# Evolution of X-ray emission from young massive stellar clusters

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**Abstract.** The evolution of young massive stellar cluster is modeled in order to explain the striking difference observed in the levels of X-ray emission between clusters of different age. It is shown that the level and character of soft (0.2-10 keV) X-ray emission change drastically with cluster age and are tightly linked with stellar evolution. Assuming instantaneous burst of star formation and standard initial mass function, the total X-ray luminosity of all low-mass stars $(0.1 - 3\,M_\odot)$ is higher than the total luminosity of the cluster's high-mass stars $(8 - 100\,M_\odot)$. The same time, massive stars are the brightest X-ray point sources, although they become much dimmer when they evolve to Wolf-Rayet (WR) star phase. A supernova remnant emission may be a dominant X-ray source in an old enough cluster, but only for a relatively short time of a few thousand years. The diffuse X-ray emission originates from the intercluster wind heated by the kinetic energy of stellar winds and supernova explosions. When massive stars reach the WR phase, the level of diffuse emission rises due to the powerful WR stellar winds. Subsequent SN explosions pump the level of diffuse emission even higher. The clusters older then $\approx 2\,$Myr may have no bright stellar point sources, but a relatively high level of diffuse emission. The above scenario provides a plausible explanation of the X-ray observations of the Arches and the Quintuplet cluster in the Galaxy as well as of a sample of LMC clusters.

## 1. Observations of young rich stellar clusters

Recently a sample of rich young stellar clusters located in the Large Magellanic Cloud (LMC) was observed with X-ray observatories. The sample contains clusters of masses comparable to the Galactic globular clusters and covers a wide range of ages, from $10^6$ to $10^8$ years. The X-ray images of clusters shown in Fig. 1 differ drastically. While the youngest cluster, R136, displays a wealth of bright point sources and little diffuse emission (Portegies Zwart et al. 2002), more evolved clusters are weak in X-rays, with no point sources above the level of background. A similar picture emerges from observations of the most massive Galactic stellar clusters the Arches and the Quintuplet. Recently, Law & Yusef-Zadeh (2004) pointed out that the character of X-ray emission differs between Arches and Quintuplet clusters. X-ray emission from the Arches is dominated by luminous point sources with little diffuse emission. In contrast, the level of diffuse emission in the Quintuplet is much higher, with no point sources being confidently detected. The purpose of this paper is to explain why older clusters have less stellar point X-ray sources and more diffuse emission compared to the younger ones.

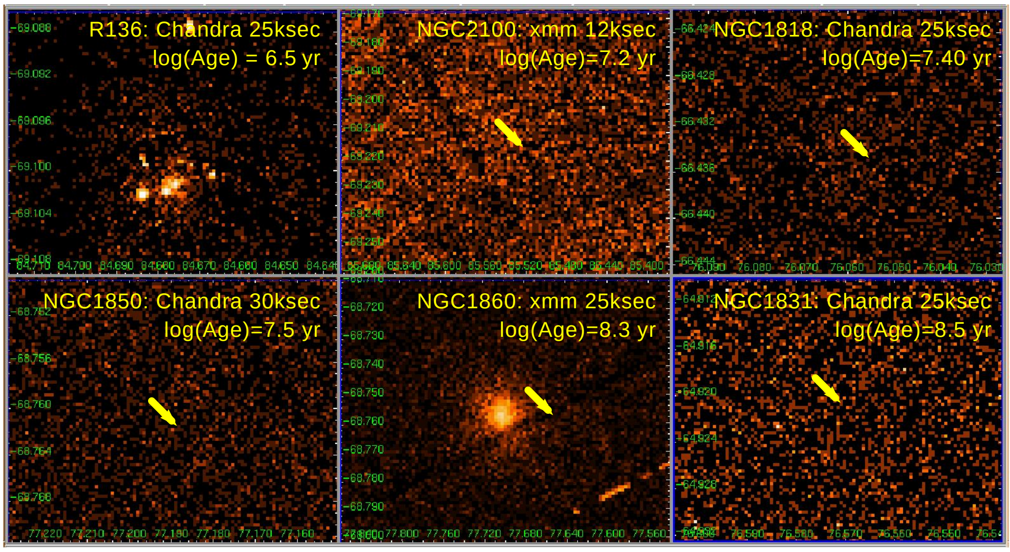


Figure 1. XMM-Newton and Chandra images of stellar clusters in the LMC. The celestial positions of the clusters are indicated by arrows. While R136 is clearly visible in the top left frame, other older cluster are not detectable. The cluster coordinates and ages are from Mackey & Gilmore (2003)

Let us consider the evolution of X-ray emission from an idealized cluster (aged between one and eight million years) with mass $M_{\rm cl} = 10^6 M_\odot$, solar metallicity and standard initial mass function, $\xi(M) = M_0 M^{-2.35}$.

The time dependent X-ray luminosity of a cluster is the sum of diffuse and point source emission:

$$L_{\rm X}(t) = L_{\rm X}^{\rm point}(t) + L_{\rm X}^{\rm diffuse}(t), \tag{1}$$

where

$$L_{\rm X}^{\rm point}(t) = \int_{M_{\rm min}}^{M_{\rm max}} \xi(M)\ L_{\rm X}(M,t)\ dM, \tag{2}$$

and $L_{\rm X}(M,t)$ is the luminosity of a star with mass $M$ at age $t$.

