Research Article

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H α emission from gaseous structures above galactic discs

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Abstract: Extraplanar structures of ionized gas are detected in numerous edge-on galaxies. Whether HII regions or supernovae (SNe) responsible for its ionization is still debated. Here, we consider the H α emissivity from shells of superbubbles driven by SNe explosions in a stellar cluster located either in the midplane or above the midplane of the disc. We found that these shells form filamentary structures emitting brightly in H α line at height of ~ 0.6 – 1.6 kpc above the disc depending on cluster location and gas metallicity. The H α surface brightness ranges within $\sim 10^{-17}$ – 10^{-16} erg s $^{-1}$ cm $^{-2}$ arcsec $^{-2}$ are close to the values observed in edge-on galaxies. We conclude that the H α emission of extraplanar structures can be explained by recombination in collisionally ionized gas of unstable shells driven by multiple SNe.

Keywords: galaxies, halos – starburst – ISM – ISM, bubbles – shock waves – supernova remnants

1 Introduction

Diffuse ionized gas (DIG) is detected at large heights above the midplane of numerous edge-on galaxies (Haffner *et al.* 2009). Its properties are related to star formation processes in the underlying disc. The ionization of the DIG is believed to be governed by UV photons produced by OB stars (Dettmar 1990, Haffner *et al.* 2009) and a small contribution from hot low-mass evolved stars (Flores-Fajardo *et al.* 2011, Belfiore *et al.* 2021), whereas the origin of

filamentary structures in the DIG is usually connected with the disc-halo exchange by multiple supernovae (SNe) explosions (Norman and Ikeuchi 1989, Dettmar 1990).

A gas in unstable shells of bubbles driven by multiple SNe is nearly fully ionized and emits efficiently in recombination lines during a long period, which is close to cooling time. Gaseous fragments that originated from disintegrated SNe shells can be elevated on several scale-heights, but only small fraction of them can have high velocity to escape the disc entirely, and a major part of these fragments returns to the disc (*e.g.* Vasiliev *et al.* 2019), so that the DIG should be replenished by further SNe explosions and probably have transient nature. In this sense it is important to understand what fractions of heating and ionization stemmed from these two sources: OB stars and SNe shocks, can the ionization of the DIG be explained solely recombination in collisionally ionized gas of unstable shells driven by multiple SNe.

Extraplanar structures of ionized gas are well revealed in edge-on galaxies such as NGC 891 in H α line (Dettmar 1990, Rossa and Dettmar 2000, 2003, Rossa *et al.* 2004, Boettcher *et al.* 2016) and in dust absorption (Howk and Savage 1997, 1999) as well. This galaxy is similar to the Milky Way (Fraternali *et al.* 2011, Schechtman-Rook and Bershadsky 2014), so that our study may be useful for understanding the origin of warm ionized and neutral gaseous structures in our Galaxy (Haffner *et al.* 2009).

In this article, we consider the SNe-driven bubbles, which produce vertical filamentary structures of 1–2 kpc above the midplane, and their H α emissivity. The article is organized as follows. Section 2 contains our model. In Section 3, we describe the results. Section 4 summarizes our conclusions.

2 Model

We carry out 3-D hydrodynamic simulations (Cartesian geometry) of SNe explosions inside a cluster located in the galactic disc. Here, we present a short description of the model, and more details on the set-up of the disc and

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numerical methods can be found in Vasiliev *et al.* (2019) and Drozdov *et al.* (2022).

We set up a gaseous disc to be initially in the hydrostatic equilibrium in a gravitational potential (like in many previous papers, see *e.g.* de Avillez 2000, Hill *et al.* 2012, Walch *et al.* 2015, Li *et al.* 2017, Vasiliev *et al.* 2019), which consists of three components: a dark matter halo, stellar and gaseous discs. Here, we consider a galaxy similar to the Milky Way or NGC 891. Therefore, we use the model of gravitational potential built by Kalberla (2003) at the cylindrical radial distance 3 kpc from the Milky Way centre (see Figure 7 in Kalberla 2003). In our models, the stellar disc scale height is $z_* = 0.3$ kpc, the values for stellar and gas surface densities are $\Sigma_* = 180 M_\odot \text{ pc}^{-2}$ and $\Sigma_g = 11.5 M_\odot \text{ pc}^{-2}$, respectively. The latter corresponds to the volume gas density equal to 3 cm^{-3} at the midplane. At large heights, the number density is kept uniform at 10^{-3} cm^{-3} . Initially, the gas temperature is $9 \times 10^3 \text{ K}$; the gas metallicity is kept constant within the whole computational domain. We adopt two values $[Z/H] = 0$ and -0.3 .

