1. INTRODUCTION

Massive OB stars, or their groups (young clusters or OB associations), inject a large amount of mechanical energy via stellar winds and violent supernova (SN) episodes into the interstellar medium (ISM). They sweep up their environment, producing the so-called bubbles and superbubbles (produced by a single star or multiple stars, respectively). The standard models of these bubbles are those by Weaver et al. (1977) and Chu & Mac Low (1990). They consider the mechanical energy input of a stellar wind and predict an extended bubble structure of shock-heated gas that emits mainly in X-rays, surrounded by a cool shell of swept-up material that is bright at optical wavelengths. These models have been compared with several observations, and the X-ray observed luminosities often exceed the theoretical predictions (i.e., Chu & Mac Low 1990; Wang & Helfand 1991).

Later, Oey (1996b), based on the observations of Rosado et al. (1981, 1982) and Rosado (1986), proposed two categories of superbubbles: high-velocity and low-velocity. High-velocity superbubbles are characterized by a shell expansion velocity \( v_s \gtrsim 25 \text{ km s}^{-1} \), and they are as common as the low-velocity ones (e.g., Rosado 1986). The difference, however, lies in the fact that it is virtually impossible to obtain expansion shell velocities in excess of \( 25 \text{ km s}^{-1} \) in superbubbles with large diameters (about 100 pc) without additional acceleration, e.g., an impact from a supernova remnant (SNR). The energy injected by SN explosions would be an extra source of heating for the gas inside the superbubble; this could explain the observed X-ray excess.

In this work, we have turned our attention to the superbubble N70 in the Large Magellanic Cloud (LMC). N70 is an almost circular superbubble of approximately 50 pc in radius. The superbubble is driven by the OB association LH 114 (Lucke & Hodge 1970), which contains more than a thousand stars. Oey (1996a) classified seven of them as O-type stars and estimated the mean age of the OB association to be around 5 Myr. Rosado et al. (1981) and Georgelin et al. (1983) found in N70 \([S\,\text{ii}]/\text{H}\alpha\) line ratios with values larger than those in photoionized \( \text{H}\alpha \) regions, but lower than those of SNRs in the LMC. The measured expansion velocity of this superbubble (\( \sim 70 \text{ km s}^{-1} \)) is consistent with shock models that also reproduce the \([S\,\text{ii}]/\text{H}\alpha\) ratio of Rosado et al. (1981). However, the dynamic age derived with this velocity does not agree with Oey’s model (1996b).

Reyes-Iturbide et al. (2011) calculated the thermal X-ray luminosity for the superbubble N70 (DEM 301) with the XMM-Newton observations from Jansen et al. (2001). For the analysis of the X-ray spectrum, they used three individual data sets, adjusting them jointly. They extracted spectra from the EPIC/MOS1, EPIC/MOS2, and EPIC/PN event files. The spectra were fitted with a two-component model consisting of a thermal plasma-MEKAL (Kaastra & Mewe 1993) and nonthermal power law. The resulting spectra were analyzed jointly using the XSPEC spectral fitting package, where the fit has an absorption column density of \( N_H = 1.4 \pm 0.5 \times 10^{20} \text{ cm}^{-2} \) (in agreement with the measures of column densities in the LMC direction; see Dickey & Lockman 1990). The X-ray luminosity in the 0.2–2 keV energy band with absorption correction was found to be \( 1.6 \times 10^{35} \text{ erg s}^{-1} \).

Here, we present a series of three-dimensional numerical simulations of the N70 superbubble using the physical properties (stellar types, positions, etc.) of the stellar cluster in its interior. We analyze the resulting morphology, dynamics, and thermal X-ray emission, and compare it with observations of N70. The paper is organized as follows: In Section 2, we provide a brief review of the models and theoretical predictions of the emission in superbubbles. In Section 3, we describe the numerical simulations. The results of the simulations are analyzed in Section 4. In Section 5 we discuss the \( \text{H}\alpha \) and X-ray emission from our models and a summary is provided in Section 6.

