POINT EXPLOSION WITHIN A CAVITY WITH A POWER-LAW DENSITY DISTRIBUTION

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ABSTRACT. An exact analytic solution based on the Kompaneets approximation is found for a shock wave expansion from a point explosion within a pre-existing interstellar gas cavity with a power-law gas density distribution. An obvious shock deviation from the spherical symmetry is revealed for the off-center explosion. It is assumed this may give a reason for the complex morphology that is observed in some supernova remnants.

Key words: Shock waves: supernova remnants: interstellar medium.

1. Introduction

Massive stars, precursors of types II and Ib supernovae (SN), intensively lose mass during their evolution. The ejecta velocities reach 2000 km s^{-1}, and the mass loss rate is 10^{-5} - 10^{-7} $M_{\odot}$ yr^{-1}. Energetic stellar winds push powerful shock waves through an ambient interstellar medium (ISM), and produce large cavities, which are surrounded by the dense shells, and are filled with a hot, low density gas. The characteristic scale of the cavities around massive star clusters may be compatible or even exceed the characteristic thickness of the galaxy gas layer and reach several hundred parsecs (Heiles, 1982). Thus, one could expect that many SN explosions occur within a pre-existing interstellar gas cavities. This rises the problem of a point explosion inside a cavity with a *radially-increasing* density distribution (Cox D.P. & Franco J., 1981). A general problem is not a spherically-symmetric because a precursor star proper motion with respect to the ISM. A propagating star formation (Palouš et al., 1994) with the young HII regions at the large-scale cavity edge is an another reason for the off-center energy deposition.

In the current consideration we use Kompaneets (1960) approximation. The shape of the shock front then follows from the equation (Korycansky, 1992):

$$\left(\frac{\partial\theta}{\partial y}\right)^2 = \frac{\rho_0}{\rho}\left[\left(\frac{\partial\theta}{\partial r}\right)^2 + \frac{1}{r^2}\right], \qquad (1)$$

where r and θ are spherical coordinates, y is the dimensionless time, and ρ is the ambient gas density distribution.

2. The input model and it's limitation

For simplicity, here we assume a power-law density distribution within a cavity and ambient medium. For expanding, rather young cavity the initial gas density distribution is assumed to be

$$\rho(r) = \begin{cases} \rho_0\left(\frac{r}{R_0}\right)^n, & r < R_0, \\ \rho_0\left(\frac{r}{R_0}\right)^m, & R_0 < r < R_1, \\ \rho_{ism}, & r > R_1, \end{cases} \qquad (2)$$

where R_0 and R_1 are the shell inner and outer radii, ρ_0 and ρ_{ism} are the shell maximum and the interstellar gas densities, $n > 0$ and $m < 0$.

For an old, stall cavity, shell gets thicker, and disperses within an ambient medium. In this case we assume the initial density profile to be flat out of cavity, and reads as

$$\rho(r) = \begin{cases} \rho_0\left(\frac{r}{R_0}\right)^n, & r < R_0, \\ \rho_0, & r > R_0, \end{cases} \qquad (3)$$

where index $n > 0$, R_0 is a cavity radius, and $\rho_0 = \rho_{ism}$ is the ISM gas density.

Four characteristic times (or length scales) are relevant to the problem discussed (Brighenti & D'Ercole, 1994). The main sequence lifetime (McKee et al. 1984):

$$t_{ms} = 4.4 \times 10^6 L_{36}^{-1/6}\, yr, \qquad (4)$$

where L_{36} is the mechanical input rate in the 10^{36}erg s^{-1} units.