SNe are distributed in a cluster randomly within radius 30 pc. The random times and locations of supernovae are chosen at initialization, such that for all runs with a given configuration, supernovae explode in the same time moments and locations. In all our models considered here the centre of cluster is located at the midplane ($z = 0$) and approximately 2/3 of the gaseous disc scale height, which is around 0.1 kpc.

Masses of massive stars, SNe progenitors, are distributed randomly within $10 - 40 M_\odot$ according to the Salpeter initial mass function. The number of massive members in a cluster is 300, which approximately corresponds to the total stellar mass of a cluster of $M_c \sim 4 \times 10^4 M_\odot$ (we assume one SN per each $130 M_\odot$ for a Salpeter IMF). We begin our run when the most massive SN explodes. The intervals between following SNe correspond on average to lifetime of massive stars, which relates stellar mass as $\log(t_i, \text{year}) = 10.04 - 3.8054 \log M + 1.0646 \log^2 M$ (Iben 2012). We restrict our simulations within a timescale of the longest lifetime of massive stars, *i.e.* $\sim 15 \text{ Myr}$ for a star of $10 M_\odot$.

We inject the mass and energy by individual events corresponding to three standard SNe. The mass and energy of each event are injected in one cell for a standard spatial resolution of 8 pc. Therefore, each injection carries the energy $3 \times 10^{51} \text{ erg}$ in thermal form and the mass load of $30 - 120 M_\odot$. This allows us to consider larger computational cells and assume the injection radius corresponding to the Sedov–Taylor solution to be smaller than the cooling length.

Our simulations include radiative cooling processes. We use a tabulated non-equilibrium cooling function fitting the calculated one (Vasiliev 2011, 2013). The fitted function is obtained for gas cooling isochorically from 10^8 K down to 10 K . We apply a diffuse heating term representing the photoelectric heating of dust grains (Bakes and Tielens 1994) as a dominant heating mechanism in the interstellar medium. In our simulations, the heating rate is assumed to be time independent and exponentially decreasing in the vertical direction with the scale height of the ISM disc. Such an assumption is sufficient to stabilize radiative cooling of ambient gas at $T = 9 \times 10^3 \text{ K}$.

The code is based on the unsplit total variation diminishing approach, the Monotonic Upstream-Centred Scheme for Conservation Laws (MUSCL)-Hancock scheme and the Harten–Lax–van Leer–Contact method (see *e.g.* Toro 1999) as an approximate Riemann solver.

3 Results

Multiple SNe explosions in star forming regions located in galactic discs drive bubbles expanding in galactic halos. The sizes of resulted vertical structures vary from several hundred parsecs (like bubbles around low-mass stellar clusters) to ten kiloparsecs (like the eROSITA bubbles around the Milky Way and strong superwind in M82) depending on star formation rate (see, *e.g.* Heiles 1984, Norman and Ikeuchi 1989, Lehnert and Heckman 1996, Rupke 2018). Here, we are interested in stellar clusters, which produce vertical filamentary structures of 1–2 kpc above the midplane. Vertical size depends obviously not only on mass of stellar cluster (number of SNe), but also on the properties of a disc, such as stellar scale height, stellar and gas surface densities. For the disc properties adopted here the masses of stellar cluster needed to produce 1–2 kpc vertical structures are about $M_c \sim 10^4 - 10^5 M_\odot$. We assume that total stellar mass of a cluster of $M_c \sim 4 \times 10^4 M_\odot$, which corresponds to 300 SNe. This number of SNe is taken as fiducial in further calculations.

