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X-ray observations of young stars

G. Micela

INAF - Osservatorio Astronomico di Palermo Giuseppe S. Vaiana Piazza del Parlamento 1 - 90134 Palermo e-mail: giusi@astropa.unipa.it

Abstract. I present examples of X-ray observations of young stars obtained with current X-ray observatories Chandra and XMM/Newton. The high spatial resolution of Chandra allows us to spatially resolve very crowded star forming regions (SFRs), where X-rays are able to penetrate through the circumstellar material of yet embedded, very young stars. Therefore we are able to identify new members of SFR and to study in detail X-ray properties of stars in the first phases of their life. On the other side, XMM/Newton with its large effective area, makes possible to study spectral and variability properties with a detail never obtained before.

Key words. X-ray emission – stellar coronae – young stars

1. Introduction

Observing in X-rays is a very effective way to study young stars since their X-ray emission is about three order of magnitude higher than that of older main sequence stars (Micela 2002). Therefore young stars dominate the population of normal stars in X-ray observations (except than in very deep exposures at high latitude). Therefore X-ray surveys are particularly powerful to study low mass stars in star forming regions (SFR) and young clusters, while in the optical band they are very difficult to be discriminated against old field stars. Furthermore the coronae of young stars are much more variable than in old stars, and their spectra are harder. The relevance of high energy radiation in the star formation process and in the circumstellar environment is yet an open question that is receiving a great impulse thanks to the current generation of imaging X-ray telescopes.

The simultaneous presence of two large X-ray observatories, Chandra and XMM/Newton, gives us a unique opportunity to study the properties of X-ray emission of low mass stars in SFRs and young open clusters. Indeed the capabilities of these two instruments are complementary and well suited to study different aspects of emission of young coronae: Chandra has a superb spatial resolution, of the order of 0.2” in the center of field of view, and allows us to image very crowded regions such as those in rich SFRs, while XMM/Newton has a large effective area, and therefore is able to collect a large number of photons and is particularly suited to study spectra and variability properties.

In sect. 2 I will present observations of nearby SFRs obtained with Chandra and their capability in exploring the mass function of these regions. In sect. 3 I will discuss some results of variability analysis of stars in young

Send offprint requests to: G. Micela
Correspondence to: Piazza del Parlamento 1 - 90134 Palermo

