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ON THE ORIGIN OF THE NEUTRAL HYDROGEN SUPERSHELLS

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ABSTRACT

Here we analyze if the ionized shells associated with giant HII regions represent the progenitors of the larger neutral hydrogen supershells detected in the Milky Way and other spiral and dwarf irregular galaxies. We calculate the evolutionary tracks that 12 HII shells found by Relaño et al. (2005, 2007) would have if they expanded into the interstellar medium because of multiple supernovae explosions occurring inside the cavity. We find, contrary to Relaño et al. (2007), that the evolutionary tracks of these HII shells are inconsistent with the observed parameters of the largest and most massive neutral hydrogen supershells. Thus, an additional energy source to the multiple supernovae explosions is required in order to explain the origin of the most massive neutral hydrogen shells.

Key words : ISM: bubbles — (ISM:) HII regions — ISM: kinematics and dynamics

I. INTRODUCTION

The origin of numerous holes and shells detected in the distribution of neutral hydrogen in spiral and dwarf galaxies (Heiles, 1980; Brinks & Bajaja, 1986; Puche et al., 1992) is a long standing problem (Heiles, 1984; Tenorio-Tagle & Bodenheimer, 1988). The standard model (see review by Bisnovatyi-Kogan & Silich, 1995 and references therein) suggests that the observed structures result from multiple supernovae explosions and stellar winds that occur in young stellar clusters which are often found inside small and intermediate sized shells. In such a case the kinetic energy supplied by supernovae and individual stellar winds is thermalized inside the parental cluster, resulting in a high central overpressure which drives a high velocity outflow, the star cluster wind. This outflow, when interacting with the ambient interstellar medium (ISM), forms a leading and a reverse shock which are separated by a contact discontinuity. The interstellar gas collected by the outer shock forms an expanding shell which cools rapidly to form a neutral shell whose inner skin is photoionized by the Lyman continuum from the embedded cluster. The number of ionizing photons rapidly drops with the star cluster age (Leitherer et al. 1999). This implies that after ~ 10 Myrs the driving cluster (or clusters) will be embedded into a slowly expanding neutral hydrogen shell whose radius and velocity depend on the amount of energy released by the cluster and on parameters of the ambient interstellar medium.

Hundreds of neutral and ionized shells whose radii range from a few tens to a thousand parsecs have been found in the Milky Way and in other galaxies (see, for example, Heiles 1984, Brinks & Bajaja 1986, Puche et al. 1992, Mashchenko et al. 1999, Ehlerová & Palouš 2005; Lozinskaya 1992; Chu et al. 1990; Oey & Massey, 1995; Valdez-Gutiérrez et al. 2001; Nazé et al. 2001; Lozinskaya et al. 2003; Relaño & Beckman, 2005). Many of the detected shells display expansion velocities of 10 – 70 km s^{-1} and are associated with stellar clusters, which favors the standard model for their origin.

While the standard model is broadly consistent with the parameters of many small and intermediate sized shells found around young stellar clusters and OB associations, it meets a profound energy problem when applied to larger structures whose radii are comparable to the characteristic Z-scale of the density distribution in the host galaxy (see, for example, Rhode et al. 1999; Kim et al. 1999; Hatzidimitriou et al. 2005). This has lead to several modifications of the multiple SNe hypothesis (see, for example, McClure-Griffiths et al 2002).

Recently, Relaño et al. (2007) have suggested that the population of the ionized H_α shells associated with large HII regions (Rozas et al. 1996; Relaño & Beckman, 2005) may represent the precursors of the neutral shells with larger radii and smaller expansion velocities. In order to prove this hypothesis they developed a very simplified analytic model and compared their results with the range of observed velocities and masses of the selected neutral shells.

Here we re-analyze the hydrodynamical model presented in Relaño et al. (2007). We show that their over-simplified hydrodynamic equations and their initial

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conditions, which are not consistent with the masses and radii of the largest shells, lead to overestimated expansion velocities and radii of the shells. We conclude that H_α shells associated with large HII regions cannot be the progenitors of the largest HI structures, since their masses, radii and expansion velocities are not consistent with those predicted by the multiple supernovae model.

II. MODEL EQUATIONS

To be consistent with Relaño et al. (2007) we consider here the momentum-dominated stage of the shell evolution (see Koo & McKee 1992). The expansion of the shell is defined then by the conservation of mass and momentum:

$$M = M_0 + \frac{4\pi}{3}(R^3 - R_0^3)\rho_{ISM} + \dot{M}_{SC}(t - t_0), \quad (1)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(Mu) = -4\pi R^2 (P_{ISM} - \rho_w V_\infty^2), \quad (2)$$

where M, u and R are the mass, expansion velocity and radius of the shell, respectively. R_0 is the initial radius of the shell. The first term, M_0, in equation (1) is the initial mass of the shell. The second term is the mass of the interstellar gas swept up by the expanding shell, and the last one is the amount of ejected matter that sticks to the shell from the inside and brings the momentum; t_0 is the initial time. The right-hand part of equation (2) represents the difference between the suppressing ambient gas pressure, P_{ISM}, and the driving ram pressure of the ejecta, $\rho_w V_\infty^2$. $\dot{M}_{SC}$ is the mass deposition rate provided by SNe explosions and stellar winds inside the cluster, $\rho_w(R)$ is the density of the ejected matter when it reaches the shell and V_∞ is the terminal speed of the ejected matter.

