THE EVOLUTION OF SUPERNOVA REMNANTS IN A NON-UNIFORM MEDIUM: THE FATE OF AN EVOLVING OB ASSOCIATION

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Abstract: We study the effect of multiple supernova explosions in a non-uniform interstellar medium using a two dimensional hydrodynamical code (axial symmetry assumed). Cooling effects were included. In a uniform medium two or more supernovae exploding at the same place but at different times result in a remnant with less energy than the sum of the individual explosion energies - when cooling effects are important. As a case of special interest the evolution of an OB association with many massive stars experiencing supernova explosions is presented. We show that it is difficult to produce large supershells with multiple supernovae alone, even if the sum of their explosion energies appear to be sufficient. The existence of a giant HII region preceding the explosions does not alter this conclusion. Other mechanisms should be considered to produce supershells.

1. INTRODUCTION

Several mechanisms for the production of HI shells and supershells, as observed and discussed by Heiles (1979, 1983), have been considered by a number of investigators. Tomisaka et al. (1981), Bruhweiler et al. (1980) and Kafatos et al. (1980) for example maintain that sequential (multiple) supernova explosions arising from an OB association can explain their existence. In the latter two papers the effect of stellar winds preceding the explosion are also considered. Tenorio-Tagle (1981) and Tenorio-Tagle et al. (1981) show that high velocity, high latitude HI clouds colliding with the galactic disk can produce such supershells with the observed characteristics. Originally, Heiles (1979) thought the supershells could be produced by a single explosive event (a Type III supernova?).

In the following consider the effect of supernova explosions within an OB association. We have assumed a stratified interstellar medium with a scale height of 150 pc and a density $n = 1 \text{ cm}^{-3}$ at the symmetry plane ($z = 0$). These are values typical for our Galaxy at a distance of 10 kpc from the center (Paul, et al. 1976). We first allow the UV photons from the OB association to ionize the surroundings and we follow the evolution of the resulting HII region. The time dependent UV flux was calculated

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assuming 2 10^4 stars distributed in mass according to Salpeter's initial mass function (slope: 2.45), described in more detail in Beltrametti et al. (1982). The association has about 20 stars more massive than 17 $M_{\odot}$ and 180 stars in the range 8 $M_{\odot} \leq M \leq 17$ $M_{\odot}$ (see Ostriker et al. 1974). After 7.27 million years we allowed the 20 massive stars to explode simultaneously, each with 10^{51}erg. At 9.47 million years the remaining 180 OB-stars exploded, again each with 10^{51} erg.

2. THE NUMERICAL MODEL AND SOME TESTS

We use the 2-D hydrodynamic code (with some modifications) discussed by Bodenheimer et al. (1979). The version of the code which includes supernova explosions is also used by Tenorio-Tagle et al. (1983) and Yorke et al. (1982). Numerical tests performed with the code are to be discussed in a forthcoming paper (Bodenheimer et al. 1982). Here we shall summarize some of the test results.

We place a bubble of hot gas with 10^{51} erg thermal energy and mass 1 $M_{\odot}$ in a medium of uniform density. During the subsequent expansion the remnant remains spherically symmetric; the increase of radius with time agrees very well with the solutions presented by McKee and Hollenbach (1980) for the expansion of a supernova remnant with and without cooling. We have performed tests in which we allow multiple explosions in a uniform medium. When two explosions occur within 10^4 years, the shock front of the second explosion merges with that of the first while the original remnant is still in its adiabatic phase. The expansion of the resulting remnant approaches the solution for a single 2 10^{51} erg explosion. When three explosions occur separated by 10^4 years, the solution for a 3 10^{51} erg explosion is attained. When, however, the two explosions occur within 10^5 years, cooling within the first remnant is important. The expansion falls short of the 2 10^{51} erg solution (see Fig. 1).

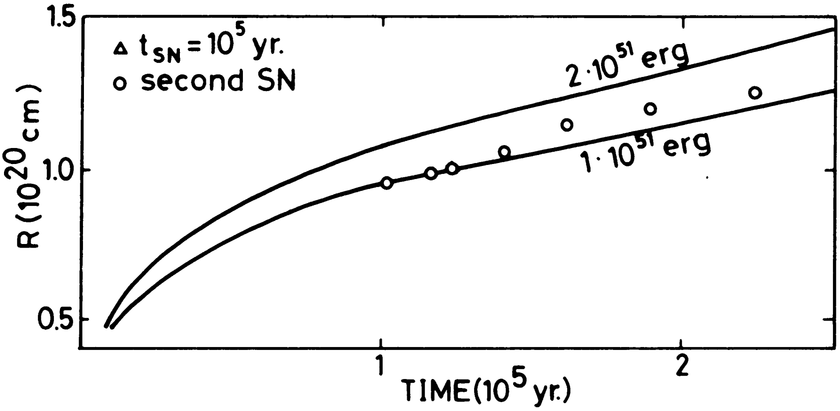

Fig. 1. The radius of supernova remnants as a function of time. The solid curves show the solutions of McKee and Hollenbach for explosions of the indicated energy in a constant density ($n = 1$ cm^{-3}) medium including the effects of cooling. The open circles show the solution for two explosions of 10^{51} erg spaced 10^5 years apart.