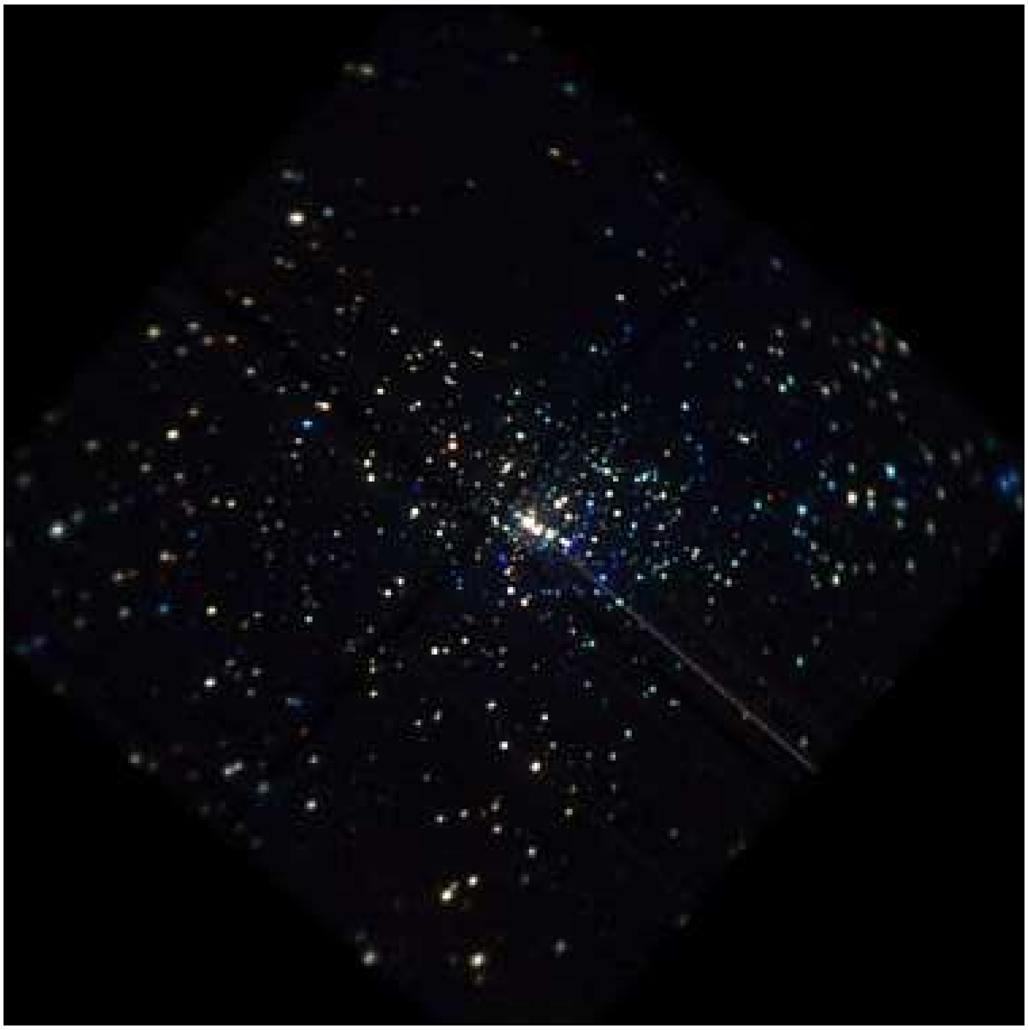

Fig. 1. Chandra observation of the Orion Trapezium region. The total exposure time is $\sim 850\, ksec$ allowing detecting more than 1600 sources. The size of the field is $\sim 16' \times 16'$.

open clusters observed with XMM/Newton. Note that I have just selected a few results among the several ones that are coming from both these observatories.

2. Chandra observations of Star Forming Regions

Chandra is producing very deep images of SFRs, allowing us to study emission from individual members even in very crowded and absorbed regions of the sky. In Fig. 1 I show the image of the Orion Trapezium obtained with 850 ksec exposure of Chandra. This is the longest exposure of Chandra on a stellar field and it is the result of a large international collaboration leaded by E. Feigelson of Penn State University, involving many tens of scientists of several institutions. This image includes more than 1600 sources, most related to members of the SFR including stars of every mass, from the more massive ones to the brown dwarfs. This