2. SUPERBUBBLE DYNAMICS AND X-RAY EMISSION

Let us consider a simple model of superbubble formation in which the stars deposit the total mechanical energy in the form...
of stellar winds. Such mechanical luminosity is given by

\[ L_w = \sum_{i=1}^{N} \frac{1}{2} \dot{M}_{w,i} v_{w,i}^2, \]

where \( \dot{M}_{w,i} \) and \( v_{w,i} \) are the mass-loss rate and the wind terminal velocity of the \( i \)-th star, respectively, and \( N \) is the total number of stars. At the beginning, the stellar winds inside the cluster volume collide with the surrounding ISM (here we assume a uniform medium with pre-shock number density \( n_0 \)) forming shells of shocked ISM material. At some point, the volume between the stars fills with the shocked material from the individual stars and the winds coalesce into a common cluster wind that forms a larger shell, a “supershell” (Cantó et al. 2000; Rodríguez-González et al. 2008, etc.). As the supershell expands with respect to the cluster center, one can distinguish a supershell structure with the following four regions:

1. A free wind region, formed by unperturbed stellar wind, which is only found around the most powerful stars;
2. A shocked wind region, formed by the interaction of several individual stellar winds. This material has been heated enough that it emits primarily in X-rays;
3. An outer region of swept-up ISM with an important optical line emission;
4. The unperturbed ISM (of uniform density of \( n_0 \)), just outside the swept-up shell.

The X-ray luminosity that arises from the internal shocked region, where the gas temperature is in the range of \( 10^6 \)–\( 10^7 \) K (\( \sim \)0.1–\( \approx \)2 keV), can be estimated as in Weaver et al. (1977) and Chu & Mac Low (1990):

\[ L_X = 3.29 \times 10^{34} I(\xi) \xi L_{37}^{33/35} n_0^{17/35} \tau_{6}^{19/35} \left[ \text{erg s}^{-1} \right], \]

where

\[ I(\xi) = \frac{125}{33} - 5\xi^{1/2} + \frac{5}{3} \xi^3 - \frac{5}{11} \xi^{11/3}, \]

\[ \tau = 0.16 L_{37}^{-8/35} n_0^{-2/35} \xi_{6}^{5/35} \]

\( \xi \) is the gas metallicity, \( L_{37} = L_w/10^{37} \), \( \tau = t/10^6 \), \( L_w \) is the mechanical luminosity of the cluster, and \( \tau \) is the cluster lifetime. If an SN explodes at the center of a stellar cluster, the total X-ray luminosity will be modified as estimated by Chu & Mac Low (1990):

\[ L(\text{SNc})_X = 8 \times 10^{33} \xi h(x_s)(1 - x_s)^{-2/5} L_{37}^{33/35} n_0^{17/35} \tau_{6}^{19/35} \left[ \text{erg s}^{-1} \right], \]

where \( x_s = r_s/R \), \( r_s \) is the radius of the remnant, \( R \) is the radius of the superbubble, and

\[ h(x) = \frac{125}{156} - \frac{5}{13} (1 - x)^{3/5} + \frac{5}{4} (1 - x)^{8/5} - \frac{5}{3} (1 - x)^{3/5}. \]

However, as mentioned above, observed X-ray luminosities exceed these predictions. In order to explain such differences, several alternatives have been explored. Chu & Mac Low (1990) proposed an off-centered SN explosion, Silich et al. (2001) studied effects of metallicity enhancement (due to evaporation of the outer shell), and Reyes-Ituribe et al. (2009) considered the interaction of the cluster wind with a high-density region in the ISM for the case of M17.

For M70, the total mechanical luminosity injected by the stellar winds of massive stars (the most massive are listed in Table 1) is around \( 7.31 \times 10^{37} \text{ erg s}^{-1} \). This superbubble evolves in an ISM with number density \( \sim 0.16 \text{ cm}^{-3} \) (Rosado et al. 1981; Skelton et al. 1999), and an average gas metallicity \( \sim 0.3 Z_{\odot} \) (typical of the LMC; Rolleston et al. 2002). M70 is quite circular with a radius of \( \sim 50 \) pc; by using the shell expansion velocity, a dynamic age of \( \sim 3 \times 10^5 \) yr can be obtained. Using these values in Equations (2) and (5), the predicted X-ray luminosity for this object is \( 3.32 \times 10^{34} \text{ erg s}^{-1} \) when only the stellar winds are taken into account, and \( 3.68 \times 10^{34} \text{ erg s}^{-1} \) if one adds a single centered SN to the cluster wind.