3. THE RESULTS

Figure 2a shows a cross-sectional view of a stratified galactic disk with parameters (scale height and density) typical of a 10 kpc galactocentric radius, shortly after an OB association is born at the galactic plane. The density contours (solid lines) mark the decrease in density ($\Delta/\log\rho = 0.5$) and the boundary between the disk and a constant density halo ($\sim 1.6 \times 10^{-28}$ gm cm^{-3}). The ionizing photon output from the cluster of 2×10^{51} photons s^{-1} produces a giant HII region which, due to the stratification, expands mainly in the direction normal to the plane. As a result the disk becomes distorted as shown in figure 2b. At $t = 7.3 \times 10^6$ yr, the most massive stars in the cluster become supernovae. Note that the decrease in ionizing radiation, a consequence of stellar evolution, has led to the recession of the ionization front and to a large expanding ring of neutral gas with a radius of 400 pc and a thickness of 50-100 pc. (see figure 2b)

The first explosion with a total energy of 2×10^{52} ergs was followed after 2.5×10^6 yr by a second explosion of 1.8×10^{53} ergs caused by 180 stars in the cluster with masses between 8 $M_\odot$ and 17 $M_\odot$ - typical of an OB association. Figure 2c shows the resultant flow, i.e. a single, almost spherical, shell expanding with a velocity $\lesssim 100$ km s^{-1}. Note that the dimensions of the original HII region are much larger than the present dimensions of the supernova remnant. Furthermore, even if one assumes that the velocity of the shell remains constant, it would require further 10^7 yr to catch up with the undisturbed galactic disk and acquire the dimensions typical of supershells (see Heiles 1979). However, after such a long time differential galactic rotation would have distorted them, making it hard to explain their usual round appearance.

One can therefore conclude that in order to construct a supershell the required energy should be deposited all at once. This, however, seems to rule out supernova explosions as it would imply a very unusual initial mass function for the stellar cluster. Therefore other mechanism(s) should be considered to explain the formation of super/rings and supershells.

ACKNOWLEDGEMENT

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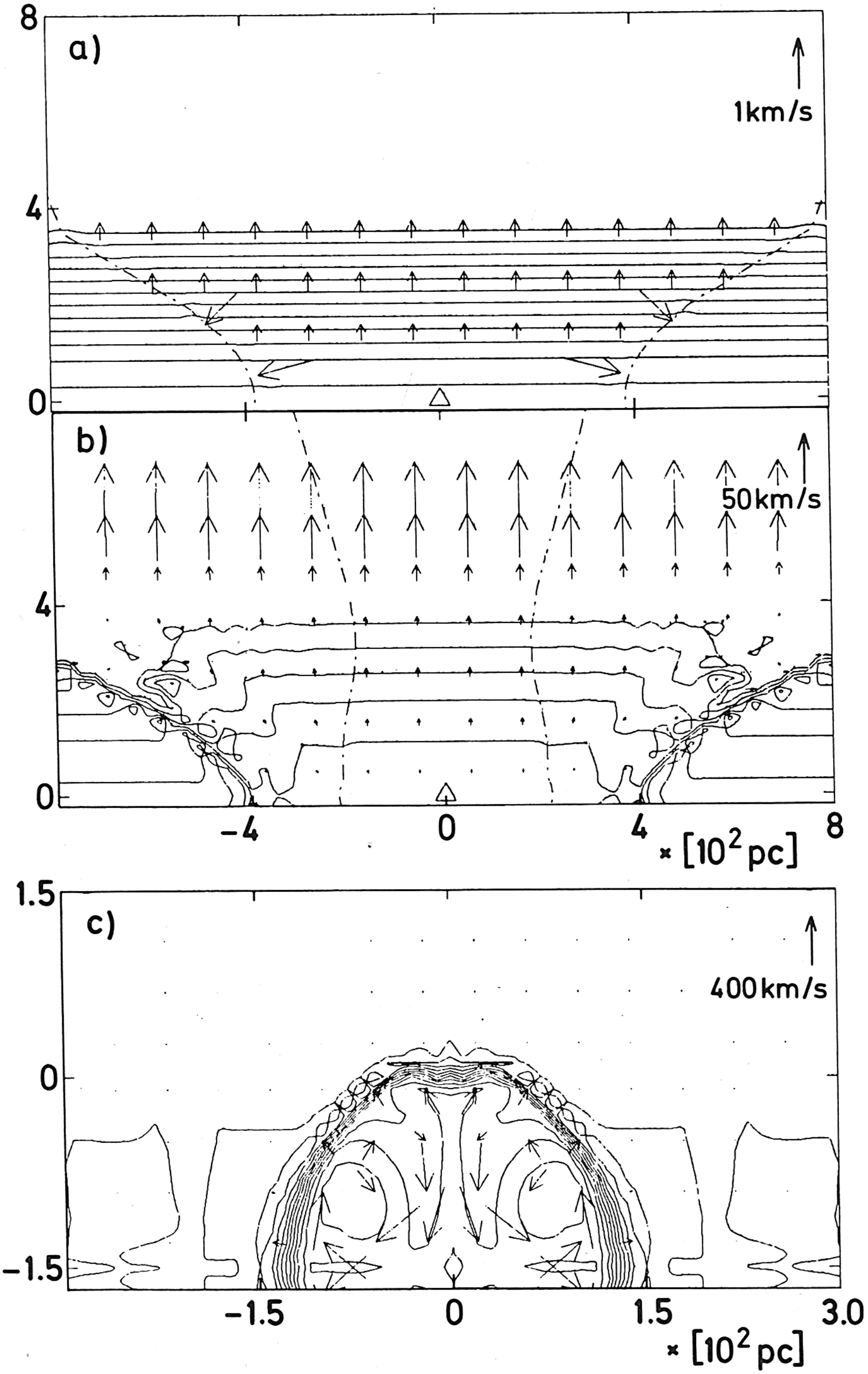
a)
1km/s
8
4
0
b)
50km/s
4
0
-4
0
4
8
x [10^{2}pc]
c)
400km/s
1.5
0
-1.5
-1.5
0
1.5
3.0
x [10^{2}pc]