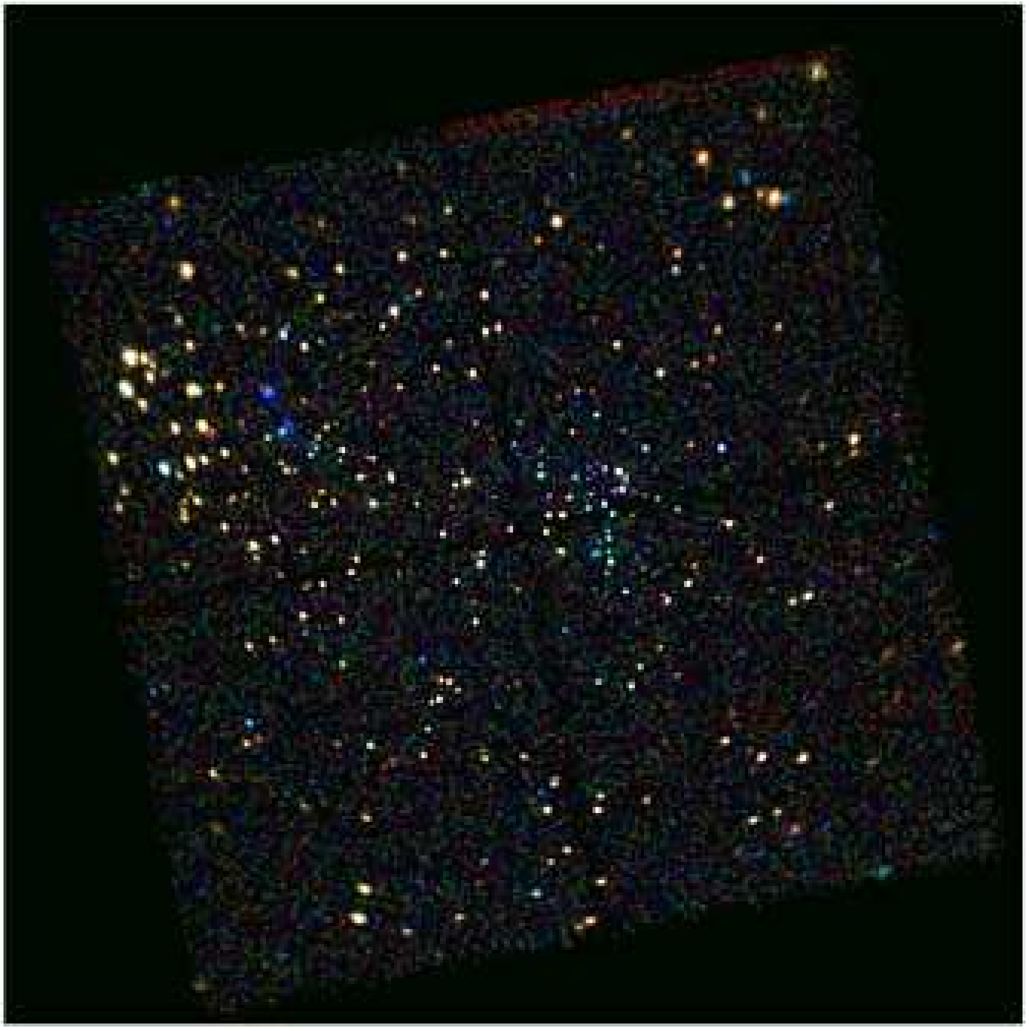

Fig. 2. Image obtained from 100 ksec Chandra exposure of the SFR NGC 2264. In this observations embedded stars, not visible in optical band, are clearly detected in X-rays (Flaccomio et al. 2004)

observation well illustrates the need of X-ray telescopes with arcsec-subarcsec spatial resolution: no other past or present telescope could image such a crowded region. The observation spans 13 days, and allows us to study coronal variability in a large sample of stars that present both impulsive and gradual variations. Indeed the majority of the sources present significant variability; many sources show flares (even more than one) during the observation. This data set will allow us to derive the statistical properties of X-ray flares in very young stars as a function of mass, accretion, rotation etc. Other sources show variations that can be associated to rotational modulation, indicating that also in these very young stars X-ray emission comes from spatially confined regions on the stellar surface.