Let us outline briefly the evolution of the bubble driven by SNe explosions in a cluster located in the midplane. Due to sufficiently high volume number density in the midplane the bubble passes to radiative phase, when it still expands in the disc. Then, at $t \sim 3.5 \text{ Myr}$ the bubble blows out of the disc. The shell of the bubble out of the disc expands almost adiabatically during several million years. At $t \sim 7 \text{ Myr}$ radiative losses become significant and the shell gets thin and unstable. It expands vertically and over the outer side of the disc. Till $t \sim 15 \text{ Myr}$

the shell reaches a height of $|z| \sim 0.5\text{--}0.7$ kpc and practically stalls. Figure 1 shows the number density slice across the centre of the cluster at this time moment. Some parts of the bubble commence to fall down to the disc. This process continues around 10–15 Myr (e.g. Vasiliev *et al.* 2019). So that the maximum height of this bubble is $|z| \sim 0.7$ kpc, which remains without significant changes around 10–15 Myr.

Stellar clusters are not located at the midplane exactly. They are usually shifted above or below. This is revealed in the evolution of the bubble. Let us consider the bubble driven by SNe in a cluster shifted to about 60 pc above the midplane, which corresponds to 2/3 of gaseous scale height of the disc model adopted in our simulations. During the first 0.5 Myr the bubble expands inside the disc. But at $t \sim 1$ Myr it quickly blows out of the disc in the low-dense direction. The shell expands almost adiabatically in the halo and reaches $z \geq 1$ kpc till $t \sim 7$ Myr, when it becomes radiative. This height is around two times larger than that reached by the shell driven by SNe explosions from a cluster located in the midplane exactly. Note this value is achieved in one direction, in the other the shell is still locked in the disc. Then, the thick shell expanding into the halo is separated into two parts around $t \sim 10\text{--}11$ Myr: the outer part becomes radiative and thin, the inner part having lower density remains thick and follows the outer one. This picture is kept almost unchangeable for several million years, and it is clearly seen in Figure 2, which presents the density slice of a bubble driven by a cluster of 300 SNe located at 60 pc above the midplane

at time moment 15 Myr. The bubble is stalled and attains the maximum height of $z \sim 1.4$ kpc. One can note that the shell appears to contain larger mass on lower heights, i.e. the shell is massive at lower ($z \sim 0.4\text{--}0.6$ kpc) heights and less massive at large ($z \geq 0.7$ kpc) heights.

Using the H α line emissivities from the CLOUDY code (Ferland *et al.* 2017) matched to the cooling rate for a given temperature (Vasiliev 2013), we calculate H α emission along each line-of-sight to obtain the brightness distribution in superbubbles seen edge-on (see also Vasiliev *et al.* 2015a, 2015b, 2017). Figures 3 and 4 present the H α intensity maps from bubbles driven by clusters of 300 SNe located at the midplane and at 60 pc above the midplane at the time 15 Myr. There are many H α filamentary structures above the disc. For both locations of a cluster the most bright part of the bubble lies below ~ 0.6 kpc. The H α intensity of this part is varied within $\sim 10^{-17}\text{--}10^{-16}$ erg s $^{-1}$ cm $^{-2}$ arcsec $^{-2}$. Figure 2 depicts that the thin shell reaches larger heights, but there it emits less efficiently, its H α intensity does not exceed $\sim 10^{-17}$ erg s $^{-1}$ cm $^{-2}$ arcsec $^{-2}$.

In these models, the solar metallicity is assumed both in the disc and in the halo. However, the gas metallicity above one scale height and in the halo is apparently lower than that in the disc and its value varied within $[Z/H] \sim -(0.1\text{--}0.6)$ (e.g. Miller and Bregman 2015, Anderson *et al.* 2016, Hodges-Kluck *et al.* 2018). Spatial variations of metallicity are known also in the disc: in the solar vicinity they can reach about half an order of magnitude (e.g. Luck *et al.* 2006). In order to understand the influence of such variations on to bubble evolution, we

Figure 1: Density slice of a bubble driven by a cluster of 300 SNe located at the midplane at time moment 15 Myr. The gas metallicity is $[Z/H] = 0$.

Figure 2: Density slice of a bubble driven by a cluster of 300 SNe located at 60 pc above the midplane at time moment 15 Myr. The gas metallicity is $[Z/H] = 0$.