## 2. Evolution of diffuse emission from cluster wind

The interstellar medium of a rich stellar cluster has a constant supply of gas, $\dot{M}(t)$, due to the mass loss by a large number of massive stars and, later on, supernovae explosions. The fraction $\alpha$ of kinetic energy input, $\dot{E}(t)$, from individual stellar winds and SNe is thermalized, heating the intercluster gas to X-ray emitting temperatures. Chevalier & Clegg (1985) have shown that winds from star formation regions can be described as a self-similar process, and obtained solutions applicable to mass-loaded cluster winds. From the scaling laws of self-similar solutions, the emission measure and the temperature of a cluster wind are

$$\mathrm{EM}(t) \propto \dot{E}^{-1} \dot{M}^{3} R^{-1}, \tag{3}$$

and

$$T_{\mathrm{X}}(t) \propto \dot{M}^{-1} \dot{E}. \tag{4}$$

Then, the X-ray luminosity of the cluster wind becomes

$$L_{\mathrm{X}}^{\mathrm{diffuse}}(t) = \Lambda(T_{\mathrm{X}}) \ \mathrm{EM}(t), \tag{5}$$

where $\Lambda(T_{\mathrm{X}})$ is the cooling function.
Hence, if mass-loss rate, $\dot{M}$, and kinetic energy input, $\dot{E}$, are known at a given epoch, the luminosity of a cluster wind can be obtained. The Starburst99 population synthesis model, described in Leitherer et al.(1999), was used to provide $\dot{M}$ and $\dot{E}$ over a large range of cluster ages. The fraction $\alpha$ of energy input that is spent on the heating of the cluster wind, was estimated by comparison of the observed diffuse X-ray luminosity of the Arches and Quintuplet with the model, and is of the order of few per cent. Using this value, the diffuse X-ray luminosity of a model cluster is calculated and shown in Fig. 2. As can be seen, the level of diffuse emission varies significantly during cluster history, and reaches its maximum when majority of massive stars have entered the WR stage. This can provide an explanation for the higher level of diffuse emission in the Quintuplet (3-5 Myr) compared to the Arches (1-3 Myr). The next step is to trace the evolution of X-ray emission from stars in order to understand why there are fewer bright point sources in the older clusters then in the younger ones.

## 3. Evolution of emission from stellar point sources

In order to compute the evolution of X-ray luminosity of stars, we a) calculate the number of stars in each mass bin; b) estimate the lifetime a star of given mass; c) use the mass-luminosity relation; d) apply a correlation between X-ray and bolometric luminosity. Thus the X-ray luminosity as function of age is obtained for each mass bin.

The mechanism of X-ray emission is different in low- and high-mass stars. Low-mass stars emit X-rays as result of magnetic activity connected with the presence of outer convective layers. Massive stars, on the other hand, are X-ray emitters due to shocks either intrinsic to their powerful stellar winds or produced by wind-wind collision in binary stars. Stars with masses between 3 and 10 $M_{\odot}$ do not, generally speaking, emit X-rays. This is the consequence of the disappearance of convective envelopes for stars more massive then $3\,M_{\odot}$, and the weakness of stellar winds for stars less massive then $10\,M_{\odot}$.

To trace the evolution of X-ray emission from an ensemble of low-mass stars we took as a template the study of stars in the Orion Nebular Cluster (ONC) by Flaccomio et al. (2003). It was found that median X-ray luminosities of low-mass stars ($M \lesssim 3M_{\odot}$) increase with increasing mass and decreasing stellar age. We summarize those results in the left panel of Fig. 2. The X-ray luminosity of each individual low-mass star is not high ($< 10^{31}\,\mathrm{erg\,s^{-1}}$). The large number of these X-ray dim stars fill the whole cluster volume. Thus the X-ray surface brightness due to the low mass stars is quite small. Nevertheless, integrated over the whole cluster volume the total X-ray luminosity of low-mass stars exceeds all other sources, most dramatically at the early stages of cluster history.

