ON THE X-RAY EMISSION FROM MASSIVE STAR CLUSTERS AND THEIR EVOLVING SUPERBUBBLES

SERGIY SILICH, GUILLERMO TENORIO-TAGLE, AND GABRIEL ALEJANDRO ANORVE-ZEFEERINO
Instituto Nacional de Astrofisica Optica y Electronica, AP 51, 72000 Puebla, Mexico; silich@inaoep.mx
Received 2005 June 22; accepted 2005 August 27

ABSTRACT

Here we discuss the X-ray emission properties from the hot thermalized plasma that results from the collisions of individual stellar winds and supernovae ejecta within rich and compact star clusters. We propose a simple analytical way of estimating the X-ray emission generated by super star clusters and derive an expression that indicates how this X-ray emission depends on the main cluster parameters. Our model predicts that the X-ray luminosity from the star cluster region is highly dependent on the star cluster wind terminal speed, a quantity related to the temperature of the thermalized ejecta. We also compare the X-ray luminosity from the super stellar cluster (SSC) plasma with the luminosity of the interstellar bubbles generated from the mechanical interaction of the high-velocity star cluster winds with the interstellar medium (ISM). We found that the hard (2.0–8.0 keV) X-ray emission is usually dominated by the hotter SSC plasma, whereas the soft (0.3–2.0 keV) component is dominated by the bubble plasma. This implies that compact and massive star clusters should be detected as pointlike, hard X-ray sources embedded into extended regions of soft diffuse X-ray emission. We also compared our results with predictions from the population synthesis models that take into consideration binary systems and found that in the case of young, massive, and compact super star clusters the X-ray emission from the thermalized star cluster plasma may be comparable to or even larger than that expected from the high-mass X-ray binary (HMXB) population.

Subject headings: galaxies: star clusters — ISM: bubbles — stars: winds, outflows — X-rays: ISM

1. INTRODUCTION

In many starburst galaxies and in interacting and merging galaxies, a substantial fraction of star formation is concentrated in a number of compact, young, and massive stellar clusters or SSCs (see, for example, Holtzman et al. 1992; Ho 1997; O’Connell 2004 and references therein). The high stellar densities and large energy and mass deposition rates, provided by stellar winds and supernovae (SNe) explosions, suggest that SSCs are potentially strong X-ray emitters (Chevalier 1992).

Indeed, the X-ray emission from NGC 3603, the Arches cluster in our Galaxy, and R136 in the Large Magellanic Cloud (LMC)—the local analogies to low-mass SSCs—has been detected (Moffat et al. 2002; Yusef-Zadeh et al. 2002; Stevens & Hartwell 2003). The X-ray emission from the Arches cluster has a diffuse component and five discrete sources. Overall, 40% of the observed emission is diffuse and 60% comes from the discrete sources. The absorption-corrected X-ray luminosity (between 0.5 and 8 keV) is \( L_X \approx (0.5–3) \times 10^{35} \) ergs s\(^{-1}\), and the best spectral fit requires the metallicity of the X-ray plasma to be 4–5 times solar (Law & Yusef-Zadeh 2004). Similarly, the X-ray luminosity from R136 in 30 Doradus is \( L_X = 5.5 \times 10^{34} \) ergs s\(^{-1}\) (Stevens & Hartwell 2003). On the other hand, an examination of the XMM-Newton observations led Smith & Wang (2004) to the discovery of the diffuse X-ray emission from a 100 pc superbubble, 30 Doradus C, associated with a rich OB association, LH 90, located southwest of the center of 30 Doradus. The examination of the X-ray spectrum also indicates an overabundance of \( \alpha \)-elements in the bubble plasma by a factor of \( \sim 3 \), compared to the metallicity of the LMC.

X-ray emission detected in distant galaxies presents two components overall: an extended diffuse component that seems to be related to a collection of superbubbles associated with individual star clusters, and a number of unresolved pointlike sources (Summers et al. 2004; Metz et al. 2004; Smith et al. 2005). In some cases, the X-ray emission shows good coincidence with the young stellar clusters (Metz et al. 2004). However, there are also many examples of X-ray regions that do not present any evidence of active star formation. In other cases the X-ray sources seem to be shifted relative to the nearby star clusters, and some massive clusters seem to emit no X-rays at all (Kaaret et al. 2004). Thus the origin of the X-ray emission in distant galaxies and the dependence of the detected X-ray emission on the parameters of the embedded star clusters remain controversial.

Here we discuss how the mechanical energy deposited by stellar clusters restructures the host galaxy ISM while producing a hot plasma that should be detected in the X-ray regime (see §2). In §3 and 4 we demonstrate that the mechanical energy from SSCs leads to a two-component plasma model: a high-temperature, over-abundant in \( \alpha \)-elements plasma, ejected from the star cluster; and a lower temperature, extended, interstellar bubble component. Here we discuss how the luminosity of the hot component depends on the star cluster parameters, and in §5 we compare the contributions from both components when evolving in different interstellar environments and as a function of time.