It was assumed in equations (1)-(2) that the parameters of the cluster remain constant during the evolution and that the expansion velocity of the shell is much smaller than that of the ejected matter, $u \ll V_\infty$. The mass deposition rate, $\dot{M}_{SC}$, and the density of the ejecta, $\rho_w(R)$, then are:

$$\dot{M}_{SC} = 2L_{SC}/V_\infty^2 \quad (3)$$

$$\rho_w = \dot{M}_{SC}/4\pi R^2 V_\infty, \quad (4)$$

where L_{SC} is the rate of mechanical energy supplied by supernovae and stellar winds.

Combining equations (1) and (2) one can obtain:

$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{4\pi R^2 V_\infty^2 (P_{ISM} + \rho_{ISM} u^2) - 2L_{SC}(V_\infty - u)}{[M_0 + 4\pi\rho_{ISM}(R^3 - R_0^3)/3]V_\infty^2 + 2L_{SC}(t - t_0)} \quad (5)$$

$$\frac{\mathrm{d}R}{\mathrm{d}t} = u \quad (6)$$

One can solve these equations numerically if the initial radius R_0, mass M_0 and velocity u_0 of the shell, the density of the ambient interstellar medium, ρ_{ISM}, and the embedded cluster parameters, L_{SC} and V_∞, are known.

Relaño et al. (2007) find an analytical solution to these equations in the particular case that the density in the HII region is identical to the average density in the ISM, the pressure in the ISM is negligible and all momentum supplied by SNe is injected instantaneously at an early (1 Myr) stage of the shell evolution. We shall drop all these simplifications and solve equations (5) and (6) numerically.

III. INITIAL CONDITIONS

We assume that during ~ 40 Myr (the characteristic life-time of a $8M_\odot$, star - the lowest mass star which will eventually explode as a supernova) the embedded cluster continuously throws away gas released by SNe and stellar winds whose momentum supports the expansion of the outer shell, and that the pressure in the surrounding medium is not negligible.

We start our integration at the same initial time, $t_0 = 10^6$ yr, and with the same initial mass, M_0, as in Relaño et al. (2007), but with initial radii, R_0, and expansion velocities, u_0, derived from the H_α observations of the ionized shells. R_0 is approximately 0.3 times the radius of the HII region (the radius of a wind blown shell in the adiabatic model, according to Relaño et al., 2007), and u_0 is the observed velocity of the H_α shell. For example, in the case of NGC 1530-8, R_0 = 104 pc and u_0 = 64.7 km s^{-1}, respectively. We use the initial mass of the shell, M_0, which is identical to that adopted by Relaño et al. (2007). For example, in the case of NGC 1530-8 it is $M_0 \simeq 8.9 \times 10^4$ $M_\odot$.

We drop then Relaño's et al. assumption that in all cases the progenitor shell evolves within the same ISM whose number density is n_{ISM} = 0.1 cm^{-3} and calculate the density of the ISM using the masses and radii of the HI shells and their progenitors:

$$\rho_{ISM} = \frac{M_{HI} - M_0}{\frac{4\pi}{3}(R_{HI}^3 - R_0^3)} \quad (7)$$

Thus, in our calculations we derive the density of the ISM for each couple of HI and HII shells from their observed parameters. For instance, in the case of GSH 285-02+86, from the list of McClure-Griffiths et al. (2002), the interstellar gas number density would be 0.75 cm^{-3}, if one uses as the progenitor the HII shell N8 found by Relaño et al. (2007) in the spiral galaxy NGC 1530.

The average mechanical luminosity of the embedded cluster has been calculated from the Starburst99 synthetic model (Leitherer et al. 1999) under assumption of the instantaneous burst of star formation. The average mechanical luminosity of the cluster then is:

$$L_{SC} = E_{SW+SN}/\tau, \quad (8)$$

where we choose τ = 10 Myr.