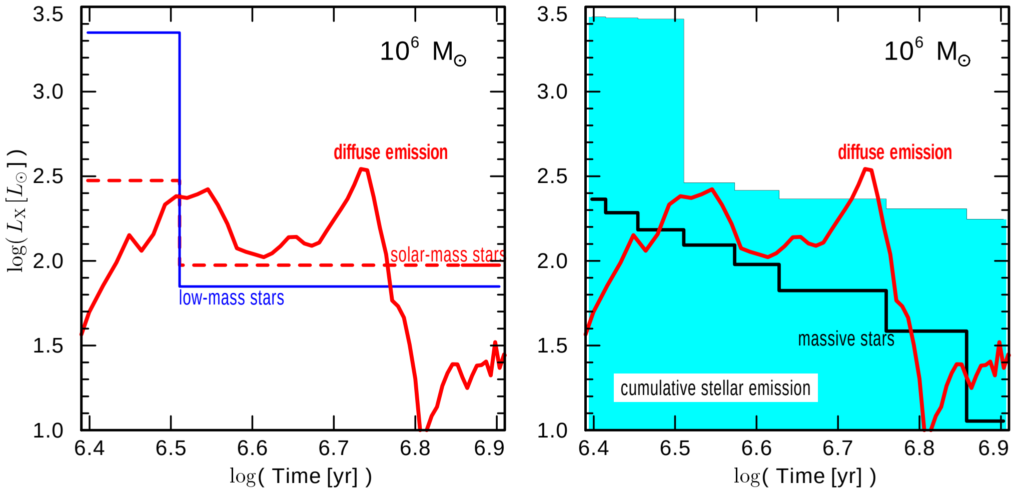


Figure 2. Calculated evolution of the X-ray luminosity of a $M_{\mathrm{cl}} = 10^6 M_\odot$ stellar cluster. Thick line in both panels represents the diffuse emission of the cluster wind $L_{\mathrm{X}}^{\mathrm{diff}}$. Until log(Time) $\approx$ 6.6 the mass and energy input is dominated by stellar winds, while SN explosions prevail later. A depression seen at around log(Time) $\approx$ 6.8 is a computational issue (see Leitherer et al. (1999) for details). The model predicts a higher level of diffuse emission for a cluster old enough to contain a significant fraction of WR stars. *Left panel*: Cumulative X-ray luminosity of low- and solar-mass stars (solid and dashed lines correspondingly) compared to the diffuse emission. For the youngest stellar clusters the dominant point sources of X-rays are low-mass stars. Being weak X-ray sources, but quite numerous, those objects are difficult to spatially resolve. *Right panel*: X-ray luminosity from massive stars (solid line) and total X-ray emission from all stellar sources (shadowed area) compared to the diffuse emission.

There are significantly less young OB-stars than low-mass stars, but each of the former is a relatively bright X-ray source (typically $\gtrsim 10^{32}\,\mathrm{erg\,s^{-1}}$). Massive stars tend to concentrate in the cluster core, filling a smaller volume than low-mass stars. Both theory and observations suggest, that the majority of massive stars in dense clusters reside in multiple systems. Therefore, the well known correlation between bolometric and X-ray luminosity for O stars, $L_{\mathrm{X}} \approx 10^{-7} L_{\mathrm{bol}}$ (Berghöfer et al. 1997), shall be explicitly verified for binary stars. For this purpose a sample of O-type spectroscopic binary systems with available deep exposures was selected. Linear regression analysis was used to check the correlation between $L_{\mathrm{X}}$ and $L_{\mathrm{bol}}$. The presence of such correlation, being exactly $\log L_{\mathrm{X}} = \log L_{\mathrm{bol}} - 7.0$, came out as a surprise! It is likely that the bulk of X-rays in a binary O star originates in the colliding wind zone. The properties of the X-ray emitting plasma in this zone are sensitive to the parameters of the binary systems. Hence, the proportionality $L_{\mathrm{X}} \propto L_{\mathrm{bol}}$ for binaries is puzzling.

Depending on its initial mass, after about 2 Myr, an X-ray bright O type star will evolve to a WN, and then to a WC star. The X-ray emission from WR stars is enigmatic, although the expectation is that the same mechanism as in O winds may operate there. The growing number of observations of WR stars reveal a complex picture. There is no correlation between bolometric and X-ray luminosity for WN stars (Ignace et al. 2000). Although some WN type stars are bright X-ray sources (e.g WR25), others were not detected in X-rays (e.g. WR61, WR40, WR16 and WR124). The overall detection rate even among the closest WN stars is much lower then for O-type stars. Moreover, Oskinova et al. (2003) have shown that there never been any confident detection of a single WC star, and only 18% of binary WC stars are X-ray sources. Based on available data, one may assume that, in general, WR stars are insignificant X-ray sources.

Hence, we adopt $L_{\rm X} = 10^{-7} L_{\rm bol}$ for O-stars and compute the X-ray luminosity of massive stars on age as function of age. The stellar life-times listed in Massey (2003) were used for different mass bins. As shown in the right panel of Fig. 2 the luminosity of massive stars strongly declines with age. This explains the absence of bright point sources in the LMC clusters older than R136 shown in Fig.1, as well as the observed lack of point sources in the Quintuplet.

## 4. Discussion

We propose a scenario for the evolution of X-ray emission from a young massive cluster. The numerous low-mass stars are the dominant source of cumulative X-ray emission. However, each individual low-mass star is a weak source compared to a massive luminous star. Being distributed over the whole volume of the cluster, the low-mass stars are difficult to resolve as individual sources. Massive O-type stars are concentrated in the cluster core, and are the brightest point sources. Evolving to the WR stage, massive stars become, in general, dimmer X-ray sources, but increase their input of mass and energy into the intercluster medium. The heated and thermalized cluster wind is a diffuse X-ray source. At the time when the majority of massive stars have become WR stars, the diffuse emission of the cluster wind may surpass the point sources. The surface brightness of clusters at this evolutionary stage is expected to be low, in accordance with the available observations of older LMC and Quintuplet clusters.

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