Fig. 2 shows the image obtained with a 100 ksec exposure of the SFR NGC 2264

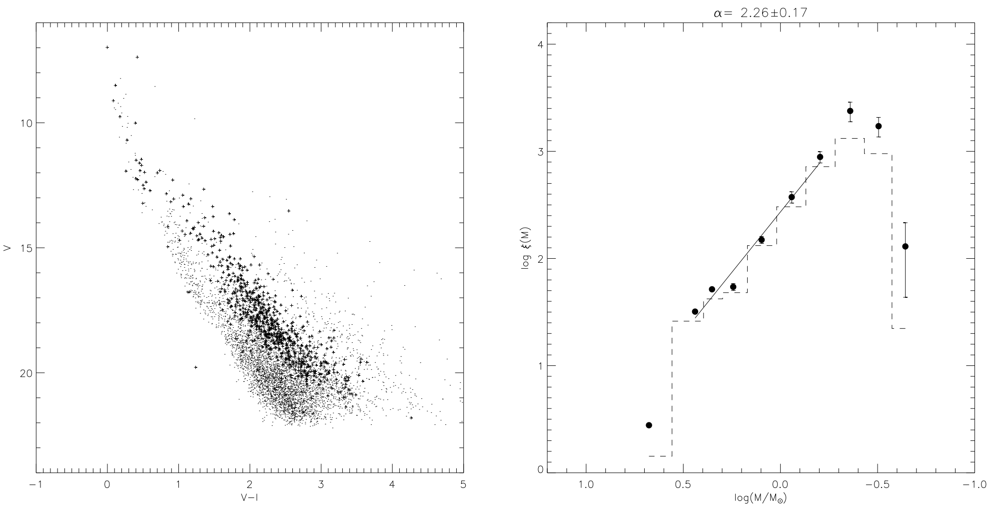

Fig. 3. Optical photometry in the NGC 6530 field of view. Crosses indicate X-ray detected stars. X-ray sources mark the cluster region, that at the cluster distance corresponds to an age of few Myr (left panel). IMF derived for NGC 6530 from 60 ksec observation of Chandra/ACIS-I, complemented with the optical photometry (right panel). The histogram represents the Mass Function without any corrections. Dots mark the IMF, corrected for incompleteness, using the X-ray luminosity functions for each mass bin of Orion (Flaccomio et al. 2003).

(Flaccomio et al. 2004). This is a very young region, with significant differential reddening and more than one site with active stellar formation. Particularly notable are two groups of sources with hard X-ray spectra, spatially coincident with two previously known infrared clusters, invisible in the optical band. Indeed X-ray photons are able to penetrate dense interstellar medium, much more efficiently than optical light. Thus X-ray observations together with infrared ones are the only way to study very young and still embedded stars and, therefore, they play a key role in our understanding of star formation processes.

Chandra observations of SFRs are very powerful to identify low mass members and therefore they help us to derive the Initial Mass Function down to low masses. As an example, I will present here the results obtained from the Chandra observation of the young SFR NGC 6530 at a distance of $\sim$ 1.8 kpc. In this case we have been able to compute the IMF (Prisinzano 2003) thanks to the Chandra observation (Damiani et al. 2004), together with deep optical photometry, crucial for estimating stellar masses. X-ray emission has been used as membership criterion to select cluster members (see Fig. 3, left panel). The cluster sequence is completely blended with field stars and without X-ray data, member selection would be impossible (contamination from field X-ray sources is only at few percentage level as discussed in detail by Damiani et al. (2004)). The derived IMF (Fig. 3) has a slope similar to that obtained for Orion, with which NGC 6530 shares many properties and environmental conditions.

3. Coronal variability studies of young stars

Variability is a common property of young stars. Involved phenomena are complex and are related to the physical origin of the emission. Young stars present large X-ray flares, much larger than those observed in the Sun, together with smaller amplitude variations. In some cases the quiescent emission is very low

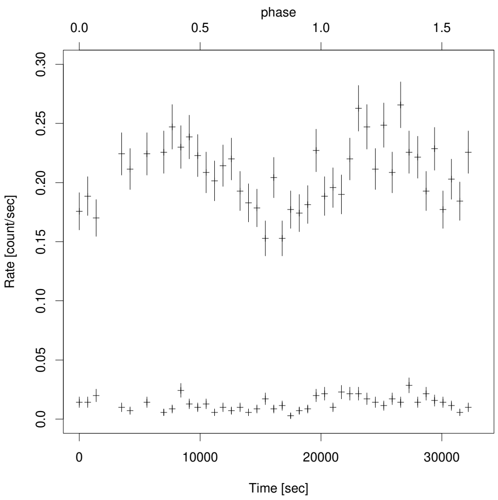

Fig. 4. X-ray light curve of the dG star VXR 45 member of IC 2391 open cluster. Phase refers to the optical period (19 ksec). Background light curve is reported on the bottom.

and stars can be detected only during flare activity. Young stars could present also gradual variations, likely due to emergency and evolutions of active regions, and in some cases periodic modulation that can be associated to rotation.