The X-ray luminosities predicted by the standard models are an order of magnitude less than the observed value. The difference seems too large to be explained by metallicity effects as proposed by Silich et al. (2001), and the ISM around it is fairly homogeneous (unlike in M17 where the inhomogeneity of the medium suffices to explain the X-ray luminosity). In addition, Oey (1996b) showed that it is essentially impossible to obtain expansion velocities (\( \geq 25 \text{ km s}^{-1} \)) in superbubbles with a radius of a few tens of parsecs without induced acceleration (an SNR impact was proposed in that paper). Thus, given the high X-ray luminosity and expansion velocity we choose to consider an off-centered SN explosion, with the restriction that it cannot be too far from the center because of the quasi-spherical shape of M70. The SN possibility is also consistent with the stellar population models of M70 presented by Oey (1996b), in which 13 massive stars are found in the range of 12–40 \( M_{\odot} \). A \( \sim 60 M_{\odot} \) star could be expected using a standard initial mass function of M70 and, if formed with the rest of the cluster, it would already have exploded as an SN.

Table 1 shows the coordinates and spectral types of the most massive stars inside N70. In the same table, we include characteristic values of the terminal wind speed and mass-loss rate associated with stars of such spectral types (de Jager et al. 1988; Wilson & Dopita 1985; Leitherer 1988; Prinja et al. 1990; Lamers & Leitherer 1993; Fullerton et al. 2006).

3. The Numerical Models

In order to estimate the X-ray emission and shell dynamics in N70, we computed three-dimensional numerical simulations with the full, radiative gas dynamic equations. We use a tabulated cooling function obtained with the CHIANTI database, using a metallicity \( \xi = 0.3 Z_{\odot} \) (consistent with that of the LMC; see Rolleston et al. 2002). The simulations include multiple stellar wind sources in the three-dimensional adaptive grid with a metallicity \( \xi = 0.3 Z_{\odot} \) (consistent with that of the LMC; see Rolleston et al. 2002). They were computed with a maximum resolution of 0.4296 pc (corresponding to 2561 grid points at the maximum grid resolution) in a computational domain of 110 pc (along each of the three coordinate axes). We do not include thermal conduction effects in any of our models.

In all runs, we assumed that the computational domain was initially filled by a homogeneous ambient medium with temperature \( T_0 = 10^4 \text{ K} \) (as would be expected in the photoionized region around the massive OB association) and density

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4 The CHIANTI database and associated IDL procedures, now distributed as version 5.1, are freely available at http://www.antdarl.nrl.navy.mil/chianti.html and http://www.arcetri.astro.it/science/chianti/chianti.html.
Table 1
Coordinates and Spectral Types of the Most Massive Stars Inside N70

| Star          | R.A. (h m s) | Decl. (°′″) | Spectral Type | \( V_{\infty} \) (km s\(^{-1}\)) | \( \log (M) \) (\( M_{\odot} \) yr\(^{-1}\)) |
|---------------|--------------|-------------|---------------|---------------------------------|---------------------------------|
| D301-1005     | 5 43 08.33   | −67 50 52.5 | O9.5 V       | 1500                            | −6.9                            |
| D301SW-1a     | 5 43 15.50   | −67 51 09.7 | O8 III(f)    | 2000                            | −6.6                            |
| D301SW-1b     | 5 43 15.50   | −67 51 09.7 | O9: V        | 1500                            | −6.8                            |
| D301SW-3      | 5 43 12.87   | −67 51 16.3 | O3 If        | 4100                            | −4.90                           |
| D301NW-4      | 5 43 17.70   | −67 50 36.6 | O5: IIIe     | 2900                            | −6.2                            |
| D301NW-8      | 5 43 15.98   | −67 49 51.2 | O7 V((f))    | 2000                            | −6.6                            |
| D301NW-9      | 5 43 24.60   | −67 50 31.1 | O9.5 V       | 1500                            | −6.9                            |
| D301NE-5      | 5 43 34.85   | −67 50 40.9 | B0.5 V       | 2000                            | −7.25                           |
| D301NW-12     | 5 43 23.79   | −67 50 21.5 | BO V         | 2000                            | −7.3                            |
| D301NW-13     | 5 43 06.71   | −67 49 56.0 | B1 V         | 1700                            | −6.51                           |
| D301SW-9      | 5 43 10.03   | −67 52 21.3 | B1.5: V      | 900                             | −5.26                           |
| D301NW-15     | 5 43 12.25   | −67 50 28.2 | B1.5 V       | 900                             | −5.26                           |
| D301NW-18     | 5 43 11.13   | −67 50 40.3 | BO V         | 2000                            | −7.3                            |

Figure 1. Stellar distribution of the \( xy \)-plane (top panel) and \( xz \)-plane (bottom panel) for all the numerical models.