2. SUPER STAR CLUSTER WINDS AND THEIR IMPACT ON THE ISM

The interaction of the high-velocity outflow that results from the energy injected by multiple stellar winds and SNe explosions within a star cluster volume leads to a major restructuring of the ISM. The evolution under the assumption of a uniform density case causes, as in the case of a stellar wind (Weaver et al. 1977), several physically distinct regions (see Fig. 1) promoted by the shock waves (inner and outer shocks) that result from the wind-ISM interaction. The X-ray emission from such structures must first take into account the central star cluster (zone A) filled with the thermalized, high-temperature plasma injected by winds and SNe. There the large central overpressure that results from...
X-RAY EMISSION FROM SSCs AND THEIR SUPERBUBBLES

3. THE INNER STRUCTURE OF THE X-RAY REGION

In the adiabatic solution the temperature and density of the gas at the star cluster surface, \( r = R_{SC} \), may be inferred from the mass and energy conservation laws (see eqs. [4] and [6] in Silich et al. 2004). They are

\[
T_{SC} = \frac{2(\gamma - 1)\mu_1}{\gamma(\gamma + 1)k} \frac{L_{SC}}{M_{SC}} = \frac{\gamma - 1}{\gamma(\gamma + 1)} \frac{\mu_1 V_k^2}{k} \frac{_{A,\infty}}{T_{A,\infty}} = 1.1 \times 10^7 V_{1000}^2 \frac{K}{\text{g cm}^{-3}},
\]

(1)

\[
\rho_{SC} = \frac{M_{SC}}{4\pi R_{SC}^2 c_{SC}} = \left( \frac{\gamma + 1}{\gamma - 1} \right)^{1/2} \frac{L_{SC}}{2\pi R_{SC}^2 V_{A,\infty}} = 3.3 \times 10^{-24} \frac{L_{18}}{R_{SC,1}^2 V_{1000}^3} \text{ g cm}^{-3},
\]

(2)

where \( L_{SC} \) and \( M_{SC} \) are the mechanical energy and mass deposition rates, \( k \) is Boltzmann’s constant, \( \gamma = 5/3 \) is the ratio of specific heats, \( \mu_1 = 14/23m_H \) is the mean mass per particle for a fully ionized plasma, \( c_{SC} = (\gamma kT/m) = (\gamma - 1)/(\gamma + 1) \) is the sound velocity at the star cluster edge, and \( V_{A,\infty} = (2L_{SC}/M_{SC})^{1/2} \) is the resulting wind adiabatic terminal speed; \( L_{18} \) is the mechanical luminosity of the SSC measured in units of \( 10^{38} \text{ ergs s}^{-1} \), \( R_{SC,1} \) is the star cluster radius measured in units of 1 pc, and \( V_{1000} \) is the wind adiabatic terminal speed in units of 1000 km s\(^{-1}\). The temperature and density of the gas inside the star cluster are always close to the adiabatic values if the stationary wind regime is possible.

On the other hand, from the work of Chevalier & Clegg (1985) and Cantó et al. (2000), who considered the adiabatic solution for SSC winds, and from the recent semianalytical radiative solution of Silich et al. (2004), we know that the density and temperature inside of the star cluster volume remain almost constant [in the adiabatic case, the ratio of the temperature at the star cluster surface to the central temperature is \( T_{SC}/T_C = 2(\gamma + 1)/\gamma = 0.75 \)] and are completely defined by the star cluster parameters \((L_{SC}, M_{SC}, R_{SC})\). This is also the case in the radiative solution, although one also has to take into account the chemical composition of the ejected material. Thus the density and the temperature distributions in zone A may be approximated as

\[
T(r) \approx T_{SC}, \quad \rho(r) \approx \alpha_\rho \rho_{SC}, \quad \rho_2 \rho_{SC},
\]

(3)

where the fiducial coefficient \( \alpha_\rho \) takes into consideration the deviation of density in zone A from the homogeneous distribution (the small deviation of temperature from the surface value leads to negligible changes of the X-ray emissivity).

In zone B all variables rapidly approach their asymptotic values: \( \rho(r) \sim r^{-2}, T \sim r^{-4/3} \). In the strongly radiative regime the temperature may drop faster and reach values of \( \sim 10^6 \text{ K} \) at smaller radii. However, the contribution of this zone to the total X-ray luminosity is small, and it arises mainly from a region close to the SSC surface (see § 4).

The expansion of the outer shock is supported by the thermal pressure of the thermalized wind (zone C in Fig. 1). In the case of a homogeneous ISM and a constant rate of mechanical energy deposited by the central cluster, the time evolution of the outer shock radius, \( R_{out} \), the reverse shock radius, \( R_{in} \), and of the
expansion velocity, $V_{\text{out}}$, of the outer shell are given by (Koo & McKee 1992)

$$R_{\text{out}} = 0.88 \left( \frac{L_{\text{SC}}}{\rho_{\text{ISM}}} \right)^{1/5} r^{3/5}, \quad R_{\text{in}} = 0.92 \left( \frac{L_{\text{SC}}}{\rho_{\text{ISM}}} \right)^{3/10} r^{2/5},$$

where $t$ is the bubble age and $\rho_{\text{ISM}}$ is the density of the ISM.

