X-RAY OBSERVATIONS AND STELLAR PHYSICS

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ABSTRACT. X-ray observations allow investigating the relation among coronal emission level and other stellar characteristics, still poorly considered in the standard evolutionary models, such as rotation, rotational braking due to angular momentum loss, stellar dynamos and magnetic fields, etc. Thanks to the CHANDRA and XMM high resolution spectra, physical diagnostics will be possible in earnest for stars other than the Sun and will allow to shed further light on the complex phenomena of stellar activity.

Young late-type stars are intense X-ray emitters and have been detected with past and current X-ray observatories up to distances of about 1 kpc. Because of their effectiveness, X-ray observations are becoming an election method for the study of the Initial Mass Function (IMF) at the low-mass end. I will discuss some recent results obtained by studying young clusters/associations and in general the young stellar population in the Galaxy and the perspective role that CHANDRA and XMM will play.

I will also discuss the need for small dedicated missions to address scientific problems that will be largely uncovered by both CHANDRA and XMM and by observatory-class missions today conceived.

1. The impact of CHANDRA and XMM in view of recent advances

Thanks to the EUVE, ROSAT, ASCA and SAX observations in the last years we have seen a flourishing of results with important impact on coronal physics and, more generally, on stellar physics. In the following I will present my own view of major recent advances[1] on stellar coronae, together with the role that the now-coming large X-ray Observatories, CHANDRA and XMM, will have to address the presently open questions.

1.1. Stellar flares as a tracer of coronal structure

Flares have been observed in all kinds of late-type stars (Schmitt 1994) giving further support to the paradigm that activity is of magnetic origin for all stars later than F3. Recently studies of the decay phase of stellar flares have demonstrated to be a powerful way to constraint the size of the coronal structures and of the other relevant physical parameters (pressure, densities, temperatures, magnetic fields, etc) governing stellar coronal loops. In particular, the approach of Reale et al. (1997) and Reale & Micela (1998), based on the application of full hydrodynamic simulation results to the flare evolution, allows us to test and to account for the presence of continuous heating during the decay phase. This more realistic interpretational framework, recently adopted by Favata et al. (1999a,b) and Favata & Schmitt (1999), results in more compact (and

[1] Since the field has largely expanded I am not even attempting to fully cover the published literature. Instead I will just cite spotted examples of current research or specific review papers.

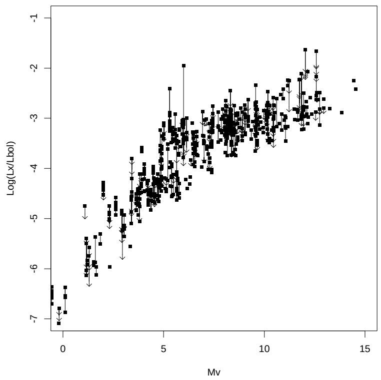

Fig. 1. The log(L_X/L_{Bol}) as a function of the absolute V magnitude for the Pleiades cluster members (from unpublished re-analysis of all available PSPC and HRI data). The vertical lines joint values for the same stars observed at different times. The very extreme values around -2, are due to the occurrence of strong flares.

less unrealistic) size of the flaring coronal loop and provides one of the few ways to characterize stellar coronae.

The study of coronae of hybrid giants, and in particular the evidence of continuous variability at high energies (Kashyap et al. 1994), likely due to continuous appearing of small size flares, and the contemporary presence of strong stellar winds and confined coronal plasma associated to open and close magnetic structures, respectively, asks for explanation of the heating process and, even more indirectly, on the nature of dynamo at work. The observational evidence suggests a magnetic topology more complex than the simple dipole one prevailing in the Sun.

The spotted nature of the time coverage of recent observations, due to the low orbit of the space observatories, has clearly limited a deeper insight of the physical processes at work. The long uninterrupted observations soon possible with CHANDRA and XMM will have a crucial role in addressing many of the still open questions.