Figure 2

Figure 2. The Gas Dynamics around an OB Association.

a) Cross-sectional view of the galactic disk shortly after the birth of the OB-association (triangle). The interstellar medium is stratified with a scale height of 150 pc and has a density of 1 cm^{-3} at the symmetry plane. The density contours are shown. The UV photons of the association have ionized the medium inside the dotted line. The length of the arrows are proportional to the gas velocity.

b) Same as in figure 2a at t = 7.27 million years. The ionization front has receeded since the most massive stars have moved away from the main sequence and soon will become supernovae.

c) Enlargement of the region around the OB-association at t ∿ 10 million years.

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DISCUSSION

MONTMERLE: 1) What kind of IMF did you use, and how sensitive are your results to the adopted spectral index? 2) With so many massive stars, you would expect SN explosions to take place in low-density cavities created by their stellar winds. Did you take this effect into account?

YORKE: 1) We adopted the Salpeter IMF with slope $\alpha=2.45$. We also computed the UV flux of an OB association with an IMF of $\alpha = 2$ and 3. We find that the rate at which the UV flux decreases as the association ages is almost identical, so that we expect the same behaviour of the HII region prior to the SN explosions. An association with $\alpha=2$ has ∿5 times more massive stars than an association with $\alpha=2.45$ provided that the total number of stars stays constant. Five times more energy would not lead to the formation of superrings.

2) The energy deposited into the gas by the ionizing flux of the OB association is greater than $6 \cdot 10^{54}$ ergs, while the energy released by stellar winds produced by 28 B0 stars with -10^{-6} M_o/yr each lasting $3 \cdot 10^6$ yrs and wind velocities of $2 \cdot 10^3$ km/sec (Bruhweiler et al., 1980) is ~ $7 \cdot 10^{50}$ ergs. Therefore, the evolution of the H II region prior to the SN explosions has greater influence on the environment of the association. Furthermore, there is still no proof that such strong winds operate during the whole lifetime of the stars. Therefore we believe that stellar winds produce only a negligible effect compared to supernovae explosions and the H II region evolution.

GULL (T.R.): 1) Did you include stellar winds in your model? 2) Why do you wait so long before your model allows SNs to occur? 3) Did you consider closer and more distant radii from the Galactic Center?

YORKE: 1) We did not include stellar winds and as stated above we do not believe to neglect an important effect.
2) According to recent stellar evolution calculations (Weaver et al., 1978, Ap.J. 225, 1021) massive stars ($15\ M_o < M < 25\ M_o$) become SN after $7 \cdot 10^6$ years.
3) Calculations already exist and will be presented in a future paper.