The shocked ISM in zone D remains adiabatic until the evolution time becomes larger than its characteristic cooling time-scale, $t_{\text{cool}}$ (Mac Low & McCray 1988), when

$$t \geq t_{\text{cool}} = 2.3 \frac{Z_{\text{ISM}}}{n_{\text{ISM}}} \times 10^4 n_{\text{ISM}}^{0.71} L_{38}^{0.29} \text{yr},$$

where $Z_{\text{ISM}}$ is the ISM gas metallicity measured in solar units and $n_{\text{ISM}}$ is the ISM gas number density. When $t$ exceeds $t_{\text{cool}}$, the gas in zone D becomes thermally unstable and collapses into a thin cold expanding outer shell. After this stage the density and the temperature distributions inside the bubble (zone C) are dominated by thermal evaporation of matter from the cold shell into the superbubble. If thermal evaporation is not blocked by magnetic fields, the density and the temperature distributions in zone C are (Weaver et al. 1977; Mac Low & McCray 1988)

$$n(x) = n_0 (1 - x)^{-2/5}, \quad T(x) = T_0 (1 - x)^{-2/5},$$

where $x = r/R_{\text{CD}}$ is the fractional radius, $R_{\text{CD}}$ is the radius of the contact discontinuity, $n_0$ and $T_0$ are functions of the evolutionary time: $n_0 = 1.0 \times 10^2 L_{38}^{10/3} n_{\text{ISM}}^{3/5} r^{-22.35}$ cm$^{-3}$, $T_0 = 5.5 \times 10^3 L_{38}^{2.35} n_{\text{ISM}}^{2.35} r^{-3.55}$ K, and $r$ here is measured in years.

4. THE X-RAY MODEL

Once the distributions of density and temperature in the various zones described above (zones A, B, and C, including at earlier times zone D) are known, one can calculate the X-ray luminosity from the whole remnant. This is given by

$$L_X = 4\pi \int_0^{R_{\text{out}}} r^2 n^2 \Lambda_X(T, Z) dr,$$

where $n(r)$ is the atomic number density, $R_{\text{out}}$ marks the location of the outer shock, and $\Lambda_X(T, Z)$ is the X-ray emissivity derived by Raymond & Smith (1977) in their hot plasma code (see Strickland & Stevens 2000). Clearly, regions in which the gas temperature is below the X-ray cutoff temperature ($T_{\text{cut}} \approx 5 \times 10^5$ K) would not contribute to the global X-ray emission.

4.1. The X-Ray Luminosity from the Star Cluster and Its Free Wind

The temperature and density distributions within zones A and B, obtained from the numerical models (see Silich et al. 2004), lead to the corresponding X-ray luminosity. The results of the calculations for 10° M$_\odot$ clusters of 1 and 10 pc radii are presented in Figure 2. The figure shows the contribution, $\epsilon_R = [L_{X, A+B} - L_X(R)]/L_{X, A+B}$, arising from concentric shells with inner radius, $R$, and outer radius equal to the X-ray cutoff radius, to the total X-ray luminosity, $L_{X, A+B}$, from zones A and B. Figure 2 shows that the contribution from the free wind region (zone B) is negligible. The value of $\epsilon_R$ for shells with radius $R \geq R_{\text{SC}}$ never exceeds $\sim 20\%$ of the cumulative emission from zones A and B. This is mainly due to the rapid decline in density ($\propto r^{-2}$) in the free wind region.

![Figure 2](image_url)

**Figure 2.** Distribution of the radiated energy along the central zones A and B. Lines display the results of the calculations for quasi-adiabatic (solid) and strongly radiative (dotted) outflows. The star cluster mass and wind adiabatic terminal speed are $10^6 M_\odot$ and $V_{\text{cut}} = 1000 \text{ km s}^{-1}$ in both cases. The star cluster radii are $R_{\text{SC}} = 10$ pc (solid line) and $R_{\text{SC}} = 1$ pc (dotted line); $L_{X, A+B} = 3.2 \times 10^{39}$ and $L_{X, A+B} = 2.6 \times 10^{38}$ ergs s$^{-1}$ in the case of the 1 and 10 pc cluster, respectively.

A good estimate of $L_{X, A+B}$ can be obtained if one approximates the density and temperature distributions within zone A by constant values (see eq. [3]). The evaluation of integral (7) then yields

$$L_{X, A+B} = 4 \frac{\rho_{\text{ISM}}}{\mu_m} \frac{\Lambda_X \rho_{\text{SC}}^2 r_{\text{SC}}^3}{3 \mu_m^2},$$

where $\mu_m = 14/11 m_1$ is the mean mass per atom. This simple analytic formula also accounts for the contribution from zone B and is in excellent agreement with the results of our semianalytical calculations (see Fig. 3) if the fiducial coefficient $\alpha_2 \approx 2.0$.

One can also obtain $\rho_{\text{SC}}$ from equation (3) and rewrite equation (8) in the form

$$L_{X, A+B} = 3.8 \times 10^{34} \Phi(T_{\text{SC}}, Z_{\text{SC}}) \frac{L_{38}^3}{R_{\text{SC}} 1.1 V_{1000}} \text{ergs s}^{-1},$$

where $T_{\text{keV}}$ is the temperature of the X-ray plasma measured in kilo–electron volts. Equation (9) is normalized to $\Lambda_X = 3 \times 10^{-23}$ ergs cm$^{-3}$ s$^{-1}$, and the normalization function, $\Phi(T_{\text{SC}}, Z_{\text{SC}})$, depends on the plasma temperature, $T_{\text{SC}}$, and its metallicity, $Z_{\text{SC}}$ (see Fig. 4). It predicts a quadratic dependence of the X-ray luminosity (zones A and B) on the star cluster mass ($L_{\text{SC}}$ scales linearly with the mass of the cluster) and is similar to the scaling relation from Stevens & Hartwell (2003) and that proposed by Oskinova (2005).