1.2. X-ray emission at the low-mass end and stellar dynamos

The many ROSAT surveys, both of field (Schmitt 1999) and cluster stars (for recent reviews see Randich, 1997; Jeffries, 1999), have shown that the **maximum** value of L_x/L_{bol}, measuring the efficiency of the activity-related phenomena, increases up to a $\sim 10^{-3}$ (cf. Fig. 1), a value that appears to indicate some kind of (yet not well understood) saturation phenomenon. The existence of low-mass stars with such a high value of L_x/L_{bol} has important implications for constraining the properties of the coronal heating process – that has to be somewhat different than the one operating on the Sun – and for tracing a dynamo different from the standard $\alpha - \omega$ one, which cannot be effective in fully convective very low-mass stars. Given the limiting sensitivity of the X-ray observations and the available optical information, the best studied samples are the Pleiades (Stauffer et al. 1994, Micela et al. 1996,1998) and the Hyades (Stern et

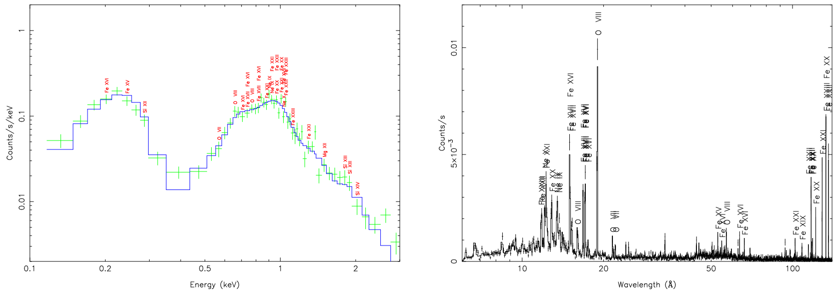

Fig. 2. (left) - The SAX LECS spectrum of AD Leo collected in about 20 ksec with indicated the position of the more prominent Fe lines emitted in the X-ray bandpass. (right) - The simulated CHANDRA LETG spectrum of AD Leo in a 100 ksec observation. The about 1000 spectral resolution will disclose for the first time the richness of the coronal spectrum and of its physics.

al. 1995), but even in these cases we have not seen in X-rays the very low-mass stars. Hence, our present evidence on the coronal emission of very low-mass stars is, at least, sparse and based on few nearby field stars (Fleming et al. 1995; Schmitt 1999). As today we have virtually no-information on the X-ray emission of brown dwarfs.

The deeper X-ray observations with CHANDRA and XMM will allow us to study in a direct way the coronal emission (if any) of brown dwarfs and very low-mass stars. Apart from being important per se this study will have a dramatic impact on the possibility to derive the IMF at the low-mass end from deep X-ray observations, as discussed below.

1.3. X-ray coronal spectroscopy

A large number of low (PSPC), tens of medium (ASCA, SAX) and few high (EUVE) resolution coronal spectra have become available during the last decade. Taking advantage of these new data several groups have started more sophisticated modeling of stellar coronae to derive the Differential Emission Measure (DEM, cf. Dupree 1996), an important tracer of the coronal heating mechanisms, and the thermal and physical structure of the corona (such as typical loop lengths, cf. Maggio & Peres 1997, Sciortino et al. 1998) and have started to investigate more complex questions such as the aging of the coronal spectra (Güdel et al. 1997), or the determination of coronal abundances (cf. Drake 1996 for a recent review) and their comparison with photospheric ones (Ottmann et al. 1998). Many studies to date are clearly hampered by the counting statistics (i.e. by the limited collecting area) and poor resolution (due to detector intrinsic physical limit) of available spectra. In order to illustrate this aspect, let us consider the SAX LECS spectrum (cf. Fig. 2) of AD Leo, a nearby dMe star, and the most intense X-ray emitter in its class. The limited spectral resolution prevents any detailed analysis of the rich forest of lines (indicated in the figure) that the best-fit model predicts. It is worth to stress that any improvement in spectral resolution needs to be accompanied by a substantial increase in collecting area at level even higher than the XMM one (cf. Fig. 6) to prevent being photon starved even for a relatively strong X-ray source such as AD Leo ($f_X \sim 3\ 10^{-11}$ erg/s/cm^2). Thanks to the large area ROSAT mirrors, the PSPC has

