Three-dimensional numerical model of the Omega Nebula (M17): simulated thermal X-ray emission

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ABSTRACT

We present 3D hydrodynamical simulations of the superbubble M17, also known as the Omega Nebula, carried out with the adaptive grid code YGUAZÚ-A, which includes radiative cooling. The superbubble is modelled considering the winds of 11 individual stars from the open cluster inside the nebula (NGC 6618), for which there are estimates of the mass-loss rates and terminal velocities based on their spectral types. These stars are located inside a dense interstellar medium, and they are bounded by two dense molecular clouds. We carried out three numerical models of this scenario, considering different line-of-sight positions of the stars (the position in the plane of the sky is known, thus fixed). Synthetic thermal X-ray emission maps are calculated from the numerical models and compared with ROSAT observations of this astrophysical object. Our models successfully reproduce both the observed X-ray morphology and the total X-ray luminosity, without taking into account the thermal conduction effects.

Key words: methods: numerical – stars: winds, outflows – ISM: bubbles – Galaxy: open clusters and associations: individual: M17 – Galaxy: open clusters and associations: individual: NGC 6618 – X-rays: ISM.

1 INTRODUCTION

The mechanical luminosity of a stellar wind ($\frac{1}{2} M \dot{w} V_\infty^2$, where $M \dot{w}$ is the mass-loss rate and $V_\infty$ is the terminal speed of the wind) is typically less than 1 per cent of the stellar radiative luminosity. The fast winds of massive stars have, however, a great influence on their surrounding interstellar medium (ISM). They sweep up the ISM creating a variety of structures, from small bubbles around single stars to large superbubbles around associations of OB stars. The interior of these bubbles or superbubbles contains shock-heated gas (with temperatures in excess of $10^6$ K), thus emits strongly in X-rays, while the outer shell is cooler and bright in optical emission lines (Weaver et al. 1977; McCray & Kafatos 1987; Mac Low & McCray 1988; Chu et al. 1995).

In the last decades, observations from old X-ray satellites, such as the ROSAT, and newer ones, such as the Chandra and XMM–Newton observatories, have found diffuse X-ray emission inside OB massive star clusters. The diffuse X-ray region is associated with hot gas contained in a superbubble produced by the interaction of the individual OB stellar winds with the surrounding environment. Nevertheless, extremely massive stars from the cluster would rapidly evolve into supernovae (SNe) explosions, in which case the superbubble will be produced by the combined action of stellar winds and SNe. In order to isolate the X-ray emission from stellar winds alone, we can study very young superbubbles, where SNe explosions are still not taking place.

The superbubble M17 contains the massive stellar cluster NGC 6618, with more than 800 stellar sources (Broos et al. 2007). This cluster has 100 stars earlier than B9 (Lada et al. 1991) and an average age of ~1 Myr (Hanson, Howarth & Conti 1997). With such a short age, it is unlikely to have produced any SN explosion; in a cluster with 100 O-type stars, the first SN explosion would occur after ~4 Myr (Knödlseder et al. 2002). Therefore, M17 provides an ideal laboratory to observe and study the diffuse X-ray emission as produced by stellar wind collisions alone. This kind of superbubbles are called 'quiescent superbubbles'.

This superbubble is highly asymmetric due to the interaction with the edge of a massive molecular cloud, M17SW, located to the west of M17 (Lada et al. 1974). In this direction, the bubble encounters resistance, while it can expand more freely to the east.
This asymmetry is evident in a large-scale map of M17 at λ 21 cm (Felli, Churchwell & Massi 1984), where two intersecting clouds or ‘bars’ are observed in emission. These have been called the northern (N) and southern (S) bars. The projected size of each bar is of ∼5.7 pc, forming an angle of ∼45° with each other on the plane of the sky (Felli et al. 1984; Brogan & Troland 2001).

The centre of the stellar cluster NGC 6618 consists of a ‘ring’ of seven O-type stars (Hanson et al. 1997), which are located between the two bars. These stars must be the dominant sources of ionizing photons on the nebula; in fact, diffuse X-ray emission is observed to be well confined within the external shell of the optical nebula (Dunne et al. 2003). Fig. 1 shows a Digital Sky Survey (DSS) image of this object. The ring of seven O-type stars is located on the west, where there is substantial obscuring material, with $A_v \sim 8$ mag (Hanson et al. 1997).

The stellar winds of these seven stars strongly contribute to the formation of a common ‘stellar cluster wind’ (Cantó, Raga & Rodríguez 2000). The collision of these winds with the surrounding inhomogeneous ISM produces the diffuse X-ray emission observed by ROSAT and Chandra satellites.