Equation (9) shows how the X-ray emission from the central zones A and B depends on the main star cluster parameters. The strong dependence on $V_{\text{A, } \infty}$ comes from the fact that close to the star cluster surface $\rho_m \sim M_{\text{SC}}/R_{\text{SC}}^2 V_{\text{A, } \infty} \sim L_{\text{SC}}/V_{\text{A, } \infty}^3$. This last
relationship leads to equation (9), as the X-ray luminosity (along with radiative cooling) is in direct proportion to the square of the gas number density. This implies that the wind adiabatic terminal velocity (or the ratio of the energy to the mass deposition rates) is the key parameter that defines the X-ray emission from the central zones. Note that equation (9) cannot be applied to very compact and massive star clusters above the threshold line (see Silich et al. 2004; Tenorio-Tagle et al. 2005), clusters for which the stationary wind solution is inhibited by radiative cooling.

4.2. X-Ray Luminosity from the Bubble

4.2.1. Adiabatic Stage

During the early stages, when \( t < t_{\text{cool}} \), the distributions of density and temperature in zones C and D are close to homogeneous and one can evaluate integral (7) analytically:

\[
L_{X, C} = \frac{4\pi}{3} \Lambda X(T_C, Z_C) n_C^2(R_{CD}^3 - R_{in}^3)
= \frac{3\Lambda X(T_C, Z_C) L_{SC}^2}{\pi \mu_m^2 V_{A, \infty}^2} \left( 1 - \frac{R_{in}}{V_{A, \infty}} \right)^2
= 9.5 \times 10^{34} \left( \frac{\Lambda X}{3 \times 10^{-23}} \right)
\times n_{ISM}^{3/5} L_{38}^{7/5} \left[ 1 - \frac{R_{in}}{V_{A, \infty}} \right]^{1/5} \times t_7^{2/5} \text{ergs s}^{-1},
\]

\[
L_{X, D} = \frac{4\pi}{3} \left( \frac{\rho_{ISM}}{\rho_a} \right)^2 \Lambda X(T_D, Z_{D, \infty}) R_{out}^3
= 4.6 \times 10^{41} \left( \frac{\Lambda X}{3 \times 10^{-23}} \right) n_{ISM}^{7/5} L_{38}^{3/5} t_7^{9/5} \text{ergs s}^{-1},
\]

where \( n_C \) and \( Z_C \) are the shocked wind (zone C) number density and metallicity, \( T_C \) and \( T_D \) are plasma temperatures in zones C and D, and \( t_7 \) is the evolutionary time measured in units of \( 10^7 \) yr. Thus at the adiabatic stage the luminosity from the outer shell highly exceeds that from the hot bubble interior and dominates the total X-ray output. This is due to the much smaller plasma density in zone C (\( \rho_C/\rho_0 \sim M_{SC}/\rho_{ISM} R_{out}^3 \sim v_{out}^2 V_{A, \infty} \ll 1 \)). However, if the metallicity of the ISM is not well below the solar value, this stage is so short (less than \( 10^7 \) yr; see eq. [5]) that we omit it from our further consideration.

4.2.2. Hot Bubble with a Cold Outer Shell

At later times the swept-up interstellar gas cools down to values well below the X-ray cutoff temperature and forms a dense outer shell separated from the hot bubble interior by the contact discontinuity (see Fig. 1). After this stage, the X-ray luminosity of zone C has been calculated by Chu et al. (1995):

\[
L_{X, C} = 3.4 \times 10^{36} Z_C I(\tau) L_{38}^{33/35} n_{ISM}^{17/35} t_7^{19/35} \text{ergs s}^{-1},
\]

where \( I(\tau) \) is the metallicity of the X-ray plasma in zone C and \( I(\tau) \) is a dimensionless integral with a value close to 2. In the models of Chu et al. (1995) the main contribution to the bubble X-ray luminosity comes from the outer, densest layers of zone C, where the density and temperature are determined by thermal evaporation of the cold outer shell. For this reason the metallicity of the X-ray gas in this zone may be different from that in zones A and B and hardly ever exceeds a few times the solar value (see Silich et al. 2001). Hereafter we assume that the chemical composition of the plasma in zone C is solar, \( Z_C = Z_\odot \). On the other hand, the temperature decreases toward the outer layers (see eq. [6]), and therefore the X-ray emission...
5. INTEGRATED PROPERTIES OF THE MODEL-PREDICTED X-RAY EMISSION AND COMPARISON WITH OBSERVATIONS

5.1. Wind Versus Bubble Luminosity

We first used our analytic results (eq. [9]) to derive the expected X-ray luminosity from clusters of different masses and different radii. The calculated X-ray luminosities from zones A and B for a range of the star cluster wind terminal speeds (1000 km s\(^{-1}\) \(\leq V_{A,\infty} \leq 1500\) km s\(^{-1}\)) are presented in Figure 5. The expected temperatures of the plasma are \(\sim 1.1 \times 10^7\) K and \(\sim 2.5 \times 10^7\) K for \(V_{A,\infty} = 1000\) and \(V_{A,\infty} = 1500\) km s\(^{-1}\), respectively (see eq. [1]). The normalization functions are \(\Phi = 0.758\) and 6.52 for \(T \sim 1.1 \times 10^7\) K plasma, and \(\Phi = 0.508\) and 3.16 for \(T \sim 2.5 \times 10^7\) K for a plasma with \(Z = Z_\odot\) and 10 \(Z_\odot\), respectively (see Fig. 4). Figure 5 shows that the X-ray luminosity from the cluster (zones A and B) is strongly dependent on the star cluster parameters and may easily vary within several orders of magnitude (the low-luminosity limits move toward smaller values if \(V_{A,\infty}\) exceeds 1500 km s\(^{-1}\)) even for a sample of clusters with a given mass. The crucial parameter, and unfortunately not a well-known parameter, is the star cluster wind terminal speed, \(V_{A,\infty} = (2L_{SC}/M_{SC})^{1/2}\). Perhaps the only reasonable way to have observational restrictions for this parameter for distant clusters is to measure the temperature of the X-ray plasma to then derive \(V_{A,\infty}\) from equation (1). This possibility may provide reasonable estimates for the most massive and compact clusters despite the presence of X-ray binaries (see below).