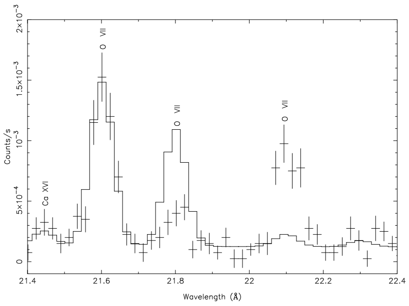

Fig. 3. The simulated 40 ks XMM RGS spectrum of BY Dra in the region of the OVII heliod triplet. The simulated spectra computed for a density of 10^9 electron/cm^3 and the model spectra (solid continuous line) computed for a density 3 order of magnitudes higher can easily be discriminated.

collected much more photons, but its poor spectral resolution has limited its capability to characterize the coronal spectra. With the CHANDRA and XMM medium-resolution ($\sim$ 70 eV) CCD-based detectors and, especially, with the high-resolution (grating-based) spectrographs our capability to investigate the coronal physics in stars different from the Sun will make a big leap forward. In this respect, let us consider the predicted CHANDRA-LETG AD Leo spectrum collected in a 100 ks observation (cf. Fig. 2). Even if the efficiency of a grating spectrograph (usually in the 20-30% range) drastically reduces the effective collecting area of CHANDRA (cf. Fig. 6) and requires long integration times, yet the richness of the spectrum is worth the price!

High resolution spectra will allow to derive in a more reliable way coronal abundances without many of the difficulties/drawbacks of current determinations based on the low-medium resolution spectra. This will help to clarify a field that is still quite controversial. The measurements of the individual intensities of helioid triplet lines will make it possible the model independent determination of coronal densities at the temperature of formation of various triplets. This is illustrated in Fig. 3, showing a simulated 40 ks XMM RGS observation of BY Dra, a low-mass active binary system with $f_X \sim 10^{-11}$ erg/s/cm^2. Indeed, the ratio of the intercombination (middle) and forbidden (right) lines furnishes a quantitative diagnostics of the coronal density. While being a very exciting possibility, I want to stress that such an analysis will only be possible for the more intense (and usually nearby) coronal sources. Even with the large collecting area of XMM RGS it will be essentially impossible to attempt such an analysis for the young stars of the Pleiades since the required observation exposures will be prohibitively too long!

1.4. Young star physics and Initial Mass Function determination

Thanks to its large field of view the ROSAT PSPC has allowed surveying most of the young open clusters and star forming regions (SFR) within few hundreds parsecs. These observations have been, more recently, complemented by the low-spatial but higher energy resolution observations of star forming regions performed with the ASCA SIS. This has allowed extending the pioneer work with the *Einstein* observatory to a more

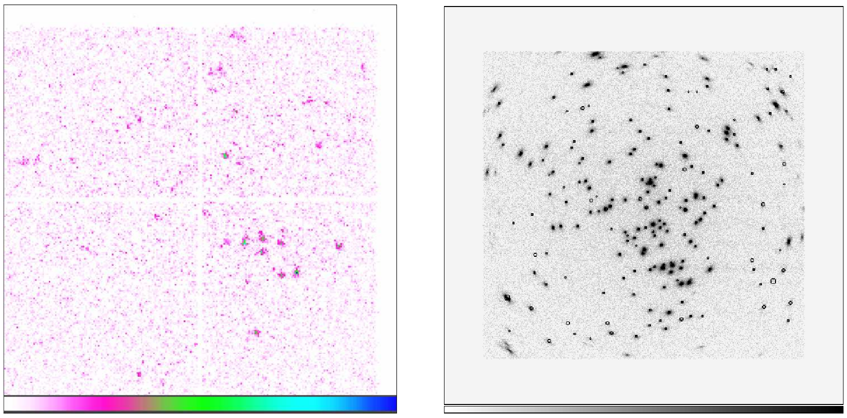

Fig. 4. (left) The predicted 50 Ksec CHANDRA ACIS observation of NGC 2264 reaching the limiting sensitivity $f_X \sim 3\ 10^{-16}$ erg/s/cm^2. Sources in the central part of the image appear in just one or two pixels. (right) The predicted 50 Ksec EPIC XMM observation of NGC 2264 reaching the limiting sensitivity $f_X \sim 7\ 10^{-16}$ erg/s/cm^2. EPIC has the advantage of 4 times larger field of view than ACIS.