\( n_0 = 0.16 \text{ cm}^{-3} \). The stellar winds are imposed in spheres of radius \( R_w = 7.94 \times 10^{18} \text{ cm} \) (\(~0.58 \text{ pc}) corresponding to 6 pixels of the grid. Table 1 gives the position of the stars in equatorial coordinates (J2000), which can be translated to parsecs considering that the cluster is at a distance of 50 kpc. Then, the wind sources are placed in the \( xy \)-plane according to their positions in the sky. Since we do not know the individual line-of-sight distance (\( z \)-coordinate) to the stars, we produce randomly picked positions in \( z \), retaining the same \( xy \) configuration. The \( z \)-distribution was obtained from a pseudo random sampling to yield a \( \propto R^{-2} \) distribution (similarly to Reyes-Irurbide at al. 2009). The maximum of the distribution, from which the \( z \) positions were sampled, is set to the maximum separation in the plane of the sky. Figure 1 shows the stellar distribution in the \( xy \)-plane (top panel) and \( xz \)-plane (bottom panel) for all the numerical models. Inside the spheres centered at the star positions, a stationary wind was imposed (at all times) with an \( \propto R^{-2} \) density profile scaled to yield the \( V_{\infty} \) and \( M \) for each star, and a constant temperature \( \propto V_{\infty}^2 \).

We run four numerical models, M1, M2, M3, and M4, to explore the effects of the mechanical energy injected by the stellar winds and the SN explosion in the superbubble dynamics and X-ray emission. The properties of the models are presented in Table 2. In model M1, we considered the energy injected by a single SN (with 10^{51} \text{ erg}) in a homogeneous ISM. Model M2 included the mechanical energy injected by the stellar winds alone. Models M3 and M4 explored the combined effect of stellar winds and an SN explosion. For model M3, we included the energy injected by an SN (similar to that in M1) inside the wind-blown bubble (as in model M2) at the center of the stellar population of N70. The SN detonation was imposed at \( t = 1.15 \times 10^5 \text{ yr} \). Finally, in model M4 we explored the effects of a slightly off-center SN; the SN explosion was placed at \((1.5, -1.5, -1.5) \text{ pc} \) from the center of the stellar distribution, also at \( t = 1.15 \times 10^5 \text{ yr} \).

4. RESULTS

4.1. Superbubble Dynamics

In order to obtain the physical flow configuration, we compute the radially dependent flow density, radial velocity, and temperature averaging over spherical concentric surfaces \( S_R = 4\pi R^2 \) (see also Rodríguez-González et al. 2007):

\[
\rho_0(R) = \frac{1}{4\pi} \int_{S_R} \rho \sin \theta \, d\theta \, d\phi;
\]

\[
v(R) = \frac{1}{4\pi \rho_0(R)} \int_{S_R} \rho v_R \sin \theta \, d\theta \, d\phi;
\]

\[
T(R) = \frac{1}{4\pi \rho_0(R)} \int_{S_R} \rho T \sin \theta \, d\theta \, d\phi;
\]
Spherically averaged flow from model M1. The density (top), temperature (center), and radial velocity (bottom) obtained from the numerical simulation are shown as functions of spherical radius \( R \). The dashed lines represent the position of the maximum value of the shell density. Where \( \theta \) and \( \phi \) are the polar and azimuthal angles, respectively; \( \rho \) is the flow density; \( T \) is the temperature; and \( v_R \) is the radial velocity (obtained by projecting the three Cartesian velocity components resulting from the numerical integration onto the direction normal to the spherical surface). That is, \( v_R = (xv_x + yv_y + zv_z)/R \).

Figures 2, 3, and 5 show the superbubble and shell distributions of density, temperature, and radial velocity (top, middle, and bottom panels) for models M1, M2, and M3, respectively, at an evolutionary time of \( 2 \times 10^5 \) yr. Model M1 (see Figure 2) forms a thin shell with maximum density at \( R = 47 \) pc. This shell contains the ISM that has been swept up by the leading shock produced by the explosion. The gas behind the leading shock cools and forms the thin shell. There the temperature is around \( 10^5 \) K, in the range of optical line emission. At the radius at which the density is maximum, the radial velocity is around \( 75 \) km s\(^{-1}\). This model does not include the stellar wind contribution, and the radial velocity drops because the interior of the bubble is cooling radiatively (the SNR has passed the Sedov phase and is well into the radiative one).

