanks to the larger effective area and lower background noise of Simbol-X, we will be able to study these rare events in better detail, but also to investigate the behavior of the more frequent medium-sized stellar flares. The simulations performed by Argiroffi et al. (2007, in these proceedings) show that we could be able to discern the presence of non-thermal components in the Simbol-X spectra if at least few tens of counts will be collected in the 20–80 keV band with the CZT detector. If the scaling between soft and hard X-ray emission found by Isola et al. (2007) for solar flares indeed holds for stellar flares of any size, the above requirement will be met for several of the known active stars within 30 pc from the Sun, provided that they will caught in flaring state. A further advantage of observing medium-sized rather than large flares is that the temperatures of the thermal components, which are indeed always present, will not be extremely large, thus allowing an easier search of non-thermal power-law tails in the stellar spectra. In this respect, other useful diagnostic tools of thermal vs. non-thermal plasma will be provided by (i) inspection of the Fe K-shell lines from H-like and He-like ions, (ii) possible detection of Fe K lines at 6.4 keV due to fluorescence or collisional ionization of neutral atoms in the stellar lower atmosphere, (iii) detailed timing analyses of the soft and hard X-ray emission, including the search of a Neupert effect with the help of symultaneous radio observations.

By enlarging significantly the stellar sample for which hard X-rays could be detected, Simbol-X will allow us to address a number of issues which require statistical studies: for example, we will be able to investigate what are the variability time scales of the hard X-ray emission and whether it occurs continuously or in a discrete, stationary or stochastic fashion; moreover, it will be possible to explore if and how this emission depends on the level of stellar magnetic activity.

Finally, if the existence of non-thermal particle populations will be confirmed, we will be able to constrain the energy distributions of the accelerated electrons, and hence the fraction of magnetic energy converted in kinetic energy after the reconnection event. Simulataneous radio observations will provide additional constraints and will allow us to understand whether the non-thermal radio emission is due to the same population of particles which produce the hard X-ray emission.

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