systematic investigation of the relation among activity and other stellar parameters. In particular, it has been possible to investigate the age-rotation-activity relation as a function of stellar mass (cf. Randich 1997) even if at the very low mass the observations still lack in sensitivity. The X-ray data for few open clusters of different metallicity but with otherwise similar characteristics (age, rotation rate distribution, etc.) has allowed to start investigating the L_X-metallicity relation which should reflect the model-predicted deepening of convection zone with metallicity. If the dynamo is active at the interface of the convection zone, the deepening is predicted to produce an increase of the dynamo efficiency, likely reflected in a higher coronal emission level (cf. Jeffries 1999).

The CHANDRA and XMM imaging detectors will have a great impact on these investigations, allowing to measure the X-ray emission of stars of virtually all clusters within 500 pc, independently on their age, and up to large distance for the most young ones (cf. Micela 1996). As a result, the parameter space will be better covered and we expect to gain a deeper understanding of the role of various parameters on stellar activity and more generally on stellar physics.

To illustrate the possibility of X-ray imaging, we show in Figure 4 simulated ACIS-I and EPIC observations of the compact NGC 2264 SFR ($\sim$ 10 Myr) at a distance of 760 pc. These simulations are based on the extrapolation of the results of the recent HRI survey of Flaccomio et al. (1999a,b) reaching the limiting sensitivity $f_X \sim 10^{-14}$ erg/s/cm^2. Since distant open clusters will be more compact, the higher spatial resolution and deeper sensitivity (for the same exposure time) make the CHANDRA imaging detectors more adequate for these investigations. This is especially true in the case of the very long exposure time ($\geq$ 50 ks) when XMM EPIC starts to become confusion and background limited.

Since young stars are intense X-ray emitters they shine in X-rays among field stars,

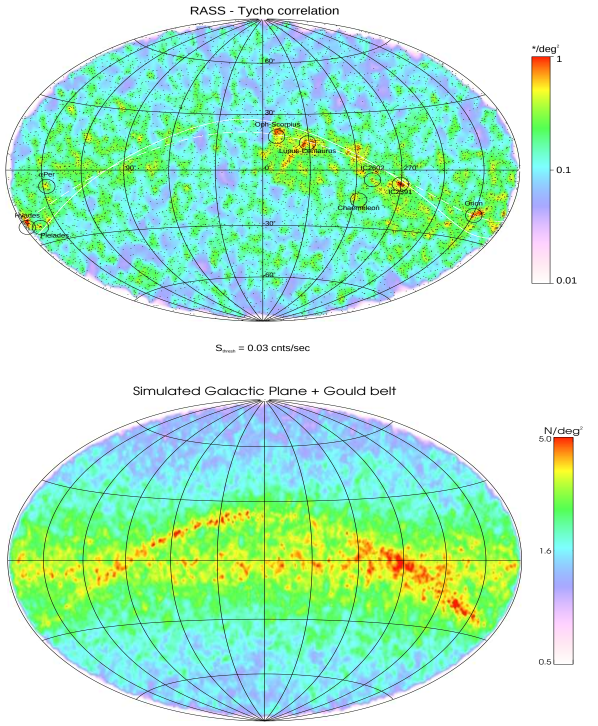

Fig. 5. (upper) - The result of the Tycho-RASS correlation. Each black point indicates a successful match. Note the enhanced density around the Galactic plane due to the Pleiades-age population and the tilted excess in the 230°–330° b range. The smoothed curves indicate the Gould Belt. (lower) A simulation of the spatial density of the X-ray–optical matches from a 5 times deeper survey than the RASS and an optical catalog complete to $m_V = 15$ for a stellar population whose spatial distribution follows the model of Guillout et al. (1998b)