The contribution of the stellar winds of the cluster in the shell dynamics is present in Figure 3. Model M2 (see Figures 3 and 4) presents a thick shell with maximum density at \( R = 44 \) pc. This shell is driven by the mechanical energy injected by stellar winds inside the cluster volume in the form of a common cluster wind (Cantó et al. 2000; Rodríguez-González et al. 2008, etc.).

Figure 3 shows an average temperature (inside the shell) of \( 5 \times 10^5 \) K (optical line emission regime) and the radial velocity at the density peak is around \( 45 \) km s\(^{-1}\) as predicted by the standard model of Weaver et al. (1977, see also Chu et al. 1995). This velocity is, however, lower than that obtained from the observations of N70 by Rosado et al. (1981).

Models M3 and M4 correspond to model M2 until \( t = 1.15 \times 10^5 \) yr, at which point we inject an SN (centered for M3, off-center for M4). Figure 5 shows the distributions of density, temperature, and radial velocity as functions of radius for model M3. From the density profile we obtain a shell position between 43 and 52 pc from the center, with a peak density around \( R = 47 \) pc. The temperature is adequate for X-ray emission inside a region of 41 pc in radius. The radial velocity profile shows an average value in the shell around \( \sim 62 \) km s\(^{-1}\). This velocity is close to the observed value.

Since in model M4 the SN is not centered, one cannot assume that radial symmetry and radial averages (Equations (7)–(9)) are no longer appropriate. However, in order to estimate an average radial velocity of the shell in this model, we use Equation (8) and the average radial velocity in the shell is \( \sim 66 \) km s\(^{-1}\) (see the velocity profile of this model in Figure 6), similar to that of model M3, and also similar to N70 observations.

### 5. \( \text{H}\alpha \) AND X-RAY EMISSION

From the results of the simulations we compute \( \text{H}\alpha \) maps, integrating the emission coefficient along the \( x \)-axis. The emission coefficient is obtained with the interpolation formula given by Aller (1987) for the temperature dependence of the recombination cascade.

We also make X-ray emission maps, using the density and temperature distributions from the simulations and plugging them into the CHIANTI atomic database and software (see Dere et al. 1997; Landi et al. 2006). The maps are obtained by integrating the X-ray emission coefficient along the \( z \)-axis. For this calculation, we assume that the ionization state of the gas corresponds to coronal ionization equilibrium in the low-density regime (i.e., the emission coefficient is proportional to the square of the density). The emission is separated into three energy bands: \([0.2–2]\), \([2–10]\), and \([10–20]\) keV. The emission coefficient for these energy bands as a function of temperature is presented in Figure 7.

We also calculate the X-ray emission as a function of time for all the models. All our models cover an evolutionary time of \( 2 \times 10^5 \) yr, corresponding approximately to the dynamic age of...
the superbubble derived by Rosado et al. (1981). In Figure 8, we present the X-ray luminosity in the energy range of 0.2–2 keV for M1, M2, M3, and M4. For visual purposes, the horizontal axis of M1 (where the SN was initiated at \( t = 0 \)) is shifted to coincide with the SN starting point of models M3 and M4 (\( t = 1.15 \times 10^5 \) yr). From the figure one can see that the X-ray luminosity for model M2 has a maximum value of \( L_X \sim 4 \times 10^{34} \text{ erg s}^{-1} \) (five times less energy than observed) reached at \( t = 5 \times 10^4 \) yr. After this time the luminosity slowly declines.

The rest of the models, in which we have included an SN, reach X-ray luminosities of \( \sim 10^{35} \) \( \text{ erg s}^{-1} \) (see Table 3). In model M1, the highest value of the X-ray luminosity is \( \sim 3 \times 10^{35} \) \( \text{ erg s}^{-1} \), and this luminosity is kept at or above the N70 observed value for \( \sim 5 \times 10^7 \) yr. However, when this model reaches the observed radius value of N70 (~50 pc, at \( t = 2 \times 10^5 \) yr), the X-ray luminosity drops below the observed value by more than two orders of magnitude.