The wind-blown cavity cooling time (Mac Low & McCray, 1988)

$$t_{cool} = 4.6 \times 10^6 \xi^{-35/22} n_{ism}^{-8/11} L_{36}^{3/11} yr, \qquad (5)$$

where ξ is the hot gas metallicity with respect to the solar one, and n_{ism} is the ambient ISM gas density. Later on it is assumed through out the paper that $t \leq t_{cool}$, e.g. that hot inner gas cooling rate is negligible, and density drops from the contact discontinuity to the bubble center. This puts a limit to the external gas density n_{ism}:

$$n_{ism} \leq 1.06 \xi^{-36/16} L_{36}^{1/2} cm^{-3}. \qquad (6)$$

When the inner bubble pressure equals with the external gas thermal pressure, the bubble stalls at a characteristic time t_{stop}

$$t_{stop} = 2.2 \times 10^6 (L_{36}/n_{ism})^{1/2} a_{10}^{-5/2} yr, \qquad (7)$$

where a_{10} is the external gas sound speed in the 10 km s^{-1} units. This characteristic time defines the transition to a subsonic motion, and the onset of the shell dispersion: The comparison of equations (7) and (4) shows, that SN explosion occurs before shell dispersion if $n_{ism} < 0.25 L_{36}^{4.2}/a_{10}^{-5}$.

Once the hot bubble interior was formed, a subsequent blast wave may to become subsonic at the fractional radius $x_{sound} = r_{sound}/R_0$ (Mac Low & McCray, 1988). For the main sequence lifetime t_{ms} this value reads as

$$x_{sound}(t_{ms}) \approx 1.2 L_{36}^{-5/36}. \qquad (8)$$

Thus, if the bubble is formed by a single star, the gas motion at the edge of the cavity remains supersonic only for low-energetic winds. Note that for O6 stars $L_{36} \approx 1.27$ (Brighenti & D'Ercole, 1994).

The mass of the hot bubble interior may be expressed at the different characteristic times as follows:

$$M(R_{ms}) = 263 n_{ism}^{2/15} L_{36}^{101/210} \mathrm{M}_\odot, \qquad (9)$$

$$M(R_{stop}) = 119 \left(\frac{L_{36}^{19}}{n_{ism}^{9} a_{10}^{41}} \right)^{1/14} \mathrm{M}_\odot. \qquad (10)$$

Equations (9)-(10) show that $10^2 - 10^3$ $\mathrm{M}_\odot$ may be evaporated into a cavity before the explosion. Thus remnant may get the Sedov stage, especially if explosion occurs at the edge of the cavity which is created by a massive star cluster.

3. The results of the calculations

Equation (1) may be solved analytically for some particular density distributions with the complete integral method (Silich & Fomin, 1982; Kontorovich & Pimenov, 1998). Figures 1a and 1b show the resulting shock wave morphologies for a shell-like density profile (2). In the both cases explosion position is indicated by a cross. It occurs nearby a density ridge (dashed line circles), at the distance $a = 0.7R_0$ (figure 1a) or $a = 0.9R_0$ (figure 1b) from the cavity center. The inner pre-existing bubble structures are identical, and assume a power-law density profiles (2) with the power-law index $n = 2$. However, the ISM gas densities are assumed to be quite different. The first model corresponds to the bubble expansion within a homogeneous ISM. The ratio of the pick to the interstellar gas density equals to $\rho_0/\rho_{ism} \approx 4$, and density gets the ISM value immediately after the density pick, at $R_1 = 1.2R_0$. The second solution may be applied for a bubble expansion within a medium with a fast density drop. In this case $\rho_0/\rho_{ism} \gg 1$, and density gets the ISM value much later, at $R_1 = 4R_0$. This corresponds approximately to the expected sharp density drop in the gaseous halo of the starburst galaxy VII Zw403, which exhibits the elongated kpc-scale X-ray emitting extensions (Papaderos et al. 1994). The deviation from the spherical symmetry is obvious for both of the models. Obviously, it is more prominent for the ISM with a sharp density gradient. However, to produce a very elongated shock structure, which is similar to the X-ray morphology of the VII Zw403, one needs a very