The luminosities are also dependent on the metallicity of the X-ray plasma (cf. Figs. 5a and 5b). For more metallic plasmas, the calculated luminosities are shifted to higher values, and the difference between the low- and high-velocity (temperature) outflows becomes even more significant as the enhanced metallicity affects less the emissivity of the higher temperature plasma (see Fig. 4).

We have also compared the X-ray emission from zones A and B with the X-ray emission from the hot bubble interior (zone C) predicted by the Chu et al. (1995) standard model. Figure 6 shows the contributions from the star cluster (zones A and B) and from the expanding superbubble (zone C) to the total 0.3–8.0 keV emission for clusters of different masses and radii evolving into an ISM with different densities. The X-ray emission from the high-temperature zones A and B may dominate only in the case of very massive (\(\geq 10^6\) \(M_\odot\)) and compact (few parsecs) star clusters evolving into a low-density ISM (see Fig. 6a). Otherwise the total luminosity is dominated by the hot superbubble interior. The contribution from the bubble plasma progressively increases with time and becomes dominant after a short while even for compact and massive clusters, if they evolve into a dense ISM (see Fig. 6b). The X-ray luminosity from star clusters decreases for larger clusters (see eq. [9]) shifting the luminosity from zones A and B well below the bubble luminosity even for massive clusters evolving into a low-density ISM (see Fig. 6c). Clearly, this tendency becomes even stronger for less massive clusters (see Figs. 6d–6f). However, even in the case of the rather dense ISM (\(n_{\text{ISM}} = 10 \text{ cm}^{-3}\)), the radius of the bubble exceeds 90 pc after 1 Myr, in the case of a \(10^5\) \(M_\odot\) cluster, and 150 pc, in the case of a \(10^6\) \(M_\odot\) cluster. This implies that compact and massive star clusters are to be detected as pointlike X-ray sources embedded into extended regions of diffuse X-ray emission.

One can also distinguish between zones A and B and zone C from their contributions to the hard and soft energy bands. Indeed, the temperature of the hot plasma ejected from the star cluster region (zone A) is defined by the ratio of the mechanical energy and mass deposition rates (or by the terminal speed of the star cluster wind) and, for reasonable values of \(V_{A,\infty}\) falls in the range 1–10 keV (see eq. [1]). At the same time, the temperature from zone C should be much softer than that from zones A and B.

![Figure 5: X-ray luminosity of SSCs and their winds (zones A + B) as a function of star cluster parameters. The shaded regions in the diagram represent (from top to bottom) the calculated X-ray luminosity for \(10^5\), \(10^6\), and \(10^7\) \(M_\odot\) clusters, respectively; \(V_{A,\infty} = 1000\) and \(V_{A,\infty} = 1500\) km s\(^{-1}\) were used to calculate the upper and lower luminosity limits for every star cluster. Panel (a) displays the results of the calculations for a plasma with solar metallicity, and panel (b) is the same for a plasma with \(Z = 10 Z_\odot\).](image-url)
of the plasma that dominates the bubble X-ray emission is much lower due to dilution with the cold material evaporated from the outer shell. This suggests that the soft component to the X-ray emission is dominated by the bubble plasma, whereas the hard component is defined by the hot thermalized ejecta (zones A and B). This conclusion is illustrated by Figure 7, which presents the results of the numerical calculations for a $10^5 M_\odot$ cluster of 1 pc radius evolving into a 1 cm$^{-3}$ ISM (shown also in Fig. 6d).

Figure 7 clearly demonstrates that the star cluster ejecta dominates the hard X-ray emission even if the total luminosity is completely defined by the bubble plasma. Note that because of the assumed constant emissivity of the X-ray plasma, equation (12) overestimates the X-ray emission from the bubble interior by a factor of $\sim 2$.

From equation (9) one can derive the fraction, $\epsilon_X$, of the injected mechanical energy, $L_{SC}$, that is transformed into the
X-rays. The X-ray production efficiency, $\epsilon_{A+B}$, for the hard component associated with the star cluster plasma is

$$\epsilon_{A+B} = \frac{L_{X,A+B}}{L_{SC}} = 3.8 \times 10^{-4} \Phi(T_{SC}, Z_{SC}) \frac{L_{38}}{R_{SC,1}^{1/5} 10^{1000}}. \quad (13)$$

For $10^6 M_\odot$ clusters with $L_{38} = 3 \times 10^2$ it hardly exceeds 10% even for most compact clusters and decreases progressively for star clusters with smaller masses.