The maximum X-ray emission in model M3 can reach \( 10^{35} \) \( \text{ erg s}^{-1} \), but it is still significantly lower than the observed luminosity, and when the superbubble reaches the observed radius the X-ray luminosity is already five times smaller. A centered SN explosion at \( t = 10^5 \) yr (when the shell is closer to the center of the stellar cluster) could help to reach the N70 X-ray emission, but by the time it reaches a 50 pc radius the luminosity would be down to a value of \( \sim 3 \times 10^{34} \) \( \text{ erg s}^{-1} \) (comparable to model M2).

The maximum X-ray luminosity in model M4 is \( \sim 2 \times 10^{35} \) \( \text{ erg s}^{-1} \). This luminosity is above the observed value for a timescale of \( \sim 7.5 \times 10^4 \) yr. By the time the superbubble reaches a radius of \( \sim 50 \) pc the X-ray luminosity agrees well with the observations.

In Figure 9, we show synthetic X-ray emission maps for model M2. The emission in the figure is separated into three energy bands: 0.2–2, 2–10, and 10–20 keV (from top to bottom, panels (a), (b), and (c), respectively). It is readily evident that the emission is dominated by soft X-rays with only a small contribution from harder X-rays. For this model (M2), the emission in the soft X-ray band (0.2–2 keV) is three orders of magnitude larger than the emission in the 2–10 keV energy range and over five orders of magnitude larger than the harder X-ray emission (10–20 keV). The fact that the emission in hard
X-rays is negligible with respect to that in soft X-rays might seem surprising at first glance, considering that there is a large region (inner 30 pc) filled with $10^8$ K gas, which should emit hard X-rays (see the emission coefficients in Figure 7). However, the density at the interior of the bubble is quite low, and it is only beyond $\sim$30 pc that it increases (rapidly) with radius as the temperature drops to $\sim 10^7$ K. Since the thermal X-ray emission is proportional to the density squared, the result is that most of the emission observed arises from close to the shell, from a region cold enough to produce soft X-rays.

Temperatures of $10^8$ K have been observed and modeled in superstellar clusters (Silich et al. 2004, 2005), which are much more massive than the young star association in N70. The reason for such temperatures is the high terminal velocity of some of the winds ($>2000$ km s$^{-1}$). The difference is that in superstellar clusters the density of stars is significantly larger; thus, the gas density inside is enough to produce an observable amount of hard X-rays. In contrast, the massive stars in N70 are too far
Figure 9. Synthetic X-ray emission map of model M2 in (a) [0.2–2] keV, (b) [2–10] keV, and (c) [10–20] keV energy ranges.

Figure 10. Overlay of the simulated Hα emission map (gray) with contours of the synthetic X-ray emission.

apart from each other, and the emission above 2 keV is very faint compared with that at lower energies.

Figure 10 shows the Hα map and superposed X-ray isocontours of M4 model. The X-rays isocontours cover a wide range of flux of energy from $10^{-9}$ to $10^{-6}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in steps of $5 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The highest values of the isocontours are at the center in a shell just behind (inside) the optical superbubble (between 38 and 47 pc). The outer shell or superbubble is formed by the interaction of the cluster wind and its surrounding ISM.

Table 3 presents a summary of the numerical results for the dynamics and X-ray luminosities obtained from our models. In this table, we include the evolutionary time when the maximum X-ray luminosity is reached for each model ($t_{Lx}$) and the interval that the X-ray luminosity is kept above $10^{35}$ erg s$^{-1}$ ($\Delta t_{Lx}$).

In our models, we did not include the thermal conduction effects. Weaver et al. (1977) and several other authors (e.g., Chu & Mac Low 1990; Silich et al. 2001) have recently studied its importance in explaining the total X-ray emission in stellar clusters and SNRs. However, Silich et al. (2001) show that while thermal conduction might have produced an enhancement of several orders of magnitude in superbubbles with ages $>10$ Myr, for young superbubbles (such as N70) thermal conduction can only produce a difference of a factor of $\sim 5$. It is important to note that the main effect of thermal conduction is to carry material from the external shell into the bubble, thus filling the bubble with X-rays and maintaining its emission for a longer time (see also Silich et al. 2001). This is because thermal conduction drives a transfer of the material from the external shell to the center of the bubble.