In ROSAT images, M17 is observed as a blister-like structure, with an overall diameter of ∼10–12 pc, if a distance of 1.6 kpc is considered (Nielbock et al. 2001). The emission peak is located inside the stellar cluster. This suggested that the cluster is the origin of the diffuse X-ray emission, and was later confirmed by Chandra observations (Townsley et al. 2003), where the angular resolution allows one to see the individual sources. M17 was observed with ROSAT Position Sensitive Proportional Counter (PSPC) for 6.7 ks in the 0.1–2.4 keV band (Dunne et al. 2003). They found a total diffuse X-ray luminosity of $\sim 2.5 \times 10^{33}$ erg s$^{-1}$ with $kT = 0.66$–0.78 keV ($T = 7.7$–9.1 $\times 10^6$ K) and $N_H = (1$–$5) \times 10^{21}$ cm$^{-2}$.

Several models have tried to reproduce the total X-ray luminosity ($L_X$) from superbubbles, often taking into account the effects of the electron thermal conduction. However, the $L_X$ reproduced by models where thermal conduction is included (Weaver et al. 1977) is usually 2 or 3 orders of magnitude higher than the observed values, while models where thermal conduction is ignored predict an $L_X$ that is typically 2 orders of magnitude lower than observed. Most of the time, the descriptions are rather simple; they consider, for instance, that the cluster wind interacts with a homogeneous and isotropic ISM, and neglect the effects of radiative cooling. For M17, this approach is not adequate because it is a star-forming region surrounded by asymmetrically distributed high-density molecular clouds.

In this work, we present three-dimensional numerical simulations based on the properties of M17. The simulations were carried out with the adaptive grid code YGUAZÚ-A, and we considered the main characteristics of the ISM that surrounds M17. Synthetic thermal X-ray emission maps were obtained from the numerical results in order to compare the morphology and the total luminosity directly with ROSAT X-ray observations (with a field of view of ∼2′).

This manuscript is organized in the following way: in Section 2, we explain the modelling of M17, explain the initial conditions of numerical simulations and describe the simulation of the thermal X-ray emission; an archival ROSAT image of this superbubble is presented in Section 3; the results and comparison with observations are given in Section 4 and finally in Section 5, we summarize our conclusions.

## 2 MODELLING THE M17 NEBULA

As mentioned above, the stars that belong to the NGC 6618 cluster are too young to generate SN explosions. For this reason, the M17 nebula was modelled by the interaction of stellar winds alone. We only considered the stars that dominate the mechanical luminosity of the cluster, they have high terminal velocities and mass-loss rates, the values are based on the spectral types reported by Hanson et al. (1997), we list them in Table 1. The values for the terminal velocity and mass-loss rate correspond to the upper limits reported in the

### Table 1. OB stars in M17 and their stellar wind parameters.

| Name | RA(2000.0) | Dec.(2000.0) | Optical type | Spectral type | $V_\infty$ (km s$^{-1}$) | $M$ (M$_\odot$ yr$^{-1}$) | References |
|------|------------|-------------|--------------|---------------|--------------------------|--------------------------|------------|
| B98  | 18 20 35.45| −16 10 48.9 | O9 V         | k09-B1        | 2200                     | $2.6 \times 10^{-7}$     | 1,2,3      |
| B111 | 18 20 34.55| −16 10 12.1 | O5 V         | k03-O4        | 3250                     | $1.86 \times 10^{-6}$    | 3          |
| B137 | 18 20 33.14| −16 11 21.6 |              | k03-O4        | 3370                     | $2.4 \times 10^{-6}$     | 4,5        |
| B164 | 18 20 30.92| −16 10 08.0 | O7–O8 V      | k07-O8        | 3015                     | $2 \times 10^{-6}$       | 1,4        |
| B174 | 18 20 30.54| −16 10 53.3 |              | k03-O6        | 3370                     | $6.5 \times 10^{-7}$     | 1,4        |
| B181 | 18 20 30.30| −16 10 35.2 |              | k09–B2        | 2200                     | $2.6 \times 10^{-7}$     | 1,2,3      |
| B189 | 18 20 29.92| −16 10 45.5 | O5 V         | k03-O4        | 3250                     | $1.86 \times 10^{-7}$    | 3          |
| B260 | 18 20 25.94| −16 08 32.3 | O7–O8 V      | k03-O4        | 3015                     | $2 \times 10^{-6}$       | 1,4        |
| B289 | 18 20 24.45| −16 08 43.3 | O9.5 V       | k09–B2        | 1500                     | $2.5 \times 10^{-7}$     | 1,6        |
| B311 | 18 20 22.76| −16 08 34.3 |              | k05-O6        | 3065                     | $6.5 \times 10^{-7}$     | 1,2,3,4    |