One can obtain the X-ray production efficiency, $\epsilon_C$, for the soft bubble plasma from equation (12):

$$\epsilon_C = 3.4 \times 10^{-2} Z_C I(\tau) L_{38}^{2/35} n_{ISM}^{17/35} t_7^{19/35}. \quad (14)$$

It is weakly dependent on the star cluster parameters, but is dependent on the density of the ISM and becomes larger as the evolutionary time grows; $\epsilon_C$ was discussed by Cerviño et al. (2002), who finally chose an arbitrary value of $\epsilon_C = 20\%$, and by Smith et al. (2005), who collected published data for well-studied H II regions and superbubbles and concluded that for young objects $\epsilon_C \approx 0.02\%$, while for older clusters $\epsilon_C$ falls into the range 0.2%–7%.

5.2. Comparison with Nearby Clusters

A comparison of the model predictions with observed X-ray luminosities requires that parameters of the embedded star cluster (half-light radius $R_{SC}$, mass $M_{SC}$, and age $\tau_{SC}$) be obtained from the optical or infrared observations and then be compared with the observed X-ray luminosity, temperature (which is proportional to the star cluster wind terminal speed $V_{A,\infty}$), and metallicity of the X-ray plasma. The full set of required parameters is available only for a restricted sample of nearby clusters. Below we confront our model (eq. [9]) with several nearby young stellar clusters. In contrast to Stevens & Hartwell (2003), we use for comparison an observed temperature of the X-ray plasma that is an appropriate parameter for distant clusters, and we avoid using the mean weighted terminal speed derived from the analysis of the individual massive stars, embedded members of the cluster.

5.2.1. The Sample of Clusters

NGC 3603.—This cluster appears to be one of the densest and more massive clusters known in our Galaxy. Within a 1 pc radius NGC 3603 reveals a remarkable similarity to the central density and stellar density distribution of R136, the dense core of 30 Dor in the LMC (Moffat et al. 1994). However, outside $R_{SC} \approx 1$ pc, the stellar density in NGC 3603 decreases sharply, whereas the stellar density in 30 Dor continues to decrease with a similar slope to larger radii. Malumuth & Heap (1994) measured the ionizing flux from 30 Dor as a function of distance from the cluster center. They found that the number of ionizing photons from the inner 1 pc ($4\sigma$) region is $N_0 \approx 1.7 \times 10^{51}$ s$^{-1}$ (see their Fig. 16). This corresponds to a $1.7 \times 10^4 M_\odot$ cluster if compared with the Leitherer & Heckman (1995) evolutionary synthesis model and approximately 2 times smaller than the $\sim 3 \times 10^4 M_\odot$ value obtained by Brandl et al. (1996) for the inner 20$^\circ$ region of 30 Dor. Because of the identical mass distribution in R136 and NGC 3603 inside the inner 1 pc radius, we adopt a $1.7 \times 10^4 M_\odot$ value as the total mass of the NGC 3603 cluster. Sung & Bessell (2004) used optical color-magnitude diagrams for massive members of NGC 3603 and concluded that the age of the cluster is $\tau_{SC} = 1 \pm 1$ Myr. The X-ray emission from the cluster has been studied by Moffat et al. (2002), who detected around 40 point-like X-ray sources definitely associated with the star cluster and a local diffuse emission most probably associated with the hot plasma inside the star cluster and with the free wind region. Moffat et al. (2002) concluded that approximately 20\% ($2 \times 10^{34}$ ergs s$^{-1}$) of the total $1 \times 10^{35}$ ergs s$^{-1}$ X-ray luminosity in the 0.5–10 keV band is associated with the local diffuse component of solar abundance and the best-fit temperature of $kT_{core} \approx 3.1$ keV at the core and $kT \approx 2.1$ keV (which is close to the temperature at the star cluster edge that is expected from the star cluster wind model) in the outer region.

Arches Cluster.—The Arches cluster is another young ($\tau_{SC} = 2 \pm 1$ Myr; Figer et al. 1999a) and very compact ($R_{SC} \approx 0.2$ pc; Figer et al. 1999a) Galactic cluster. The mass of the cluster has...
been estimated by Figer et al. (1999b), who extrapolated the observed number of massive stars down to the low-mass cutoff limit. If a $1 M_\odot$ low-mass cutoff is adopted, the star cluster mass would be $M_{SC} \approx 1.1 \times 10^5 M_\odot$. The X-ray luminosity from the cluster was first detected by Yusef-Zadeh et al. (2002), who revealed within the volume occupied by the star cluster two pointlike sources embedded into a more extended (down to a 1.2–1.8 pc radius) X-ray halo. Law & Yusef-Zadeh (2004) found that the observed X-ray emission may be equally well fitted with an overabundant, $Z = (4–5) Z_\odot$, one- or two-temperature thermal model, or with the one-temperature plus power-law model with $\sim 1/6$ of the flux attributed to the power-law component. The required temperature of the thermal plasma is around $kT = 1.5$ keV. The models give $L_X = (0.5–1) \times 10^{35}$ erg s$^{-1}$ for the $0.5–8$ keV energy band. Overall, the pointlike sources inside the cluster contribute $\sim 60\%$ to the total emission, and the rest is distributed throughout the region with dimensions of approximately $3.6 \times 2.4$ pc. This leads to the X-ray luminosity from the cluster plasma, $L_X = (2–4) \times 10^{34}$ ergs s$^{-1}$, that is slightly larger than that from the earlier estimates of Yusef-Zadeh et al. (2002; $L_X = 1.6 \times 10^{34}$ ergs s$^{-1}$). However, the interpretation of the observed X-ray emission is ambiguous. The observed spectrum may also be fitted by the combined power law plus a 6.4 keV Gaussian component that models a fluorescent Fe Kα emission from a nearby molecular cloud. If this is the case, the contribution of the fluorescent component may confuse the estimated X-ray emission from the cluster plasma.  