The large collecting area of XMM/Newton is very well suited to detect and study variability. In Fig. 4 I report the first clear evidence of rotational modulation observed in a star different from the Sun. The star is VXR 45, a member of the young open cluster IC 2391 that just entered the main sequence, with a mass slightly smaller than that of the Sun, and with a very short optical period. The X-ray light curve, suggests a period of 20 ksec, compared with the optical period of 19 ksec. X-ray emission of fast rotators saturates at $\log(L_x/L_{bol}) \sim -3$, but in very fast rotators X-ray luminosity decreases and stars are said to be in the supersaturation regime; VXR 45 is one of the so-called supersaturated stars (Randich et al. 1998). The folding of the X-ray light curve with the optical period confirms that we are really observing X-ray rotational modulation (Marino et al. 2003). The presence of modulation in such star indicates, for the first time, that even in these very active stars, the corona is not completely covered by emitting regions, but that surface inhomogeneities have to be present.

Many young stars exhibit very frequent flaring activity, indicating that their coronae are very dynamic. Stellar flares can be much more energetic and intense than the solar ones, and, if one has good enough statistics, through time resolved spectral analysis one can derive the physical properties of the emitting structures, including loop length and the presence of sustained heating. As an example, I report in Fig. 5 the XMM/Newton light curve of a dG9 star of Blanco I, a cluster with an age of $\sim 10^8$ years. Two large flares, with e-folding times of ~ 1.4 and ~ 1.5 ksec, respectively, are present at the beginning of the observation. The flares have been modeled following Reale (2002) and the results indicate that the second flare is likely ignited by the first one, and that both occur in an arcade composed by many (~ 170) small loops with length $L = 3 \cdot 10^9$ cm and with an aspect ratio of 0.2 (Pillitteri et al. 2004). A sketch of a similar arcade is reported in Fig. 5, overlapped to a solar image taken during the *Bastille-day* flare (see Aschwanden et al. 2003) in which a phenomenon similar to the one we are suggesting here, although on a smaller scale, has been observed. Stellar flare modeling suggests that the observed large flares can be due to phenomena not very dissimilar to those occuring in the Sun but on a larger scale.

4. Conclusions

Chandra and XMM/Newton observations are producing wonderful images, spectra, and light curves of SFRs and young clusters. These observations are allowing us to gain a significant insight on the role of high energy radiation on the first phases of stellar life and to better understand the history of our Sun. In particular the study of the X-ray spectral evolution and flare frequency can help us to understand the ionization of the circumstellar environment during the stellar formation process itself and during the disk dissipation and planet formation phases. We expect that in the next years much more will be learned in this field thanks,

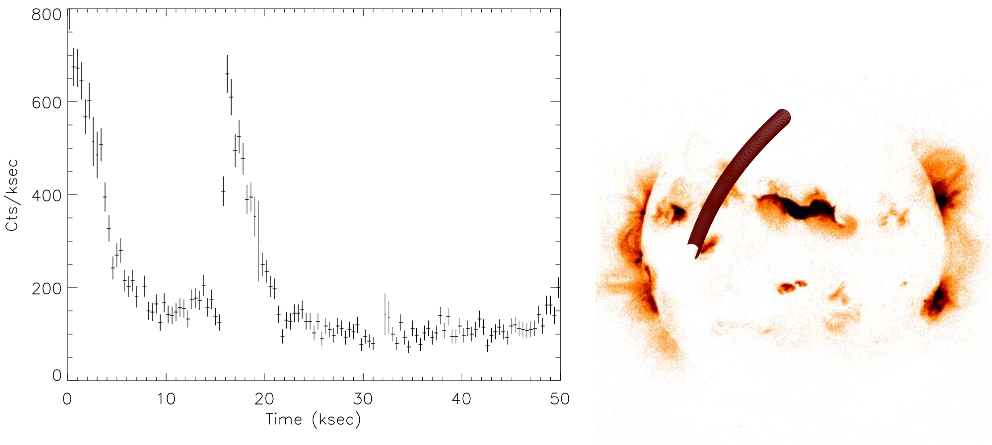

Fig. 5. Left panel: X-ray light curve of the dG9 member of Blanco 1 obtained with XMM/Newton. Right panel: Solar image during the *Bastille-day* flare, with a schematic representation of the arcade derived from modeling of the flares in the left panel.

hopefully, also to future more powerful X-ray observatories.

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