(1) de Jager et al. (1988); (2) Wilson & Dopita (1985); (3) Leitherer (1988); (4) Prinja et al. (1990); (5) Lamers & Leitherer (1993) and (6) Fullerton et al. (2006)
literature (Wilson & Dopita 1985; de Jager, Nieuwenhuijzen & van der Hucht 1988; Leitherer 1988; Prinja, Barlow & Howarth 1990; Lamers & Leitherer 1993; Fullerton, Massa & Prinja 2006). This has been done with the intention to increase the X-ray luminosities obtained from our simulations, and to compensate for the fact that all the other wind sources have been disregarded. Furthermore, a recent study of Hoffmeister et al. (2008) has shown that the number of stars in the NGC 6618 cluster is even higher than the previous estimates.

For the 3D numerical simulations, we consider that the plane of the sky corresponds to the xy plane of our simulation. Table 1 gives the position of the stars in equatorial coordinates (J2000), which can be translated to parsec considering that the cluster is at a distance of 1.6 kpc.

Since we do not know the individual line-of-sight distance (z-coordinate) to the stars, we produced three different realizations of randomly picked positions in z, while keeping the same xy configuration (see Fig. 2). The maximum of the distribution from which the z positions were sampled set to the maximum separation in the plane of the sky, and the mean was set to the distance to the cluster (1.6 kpc). The resulting yz distributions are shown in Fig. 3.

The NGC 6618 cluster is bounded by two molecular clouds at the north and south-west, observed in H I (Felli et al. 1984). These clouds have the appearance of a wedge, which confine the resulting stellar cluster wind and produce an elongated structure to the east. We model the clouds as two bars, one of which is horizontal (we will refer to it as the ‘top bar’) and the other one tilted 45° in the xy plane (which we will call the ‘bottom bar’). Their surfaces are flat and cover the entire extent of the computational domain along the z-axis (i.e. the geometry displayed in Fig. 2 is same for all values of z). The bars have a high-density contrast with respect to the surrounding ISM (of 2 orders of magnitude). The stars (wind sources) were placed inside the wedge formed by the two bars, as shown schematically in Fig. 2.

Figure 2. Stellar positions in the plane sky (the xy plane). These positions were calculated considering the RA and Dec. positions listed in Table 1 and a cluster distance of 1.6 kpc. The shaded area represents the location of the dense molecular clouds that surround the NGC 6618 cluster.

### 2.1 Initial set-up

We have carried out the 3D numerical simulations with the YGUAZ-U hydrodynamical code (Raga, Navarro-González & Villagrán-Muniz 2000; Raga et al. 2002). The code integrates the gasdynamic equations with a second-order accurate implementation of the flux vector splitting method of van Leer (1982) on a binary adaptive grid. This code was first tested by comparing simulations of shock waves and laser laboratory experiments (one bubble shock wave, Raga et al. 2000; two interacting bubbles, Velázquez et al. 2001). In the last 8 years, the YGUAZ-U code has been widely used to model several different astrophysical scenarios, such as Herbig Haro objects (Masciadri et al. 2002; Raga et al. 2002), SNe remnants (Schneiter, de La Fuente & Velázquez 2006; Reyes-Iturbide, Rosado & Velázquez 2008), jets in planetary nebulae (Velázquez, Riera & Raga 2004; Guerrero et al. 2008), interacting winds (González et al. 2004; Rodríguez-González et al. 2007) and exoplanets (Schneiter et al. 2007).

For this problem, we use a computational domain with a physical size of (12 × 12 × 4) pc (x-, y- and z-axis, respectively), and allow five levels of refinement such that the resolution at the finest level is 7.27 × 10^{16} cm. This would correspond to 512 × 512 × 128 pixels in a uniform grid. We chose this spatial resolution (3 arcsec if a distance of 1.6 kpc to M17 is assumed) to match the resolution of ROSAT raw observations (~4 arcsec; see Section 3).

The stellar winds are imposed in spheres (centred at the stellar positions) of radius R_w = 4.4 × 10^{17} cm, which corresponds to 6 pixels at the maximum resolution of the adaptive grid (always present at the wind sources). Within these spheres, we inject at every time-step material at T_w = 1000 K, with the outward velocity given in Table 1 for each star. The density inside the spheres follows...
a $r^{-2}$ law (where $r$ is the radial coordinate measured outwards from the stellar position), scaled to yield the mass-loss rates in Table 1.