hence X-ray surveys of open clusters/associations younger than the Pleiades have demonstrated to be a very effective way to search for cluster members (eg. Patten & Simon 1996, Randich et al. 1996, Micela et al. 1998). This is particularly true at low-mass end where other methods (such as proper motion) encounter discrimination difficulties. Hence X-ray surveys are a powerful technique to build an unbiased sample of members of a young open cluster/SFR, to derive an unbiased Initial Mass Function (IMF), and finally to test directly the hypothesis of the universal shape of the IMF. Such an approach has been recently taken by Lawson et al. (1996) and Flaccomio et al. (1999a,b). The CHANDRA and XMM deep observations will allow searching for very low-mass members, assessing the X-ray emission level of brown dwarfs, and, if they would emit at the same L_X/L_{bol} level of very low-mass stars, to extend the IMF determination in the brown dwarf mass domain. Since these investigations require to reach the deepest limiting sensitivity, CHANDRA imaging detectors, thanks to the narrower PSF, have again some advantages. I want to stress that since X-rays with energy higher than $\sim$

1 keV are weakly (compared to optical) absorbed they can effectively probe the early stage of star formation process when (proto-)stars are still embedded sources.

1.5. Stellar populations in the Galaxy

Surveys based on the ROSAT All Sky Survey (RASS) (Motch et al. 1997; Zickgraf et al. 1998) and smaller area pointed survey, such as the Galactic Plane Survey (Pye et al. 1997) have given important contributions to the study of the stellar content of the Galaxy. We have a clear evidence of a Pleiades-age stellar population with a scale height (around the Galactic plane) of 100 pc or less that was already seen, at lower statistical significance, through the analysis of the Einstein EMSS (Micela et al. 1993, Favata et al. 1993, Sciortino et al. 1995). There is also evidence of a lower density population of very young stars far from the cores of SFRs (Zickgraf et al. 1998; Covino et al. 1997). One of the most interesting results has been obtained by Guillout et al. (1998a) who have cross-correlated the RASS source list and the Tycho catalog showing the existence of a population of young active stars whose distribution is tilted with respect to the Galactic plane (cf. Fig. 5). Guillout et al. (1998b) have proposed a model in which this population is interpreted as the late-type stars of the Gould Belt (that indeed they better model as an inclined ellipsoidal disk-like structure). However more data (at $l \sim 90°$) on the far side of the disk are need to test the reality of the proposed structure. This is illustrated in Fig. 5 (courtesy of P. Guillout) showing the simulated result of a 5 times deeper X-ray survey than the RASS. As discussed extensively below, this is the kind of problem where both CHANDRA and XMM will be of limited help.

2. Some topics CHANDRA and XMM will not address: the role of small missions

When this paper will be printed both CHANDRA and XMM should have already started to collect new exciting images and spectra of many celestial objects. However, notwithstanding the tremendous impact we expect from these two observatories, it is not a difficult prediction that there will be important questions only marginally (if any) addressed. Limiting ourselves to the case of stellar physics, it should be evident that neither CHANDRA nor XMM could/would address questions, such as the study of the large scale distribution of young stellar population in the Galaxy, that need to observe a large contiguous area of the sky (as successfully demonstrated by Guilloult and collaborators). Similarly, high resolution spectroscopy of young stars (the nearest one being the Pleiades members) will be impossible. In this latter case, high-resolution non-dispersive[2] spectroscopy with **few** eV resolution together with new technology multi-layer coated mirrors to selectively increase the effective area at high energies is one of the most promising ways to make the best use of the available geometric collecting area. Indeed such crucial technological developments are in our hands and such studies could be, in principle, possible today. I am deeply convinced that while it is imperative for X-ray astronomers to work for the next-generation observatory class missions like the proposed

[2] The calorimeter on board Astro-E (to be launched on year 2000) **will not** have the energy resolution to be competitive with the grating spectrometers of CHANDRA or XMM.

Constellation-X (NASA) and XEUS (ESA), still, given their long-term development time and their small field-of-view ($\sim$ 10 arcmin), there is plenty of room for small dedicated missions both to address scientific questions that the future mission will not address, or to timely demonstrate the effectiveness of crucial technological developments.