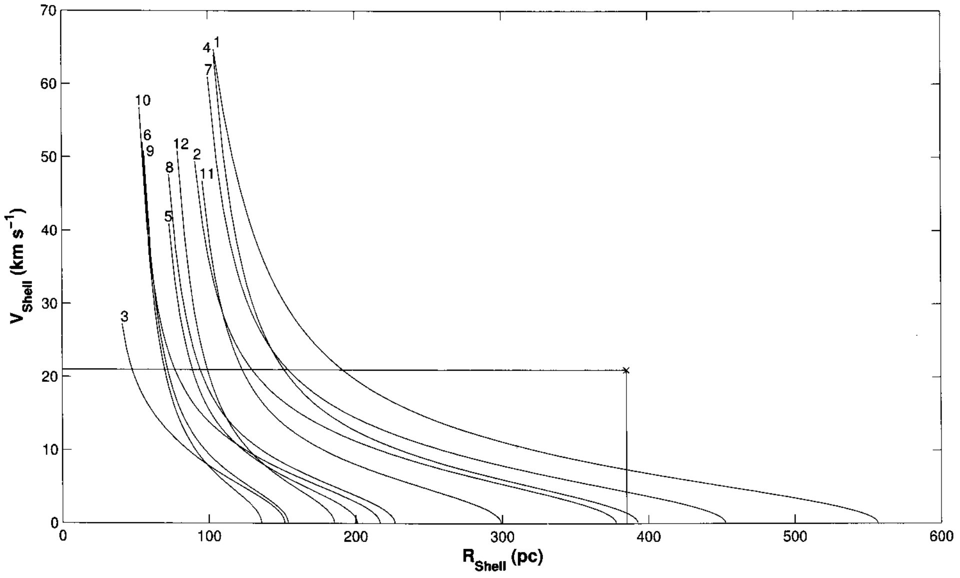

Fig. 1.— The comparison of the model predicted expansion velocities with the observed values. The results of the calculations are compared a high mass object from the list of McClure-Griffiths et al. (2002), namely GSH 285-02+86. Different lines correspond to the different initial conditions associated with 12 HII progenitor shells from the list of Relaño et al. (2007). The lines are labeled with the numbers that identify the progenitor shells in Table 1. The observed velocities and radii of the HI shell are marked by the horizontal and vertical lines, respectively. A 1500 km s^{-1} star cluster wind terminal speed was adopted for all calculations. A larger value of the terminal speed would result in even smaller predicted expansion velocities.

It was assumed that the temperature of the interstellar medium is T_{ISM} = 6000K which is a typical value in the warm neutral component of the ISM (Brinks, 1990). The thermal pressure in the ambient medium then is $P_{ISM} = k\ n_{ISM}\ T_{ISM}$, where k is the Boltzmann's constant and $n_{ISM} = \rho_{ISM}/m_H$ is the interstellar gas number density obtained from equation (7).

The last input parameter for our model, the terminal speed of the star cluster wind V_∞, is determined by the energy and mass deposition rates, and is close to the terminal velocity of individual stellar winds (Raga et al. 2001, Stevens & Hartwell 2003). We assume for our calculations that the star cluster wind terminal speed is constant and falls in the range 1500 – 3000 km s^{-1} (e.g., Leitherer at al. 1999).

IV. RESULTS

One can calculate now the evolutionary tracks for the HII shells associated with the large HII regions and compare them with the observed parameters of the HI shells. The results of the calculations are presented in Figure 1 and in Table 1.

Figure 1 compares the evolutionary tracks of the HII shells with parameters of the GSH 285-02+86 supershell found by McClure-Griffiths et al. (2002) in the Milky Way. In this case only the three most energetic progenitor shells (NGC 1530-8, NGC 3359-6 and NGC 6951-2) can reach the size of the HI supershell having a mass comparable to the observed value. However, in all these cases the model predicted velocity is too small to be associated with that measured by McClure-Griffiths et al. (2002).

Thus we found that it is easy to fit parameters of the less massive HI objects, indeed. It is also possible to fit the observed sizes, masses and expansion velocities of the intermediate-sized HI shells if one considers the most energetic HII shells as their progenitors. However this is not possible for the largest HI shells whose masses are of the order of several million solar masses. This implies that some additional physical mechanism is required in order to understand the origin of the largest neutral hydrogen supershells and fit simultaneously all their observed parameters: their masses, radii and expansion velocities.

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TABLE 1.
MODEL PREDICTIONS

ID	NAME	M $10^5 M_\odot$	R pc	V kms^{-1}
OBSERVED PARAMETERS				
	GHS 285–02+86	44	375 – 395	21
PREDICTED PARAMETERS				
1	NGC 1530–8	44	385	7.4
2	NGC 1530–22	42	378	0.1
3	NGC 1530–92	27	152	0.0
4	NGC 3359–6	44	385	1.4
5	NGC 3359–42	6.2	201	0.1
6	NGC 3359–92	1.9	136	0.0
7	NGC 6951–2	44	385	4.3
8	NGC 6951–18	9.0	227	0.0
9	NGC 6951–41	2.8	154	0.0
10	NGC 5194–312	7.9	217	0.1
11	NGC 5194–403	21	299	0.1
12	NGC 5194–416	4.8	185	0.1

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