**Quintuplet Cluster.**—The Quintuplet cluster is the smallest and oldest one ($\tau_{SC} = 4 \pm 1$ Myr; Figer et al. 1999b). The mass of the cluster is $M_{SC} = 8.8 \times 10^4 M_\odot$, and a low-mass cutoff is used (Figer et al. 1999a), and the radius is about 1 pc (Figer et al. 1999a). The X-ray emission from the cluster was detected by *Chandra*. After subtraction of the four pointlike sources, the X-ray spectrum of the Quintuplet cluster is perfectly fitted by the thermal plasma model with the plasma temperature of 2.4 keV at the star cluster center and a solar metallicity (Law & Yusef-Zadeh 2004). The absorption-corrected halo emission in the 0.5–8 keV energy band is $1 \times 10^{34}$ ergs s$^{-1}$ (Law & Yusef-Zadeh 2004). We associate the observed temperature with the plasma temperature at the star cluster surface (see § 3) and then use it as an input parameter for our model.  

### 5.2.2. The Comparison with Model Predictions

In order to compare the observed X-ray luminosities with that predicted by the star cluster wind model, we take an advantage of our equation (9) and combine it with input parameters obtained from the optical examination of the host clusters. To calculate the energy deposition rate, $L_{SC}$, provided by multiple stellar winds and supernovae explosions inside the cluster, we use a starburst synthetic model of Leitherer & Heckman (1995) and scale it with the star cluster mass. For a standard $10^6 M_\odot$ cluster we adopt a $10^{40}$ erg s$^{-1}$ energy deposition rate before the first supernova explosion ($t \leq 3$ Myr) and an average value approximately 3 times larger after the beginning of the supernovae era. The star cluster parameters and the observed and the calculated X-ray luminosities are collected in Table 1.

The calculated X-ray luminosities are listed in the last column of Table 1. They agree with the observed values within a factor of 4 and do not show a systematic shift to the smaller of larger values relative to the observed luminosities. Clearly, the analysis of a larger sample of clusters that includes more massive objects is required in order to avoid uncertainties related to estimates of masses, ages, and errors that result from the deviation of star distributions from the idealized initial mass function. For example, according to Leitherer & Heckman (1995) the energy input rate from a coeval star cluster changes sharply in a short time interval between 2 and 4 Myr. A small mistake in the age estimate may then change the predicted X-ray luminosity within a factor of 10 or more. A smaller upper mass cutoff leads to the same uncertainty. For a $10^4 M_\odot$ cluster the relative dispersion of the observed X-ray luminosity due to the discreteness of the stellar population, $\sigma_X = [(L_X - \overline{L}_X)^2/\overline{L}_X]^{1/2}/\overline{L}_X$, may reach $\sigma_X \approx 3$ (see Fig. 2 in Cervino et al. 2002), and thus the $L_X$ detected from a particular cluster may deviate from the mean value within a factor of ~3. It seems, therefore, that more massive and more evolved star clusters are better candidates to compare with our model predictions.  

Several more complications should be taken into consideration when comparing the results from equation (9) to the observed X-ray emission. In all the young stellar clusters we have considered, the observed X-ray emission presents two components: a number of unresolved pointlike sources, probably associated with the most luminous individual stars and local density enhancements resulting from the collisions of nearby stellar winds (see Ozernoy et al. [1997] and the results from Rockefeller et al. [2004]) and a diffuse component. The contribution from the pointlike sources varies from ~20% in the Quintuplet cluster to ~80% in NGC 3603 and cannot be distinguished from the star cluster diffuse component in distant clusters.  

After ~3 Myr the most massive stars leave the main sequence and explode as supernovae. This results in the formation of X-ray binary systems. The HMXBs contain a relativistic remnant of the supernova explosion (a neutron star or a black hole) that captures and accretes a wind from the secondary (O- or B-type) massive star. To transform a gravitational energy into the X-ray emission effectively, it is essential that an accretion disk is formed or a very strong magnetic field is present (see, for example, Van Bever & Vanbeveren [2000] and references therein). Thus it takes 4–5 Myr for the HMXBs to become active, depending on the upper mass limit occurring in the cluster. The HMXB phase is restricted by the lifetime of the massive secondaries and is typically a few times 10^7 yr. In the low-mass X-ray binaries (LMXBs) the optical component is a low-mass post–main-sequence star that fills its Roche lobe. In the instantaneous star formation LMXBs become active at later times and certainly dominate the X-ray emission from older clusters for which the SNe activity has terminated and the X-ray emission from zones A and B has vanished. LMXBs are often detected in
10% of the LMXBs are associated with globular clusters that Brandl, B., Sams, B. J., Bertoldi, F., Eckart, A., Genzel, R., Drapatz, S., Bisnovatyi-Kogan, G. S., & Silich, S. A. 1995, Rev. Mod. Phys., 67, 661

Vanbeveren 2000). X-ray luminosity range expected from the HMXB population (see van Bever &

Van Bever & Vanbeveren 1999; Dalton & Sarazin 1995). Van Bever & Vanbeveren number of groups (see, for example, Iben et al. 1995; Mas-Hesse 2001). NGC 3603 and the Arches and Quintuplet clusters are too young and do not contain active binaries.