2.1. Wide Field X-ray Telescope (WFXT) and Galactic Surveys

Any observatory class-mission will hardly address the problem of stellar populations in the Galaxy, since it will be impossible to devote enough time for such a demanding program! Moreover such an investigation requires the capability to obtain high-quality identifications, largely based on statistical criteria, such as spatial matching and f_X/f_V ratio, in order to make the problem feasible. This can be possible **only** if the positional uncertainties of the X-ray sources can be kept within few arcsecs over the entire explored areas. This can hardly be possible over the entire field-of-view either with CHANDRA or XMM since both are based on Wolter-I optical design, whose image quality degrades rapidly with off-axis angle. A different optical design is required, such as the one recently adopted and proven to work by O. Citterio and his group at Oss. Astr. di Brera/Merate (cf. Citterio et al. 1998, Ghigo 1999 in this volume). The image quality (as measured by the PSF HEW) stays virtually constant at $\sim$ 10" across a 1° field of view, allowing the realization of a Wide Field X-ray Telescope (WFXT). Such a telescope has been recently proposed as the core element of the Wide Area X-ray Survey mission (WAXS, Chincarini et al. 1999), proposed to the ASI small mission program, being part of an international collaboration including italian groups, the HEAD at SAO (Cambridge, USA), the X-ray Astronomy Group (Leicester, UK) and the MPE (Garching, FRG). The phase A study has demonstrated the mission being scientifically valid and realizable within a 2 year schedule. WAXS/WFXT is, in my opinion, a milestone for X-ray astronomy.

2.2. XRASE and Coronal Spectroscopy

The quest for non-dispersive spatially resolved high-resolution spectroscopy is one of the most compelling of current X-ray astronomy. While the need for spatial resolution is somewhat relaxed (but not too much) in the case of coronal physics (unless we consider the extreme angular resolution required for direct imaging of the coronal structures, cf. MAXIM mission study at http://maxim.gsfc.nasa.gov/maxim.html) the few eV spectral resolution and high throughput is a must. This is today a possible realization as illustrated in the XRASE proposal by Silver et al. (1998) to the NASA Midex program. The new-technology ultra-light multilayer-coated mirrors with angular resolution of ≤ 1 arcmin make it possible to obtain large collecting area (cf. Figure 6) even above the ~ 4 keV region where traditional mirrors undergo a substantial decrease of collecting area. The adoption as a imaging-spectrograph of a matrix of calorimeters makes it possible to reach the few eV resolution without the large loss of efficiency of gratings even for extended sources. I want to stress that *such a matrix of calorimeters can be built today* and its elements (individual calorimeter) have the required energy resolution (cf. Fig. 6) to allow the direct determination of coronal density (or to address any other physical problem that requires few eV resolution).

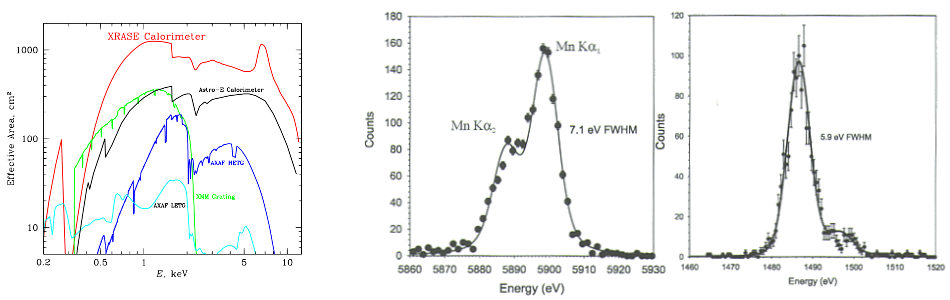

Fig. 6. (left) The effective area of the proposed XRASE and of CHANDRA, XMM and ASTRO-E high resolution spectrographs. The innovative calorimeter and mirror design allow XRASE to outperform all other missions. (right) Measured spectra of XRASE calorimeters showing that a resolution better than 10 eV has already been achieved.

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