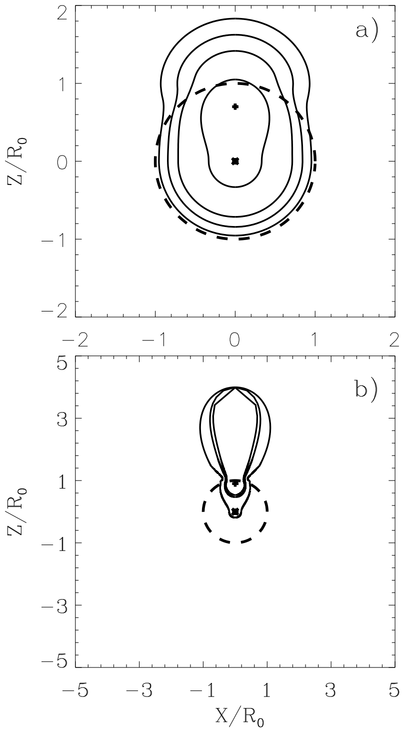

Figure 1: Shock morphology for a shell-like density distribution. a) Shock shape time evolution: $a = 0.7R_0$, $n = 2$, $R_1 = 1.2R_0$, and $m = -8$; b) Shock shape for different external gas density gradients: $a = 0.9R_0$, $n = 2$, $R_1 = 4R_0$, and $m = -8, -12, -14$.

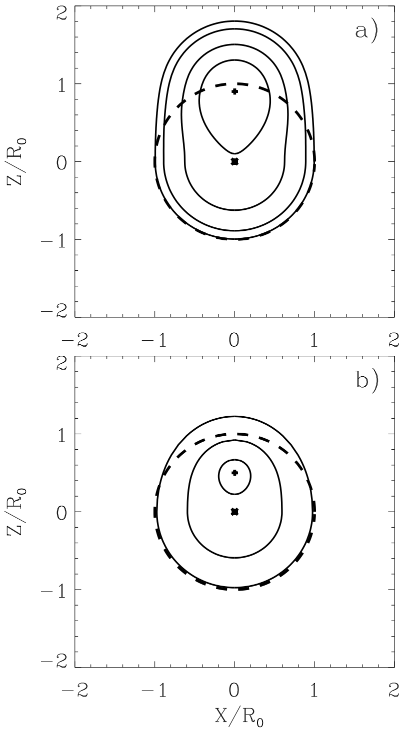

Figure 2: Shock morphology for old cavity density distribution. a) $a = 0.9R_0$, $n = 2$; b) $a = 0.5R_0$, $n = 2$.

sharp density gradient with an unacceptably low halo gas density (the halo to the ridge gas density ratio equals to $\rho_{ism}/\rho_0 = 1.4 \times 10^{-5}$, 5×10^{-8} and 3×10^{-9} for $m = -8$, -12 and $m = -14$).

The results of the calculations for the point explosion within the old cavity are shown in the figures 2a and 2b. Figure 2a represents shock morphology for the edge on explosion ($a = 0.9R_0$). Shock shape for the modest displacement of the explosion point ($a = 0.5R_0$) is shown in the figure 2b. The gas density distribution within the cavities are the same as in the previous cases, with a power-law density profile (2), and $n = 2$.

In the case 2a shock blows out of the nearest cavity wall soon after explosion, and forms a well defined cylindrical shape, whereas in the case 2b the remnant morphology remains almost spherically throughout the calculations.

4. Conclusions

- The off-center point explosion within a cavity with a radially-stratified density distribution can produce a variety of non-spherical remnants, even if the external gas density is homogeneous.
- The ultimate shock morphology depends strongly on the explosion position within a cavity and the external gas distribution. Energy deposition at the edge of the pre-existing cavity can produce an elongated remnant. However it is difficult to believe that this mechanism is responsible for the large scale extensions in the VII Zw403 because it predicts too high density gradients, and unreasonably low galaxy halo gas density.

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