The population synthesis models for massive star clusters that take into consideration binary systems have been developed by a number of groups (see, for example, Iben et al. 1995; Mas-Hesse & Cerviño 1999; Dalton & Sarazin 1995). Van Bever & Vanbeveren (2000) have used such a model to calculate the X-ray luminosity from the binary population of instantaneous starbursts with different fractions of binaries at the birth of the cluster. The HMXB component begins to contribute to the X-ray emission after ~4 Myr. The normalized per 1 $M_\odot$ X-ray emission does not depend on the initial mass of the cluster and soon reaches a value that varies between $10^{32}$ and $10^{33}$ ergs s$^{-1}$ $M_\odot^{-1}$ (see Figs. 1 and 2 from their paper).

In contrast to HMXBs, the normalized per unit solar mass X-ray luminosity from the thermalized star cluster plasma scales linearly with the star cluster mass:

$$L_{X,A+B}/M_{SC} = 2.9 \times 10^{33} \Phi(T_{SC}, Z_{SC})M_\odot/R_{SC}, T_{keV}^3 \text{ergs s}^{-1} M_\odot^{-1},$$

where $M_\odot$ is the star cluster mass measured in units of $10^6 M_\odot$.

Figure 8 shows that for the most massive and compact young stellar clusters the X-ray luminosity of the thermalized star cluster plasma (zones A and B) may be comparable to or even exceed that from the HMXBs.

6. CONCLUSIONS

We have developed a simple way of estimating the X-ray emission generated by super star clusters. The derived expression (eq. [9]) takes into consideration the intrinsic parameters of SSCs and their winds ($R_{SC}$, $L_{SC}$, $V_{A,\infty}$, and $Z_{SC}$). In particular, we have found that the expected X-ray luminosity from SSCs is highly dependent on the star cluster wind terminal speed ($L_X \sim V_{A,\infty}^{-6}$), a quantity related to the temperature of the hot thermalized plasma within the SSC volume, and scales quadratically with the star cluster mass. The proposed relation seems to be in reasonable agreement with parameters of nearby clusters and their detected X-ray emissions.

We have also compared the X-ray luminosity from the SSCs with the luminosity of the interstellar bubbles generated from the mechanical interaction of the star cluster winds with the ISM. We found that the soft component and the total X-ray emission are usually dominated by the superbubble plasma. The contribution from the SSC plasma may dominate only in the case of very massive ($\geq 10^6 M_\odot$) and compact (few parsecs) star clusters evolving into a low-density ISM. However, the hard (2.0–8.0 keV) component of the X-ray emission is usually dominated by the hot compact regions associated with the SSCs. This implies that compact and massive star clusters should be detected, as hard compact X-ray sources embedded into extended regions of soft diffuse X-ray emission.

On the other hand, the comparison with the population synthesis models that take into consideration binary systems shows that the X-ray emission from the thermalized star cluster plasma normalized per unit stellar mass increases linearly with the mass of the cluster and may be comparable to or even exceed that from the population of the HMXBs for the most compact and massive star clusters. Thus the thermalization of stellar winds and SNe ejecta, particularly in massive, young, and compact super star clusters, may present an X-ray production that is comparable to or even larger than that expected from the HMXB population.

We thank E. Jiménez Bailón and M. Cerviño for careful reading of the manuscript and helpful discussions. We also wish to express our thanks to our anonymous referee for a report full of suggestions to improve the paper. This study has been supported by CONACYT-México research grant 47534-F, and AYA 2004-08260-CO3-01 research grant from the Spanish Consejo Superior de Investigaciones Científicas. G. T.-T. acknowledges financial support from the Secretaría de Estado de Universidades e Investigación (España) ref: SAB 2004-0189 and the hospitality of the Instituto de Astrofísica de Andalucía (IAA, CSIC) in Granada, Spain.

REFERENCES

Bisnovatyi-Kogan, G. S., & Silich, S. A. 1995, Rev. Mod. Phys., 67, 661
Brandl, B., Sams, B. J., Bertoldi, F., Eckart, A., Genzel, R., Drapatz, S., Hofmann, R., Loewe, M., & Quirrenbach, A. 1996, ApJ, 466, 254
Cantó, J., Raga, A. C., & Rodríguez, L. F. 2000, ApJ, 536, 896
Cerviño, M., Mas-Hesse, J. M., & Kunth, D. 2002, A&A, 392, 19
Chevalier, R. A. 1992, ApJ, 397, L39
Chevalier, R. A., & Clegg, A. W. 1985, Nature, 317, 44
Chu, Y.-H., Chang, H.-W., Su, Y.-L., & Mac Low, M.-M. 1995, ApJ, 450, 157
Dalton, W. W., & Sarazin, C. L. 1995, ApJ, 440, 280

Fig. 8.—X-ray luminosity of zones A and B per unit stellar mass as a function of the star cluster mass. The calculations have been performed for 1 pc clusters with 1000 km s$^{-1}$ ($T_{SC} = 0.95$ keV) and 1500 km s$^{-1}$ ($T_{SC} = 2.1$ keV) terminal speeds, indicated by the solid and dotted lines, respectively. The metallicity of the X-ray plasma is solar. The shaded region in the diagram represents the X-ray luminosity range expected from the HMXB population (see van Bever & Vanbeveren 2000).