The stars and the bars are located in the top right quadrant of the numerical domain in the $xy$ plane. The bars were initialized with a uniform number density of 1000 cm$^{-3}$ and a temperature of 100 K in order to stay in pressure equilibrium with an ISM that has a density of 10 cm$^{-3}$ and a temperature of $10^4$ K.

2.2 Simulated X-ray emission

The numerical simulation provides us with density and temperature distributions for each model, which we combine with synthetic X-ray spectra to simulate the X-ray emission of M17.

The synthetic spectra were obtained with the CHANTi data base (Dere et al. 1997; Landi et al. 2006). We calculate the X-ray emission coefficient $j_x(n, T)$ in the energy range of 0.1–2.4 keV to coincide with that of ROSAT. Based on the observational works (Dunne et al. 2003; Townsley et al. 2003; García-Rojas et al. 2007), a solar abundance was assumed for M17, together with the ionization equilibrium model of Mazzotta et al. (1998). The $j_x(n, T)$ coefficients are calculated in the limit of low-density regime, which results in $j_x(n, T) \propto n^2$. To produce X-ray maps the absorption is included, assuming a uniform hydrogen column density of $N_H = 3.2 \times 10^{21}$ cm$^{-2}$.

3 ROSAT IMAGE OF M17

M17 was observed with the ROSAT satellite, with the PSPC detector. This instrument is sensitive to X-ray photons with energies in the range of 0.1–2.4 keV and has a spectral resolution energy of ~40 per cent at 1 keV, with a field of view of ~2°, covering the entire dimensions of superbubble M17 (with an angular size of ~23 $\times$ 20 arcmin$^2$).

We have used an image (binned to 4 arcsec per pixel) from an archival ROSAT Catalogue of PSPC WGA sources, which corresponds to the PSPC observations of M17 (ID:WP500311) obtained on 1993 September 12–13, with an exposure time of 6.7 ks. In order to study the spatial distribution of the X-ray emission from M17, we have increased the signal-to-noise ratio using the standard procedure of smoothing the image (Dunne et al. 2003; Townsley et al. 2003). To do this, we convolved the observations with a Gaussian function with an effective point spread function (PSF) of 5.4 pixel. In Fig. 5, we show the original (raw data) image and the smoothed version.

4 RESULTS AND DISCUSSION

We ran the models up to an integration time of $1.3 \times 10^5$ yr, which is the estimated superbubble age (Weaver et al. 1977). In Fig. 4, we present X-ray emission maps for the three models at their latest integration time. These maps show the absorbed X-ray emission, assuming a column density of $3.2 \times 10^{21}$ cm$^{-2}$ as found from ROSAT observations (Dunne et al. 2003).

The interaction of many individual stellar winds will coalesce into a common cluster wind, as studied for massive stellar clusters by Cantó et al. (2000) and Rodríguez-González et al. (2007). However, unlike those models that consider a uniform ISM, we can see from Fig. 4 that the resulting X-ray emission is not homogeneous. All models show a strong concentration of X-ray emission in regions to the top right of each map, especially for Model 2. This enhancement corresponds to strong shock waves produced by the collision of the cluster wind with the dense molecular cloud or bars. These bars are flat and focus the cluster wind flow and produce the elongated morphology observed in X-rays. To the opposite side, the cluster wind can expand more freely producing through a ‘champagne’-type flow a superbubble of ~12 pc in size. From Fig. 4, the structure seen in our simulations at the position $x \sim 10$ pc $y \sim 7$ pc corresponds to the wind of an isolated star embedded in the southern bar, which gets confined due to the high density of its surrounding medium (see Fig. 2).

The surrounding dense bars have another important effect, namely to increase the $L_X$. This effect depends on the geometry of the bars, which in our models we have considered to be flat
Table 2. Total X-ray luminosities.

|          | $L_X (10^{33} \text{ erg s}^{-1})$ |
|----------|-----------------------------------|
| ROSAT observation$^a$ | 2.5 |
| Model 1  | 1.4 |
| Model 2  | 1.6 |
| Model 3  | 1.6 |

$^a$Dunne et al. (2003).