The standard model of bubbles (Weaver et al. 1977) predicts X-ray emission from the hot interior of bubbles by including thermal conduction effects. Its success is controversial because in some cases the predicted X-ray luminosities is lower than detected (as in the case of the N70 superbubble) while, in other cases, the predicted X-ray emission is higher than detected (as in the case of the M17 superbubble; Dunne et al. 2003; Reyes-Iturbide et al. 2009). The new results on thermal conduction effects mentioned above lead us to believe that thermal conduction is not the primary origin of the difference. In this work, we propose that the inclusion of an SN explosion, as an agent to be considered in addition to the stellar winds, is more important than thermal conduction. At least two reasons support this: (1) in the case of M17, it is almost certain that no SN explosion has yet occurred, while the age of LH114, at the interior of N70, makes an SN explosion plausible; and (2) the expansion velocities predicted by the Weaver et al. (1977) model in the case of N70 are much lower than the measured velocities for this superbubble. As seen in Figures 2–5 and Table 3, only the models including an SN explosion predict a shell acceleration that could explain expansion velocities as large as the ones measured in high-velocity shells such as N70. Thus, we suggest that the main difference between high-velocity and low-velocity superbubbles is the occurrence (or lack) of an SN explosion in their interiors. Off-centered explosions can change some of the detailed structure and dynamics, but the main conclusions remain unchanged. Of course, we have explored only the N70 superbubble and need to study in detail other superbubbles (both of high- and low-velocity types) in order to confirm this suggestion.

6. CONCLUSION

We studied the dynamics and X-ray emission of superbubbles driven by cluster winds, including in our models SN explosions alone, stellar winds alone, and a combination of stellar winds and SN explosions, the latter at different times and locations. We
The radial velocity of the shell is less than $45 \text{ km s}^{-1}$. The X-ray luminosity is lower by an order of magnitude than the only the stellar winds inject mechanical energy ($M_2$), the soft density and temperature medium.

turned our attention to the superbubble N70 in order to compare our model predictions with the observations. We computed four models (M1–M4) of superbubbles using the properties of the more massive stars contained in the cluster inside the N70 superbubble, adopting the ISM density and metallicity around this superbubble. The models evolved in a homogeneous (in density and temperature) medium.

With our models we demonstrated that in the case in which only the stellar winds inject mechanical energy ($M_2$), the soft X-ray luminosity is lower by an order of magnitude than the observed value (in agreement with the standard model). The radial velocity of the shell is less than $45 \text{ km s}^{-1}$. However, the model of a single SN explosion (M1), even when the input from stellar winds is not considered, was able to reach X-ray luminosity and expansion velocity consistent with the observations. Nevertheless, a single SN explosion predicts the formation of a very thin shell, which is not in agreement with the morphology of the N70 superbubble.

Three models considered the mechanical energy injected by stellar winds; $M_2$ only considers the input from stellar winds, while M3 and M4 were combined with an SN explosion. We included the SN explosion at two different positions, near the cluster center and $\sim 2 \text{ pc}$ from the cluster center (in M3 and M4, respectively). The SN has exploded after $t = 1.15 \times 10^5 \text{ yr}$ of the evolutionary time of the cluster wind. From models M3 and M4 we obtained an X-ray emission in good agreement with the observational data during 20 and 75 kyr, respectively. The shell velocity expansion ($\sim 60 \text{ km s}^{-1}$) obtained in both models could explain the kinematics measured for this bubble. Models M3 and M4 formed a thick shell, also in agreement with the observations of N70.

As a matter of fact, both models M3 and M4 reproduce quite well the large measured expansion velocity of the N70 shell and the X-ray luminosity. Model M4 lacks spherical symmetry because in the off-centered SN the morphological difference is somewhat subtle and can be concealed for certain orientations with respect to the line of sight. Therefore, we cannot discard it. Figure 10 shows the predicted Hα emission (gray levels) and the X-ray emission (isocontours) for model M4, and Figure 11 depicts the observed ones, showing good agreement.

It is important to note that our models predict a large region inside the superbubble (the innermost $\sim 30 \text{ pc}$) with temperatures $\geq 10^8 \text{ K}$, which would result in thermal hard X-ray emission (above 2 keV). However, the density inside the superbubble is very low, and it produces only a faint emission that is overwhelmed by the soft X-rays produced in the surrounding shell.

In this paper, we did not include the thermal conduction effects. However, for young superbubbles, with ages less than 10 Myr (as well as N70), the differences between models with and without thermal conduction are only a factor of $\sim 5$ in $L_X$ (Silich et al. 2001). A more important role of thermal conduction in superbubble models is the fact that it helps sustain the X-ray emission for longer periods of time.

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