Figure 3: $H\alpha$ intensity from a bubble driven by a cluster of 300 SNe located at the midplane at time moment 15 Myr. The gas metallicity is $[Z/H] = 0$.

performed simulations in gas with two times lower metallicity: $[Z/H] = -0.3$. Figures 5 and 6 show the density slices through the bubble expanding in such an under-abundant gas. The bubble driven by a cluster located in the midplane is evolved through the same phases as the one in a gas with $[Z/H] = 0$ (Figure 1) except only that

Figure 4: $H\alpha$ intensity from a bubble driven by a cluster of 300 SNe located at 60 pc above the midplane at time moment 15 Myr. The gas metallicity is $[Z/H] = 0$.

the shell moving into the halo becomes radiative later. This leads to the larger size before the bubble stalls: its maximum height reaches ~ 1.6 kpc. In case the cluster is located out of the midplane at height of 60 pc one additional difference appears. When the shell reaches large heights it is almost dissolved in a gas of the halo. In Figure 6 it is difficult to find an exact border of the shell at large heights.

Figures 7 and 8 show the $H\alpha$ emission maps for $[Z/H] = -0.3$. One can see two separate $H\alpha$ vertical structures consisting of many small filaments, whereas bubbles evolving in solar metallicity gas look like a single structure (Figures 3 and 4). These two structures are obviously connected evolutionarily, but they seem independent due to the upper part of the shell is almost dissolved in low-dense halo. $H\alpha$ structures reach up to ~ 1.2 – 1.6 kpc above the midplane. Their $H\alpha$ intensity is lower than that for solar metallicity gas and it is ranged within $\sim 10^{-17}$ – 10^{-16} erg s $^{-1}$ cm $^{-2}$ arcsec $^{-2}$.

There are several tens of star-forming clusters in galactic disc, some of them are as massive as $M_c \sim 10^4$ – $10^5 M_\odot$. SNe explosions in such clusters are able to drive bubbles, which expand up to ~ 1 – 2 kpc above the midplane. The $H\alpha$ intensity from filamentary structures formed in our simulations ranges within $\sim 10^{-17}$ – 10^{-16} erg s $^{-1}$ cm $^{-2}$ arcsec $^{-2}$. These

Figure 5: The same as in Figure 1, but the gas metallicity is $[Z/H] = -0.3$.

Figure 6: The same as in Figure 2, but the gas metallicity is $[Z/H] = -0.3$.

Figure 8: The same as in Figure 4, but the gas metallicity is $[Z/H] = -0.3$.

Figure 7: The same as in Figure 3, but the gas metallicity is $[Z/H] = -0.3$.

values are close to those observed in NGC 891 (see *e.g.* Boettcher *et al.* 2016). Extraplanar H α structures from several shells overlap each other and form a filamentary shape above discs observed in numerous spiral edge-on galaxies like NGC 891 and so on.

4 Conclusion

In this article, we have considered the H α emissivity of filamentary structures formed in shells of SNe-driven bubbles, which are able to transport a gas to heights of 1–2 kpc above the midplane in the disc with properties like at a radial distance of 3 kpc in a Milky Way like galaxy. We have simulated the evolution of bubbles driven by SNe explosions in a stellar cluster located either in the midplane or above the midplane of the disc. Our results are summarized as follows:

- shells driven by SNe explosions in a stellar cluster of $M_c \sim 4 \times 10^4 M_\odot$ located in the MW-like disc reach maximum height of $\sim 0.6 - 1.6$ kpc above the disc depending on cluster location and gas metallicity;
- these shells form filamentary structures emitting brightly in H α line; the H α surface brightness is ranged within $\sim 10^{-17} - 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$; the values are close

to those observed in edge-on galaxies; the lifetime of filaments is about 10–15 Myr, which corresponds to the time for falling down of a dense extraplanar gas to the disc.

H α emission of extraplanar structures can be, at least partly, explained by recombination in collisionally ionized gas of unstable shells driven by multiple SNe. Diffuse extraplanar gas of edge-on galaxies is well known to carry emission lines of several ions, such as OII, NII, SII (see *e.g.* Rand 1998, Flores-Fajardo *et al.* 2011, Hodges-Kluck *et al.* 2018, Qu *et al.* 2019, Belfiore *et al.* 2021). Interrelations between these lines play an important role in constraining ionization sources of diffuse extraplanar gas. However, they suffer of contaminations from uncertainties connected with metal distributions above the disc. These questions deserve a separate detailed consideration.

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