Table 3. Metallicity versus $L_X$.

| $Z$   | $L_X (10^{33} \text{ erg s}^{-1})$ |
|-------|-----------------------------------|
| 0.3   | 0.6 |
| 0.5   | 0.9 |
| 0.7   | 1.2 |
| 0.9   | 1.4 |
| 1.0   | 1.6 |
| 1.1   | 1.7 |
| 1.3   | 2.0 |

Dunne et al. (2003) obtained an $L_X$ of $5 \times 10^{35}$ erg s$^{-1}$ for M17, employing both the Weaver et al. (1977) bubble model and the Chu et al. (1995) superbubble model. Such value is 2 orders of magnitude higher than the observed one. These models are based on the evolution of bubbles (and superbubbles) into a homogeneous medium, and they are adiabatic, although they include thermal conduction effects. In our case, it was not necessary to include the last physical process because we have obtained an $L_X$ already compatible with observations, taking into account only the inhomogeneity of surrounding ISM and including the radiative cooling.

Although thermal conduction effects should be present, as first introduced in the wind-blown bubble model by Weaver et al. (1977), there are important discrepancies between the X-ray luminosities predicted by that model and what is observed. For instance, X-ray emission should be detected in almost all the known wind-blown bubbles and superbubbles, but this is not the case (see Mac Low 2000 for a discussion). In particular, for M17, a direct application of Weaver’s et al. model (which considers thermal conduction as a crucial ingredient for the X-ray emission of the hot interior) predicts an X-ray luminosity about 100 times higher than what is measured (Dunne et al. 2003). This leads us to think that perhaps some mechanisms are present that inhibit thermal conduction, at least in the form that it is treated in Weaver’s et al. model. The presence of magnetic fields is often invoked as one of the possible inhibiting factors. In our particular case, we show that whatever mechanism might be at work, thermal conduction do not seem to play an important role in the prediction of X-ray emission from the M17 superbubble.

The X-ray emission distribution for all models (see Fig. 4) shows a general gradient, with lower emission to the left, in coincidence with the observations (see Fig. 5). Also in our models, on the left of the X-ray emitting material, strong emission is observed in the form of filaments (see Fig. 4). These filaments trace the shock front of champagne flow described above, propagating into the surrounding ISM. In ROSAT observations, bright regions or ‘clumps’ can be seen to the east (corresponding to the left in our simulations). These clumps can be produced by the propagation of strong shock waves into an inhomogeneous medium. However, these features are smoother than those obtained from the simulations probably due to the difference between observed and simulated resolutions. To make a fair comparison, we show in Fig. 6 a smoothed synthetic map of Model 2, produced by convolving the numerical results with a Gaussian beam in order to reproduce the same resolution of the ROSAT (smoothed) image in Fig. 5.

5 CONCLUSIONS

We carried our 3D numerical simulations using the adaptive grid code yguaze-a to model the M17 superbubble. Radiative losses have been included in the simulations. Three different runs of the same model were made using the known positions of the dominant wind sources on the plane of the sky (corresponding to the xy positions in our Cartesian grid) and considering three different distributions along the line of sight (aligned with our z-axis).

Our results show that the inclusion of the main features of the surrounding ISM (i.e. the presence of two dense bars or clouds around the M17 stars) plays a crucial role to explain both the observed morphology and the $L_X$ of this object.

On the one hand, the bars produce a ‘champagne’ flow effect in all models, in which the resulting stellar cluster wind is focused by such bars, producing an elongated shape in the x-direction, thus reproducing the elongated shape in the east–west direction of the observations.

On the other hand, the collision of the cluster wind with the bars maintains a high-temperature, high-density distribution in the region between the bars. This is a product of the multiple-reflected shocks and enhances the $L_X$. We obtain values of the $L_X$ of $\approx 1.6 \times 10^{33}$ erg s$^{-1}$, which are in agreement with the observations.
Figure 5. ROSAT image of superbubble M17, obtained from archival data the (ROSAT catalogue of PSPC WGA sources) in the energy range 0.1–2.4 keV. Top panel: raw data binned to 4 arcsec per pixel. Bottom panel: smoothed image obtained after convolving with a Gaussian function with a PSF of 5.4 pixel.

Figure 6. Synthetic X-ray emission map of Model 2 in the energy range 0.1–2.4 keV, smoothed with the same resolution of the ROSAT observation (Fig. 5). The bar on the top is the logarithmic grey-scale, which is given in units of erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$. Vertical and horizontal axes are given in units of pc.

The different $z$ stellar distributions employed in our runs had a rather small effect on both the morphology and $L_X$. This could be somewhat expected, because the same mechanical luminosity input is used for all the runs, and because away from the cluster centre the common wind that forms should be similar. Finally, it is notable that we obtain a reasonable estimate of the $L_X$ without the need for including thermal conduction effects.

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