

Using Numerical Simulations to Gain Insight into the Structure of Superbubbles

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Abstract. Recent high resolution observations of Galactic superbubbles have motivated us to re-examine several classes of superbubble models. We compare three classes of hydrodynamic models (the Kompaneets approximation, the thin shell model, and numerical simulations) in order to understand the structure of superbubbles and to gain insight into observations. In particular, we apply models to the W4 superbubble, which has been observed in the Pilot project of the arcminute resolution Canadian Galactic Plane Survey (Normandeau et al. 1996). Magnetohydrodynamic simulations are also performed and point the way to a fuller understanding of the W4 superbubble. We suggest that the highly collimated bubble and apparent lack of a Rayleigh-Taylor instability in the superbubble shell can be explained by the presence of a magnetic field.

1. Introduction

In a recent paper, Basu, Johnstone, & Martin (1999) have modeled the shape and ionization structure of the W4 superbubble (see Normandeau & Basu, these proceedings) using the semianalytic Kompaneets (1960) model for blast wave propagation in a stratified exponential atmosphere. Our motivation in this paper is to compare the simplified Kompaneets model with more sophisticated models for superbubble expansion in a stratified medium. Our study reveals the differences between the various models, but also shows that the more detailed hydrodynamic models face difficulties in properly accounting for the shape of the W4 superbubble. However, the highly collimated W4 superbubble may be fit by numerical models which include a magnetic field with a significant vertical (perpendicular to the Galactic plane) component.

2. Comparison of Hydrodynamic Models

We compare three classes of models for superbubble expansion in stratified media. The earliest one is due to Kompaneets (1960), and describes the propagation

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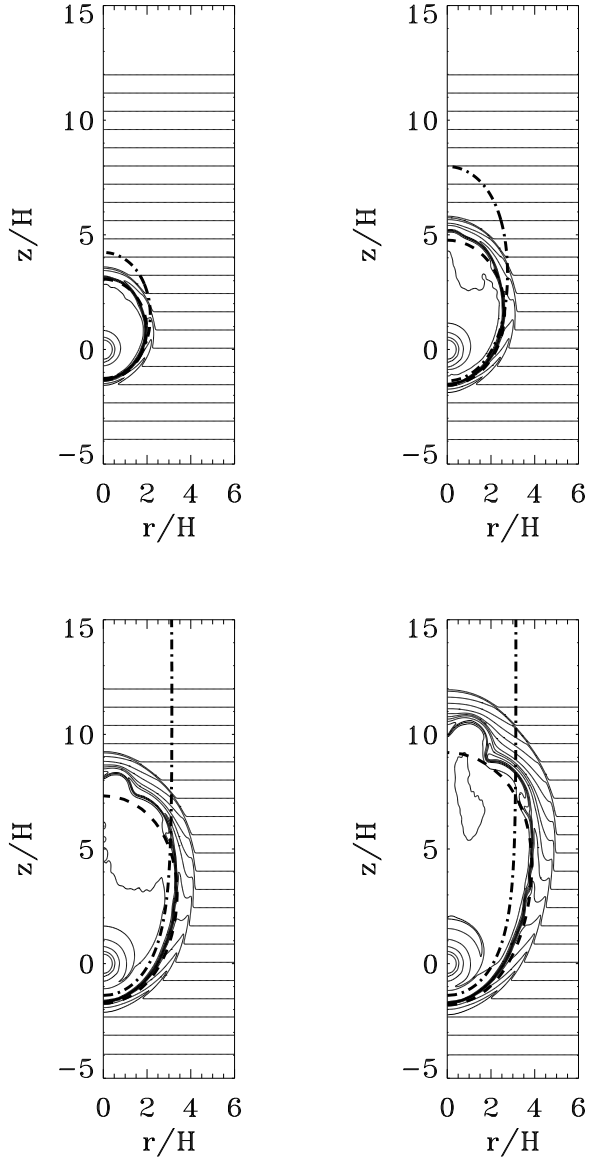


Figure 1. A comparison of numerical simulations (solid density contours; logarithmically spaced) with the position of the shell in the Kompaneets (dash-dotted line) and thin shell approximation (dashed line), for an exponential atmosphere $\rho(z) = \rho_0 \exp(-z/H)$. The four snapshots occur at dimensionless times 4.36, 6.36, 8.37, and 9.33. The unit of time is $[t] = (\rho_0 H^5 / L_0)^{1/3}$, where L_0 is the wind luminosity.

of a strong shock wave in an exponentially stratified medium. An analytic solution exists for the bubble shape at different times, and the time evolution is obtained by solution of an ordinary differential equation. The thin shell approximation (MacLow & McCray 1988) assumes a geometrically thin shell and determines its motion by direct integration of the momentum equation for various segments of the shell. Finally, numerical simulations (e.g., MacLow, McCray, & Norman 1989) provide the most complete hydrodynamic solutions. We reproduce all three calculations for an adiabatic bubble in an exponential atmosphere. The numerical simulations are performed with the ZEUS-2D code.

Figure 1 compares the shape of the bubble at four different times for the three cases. The solid density contours represent the numerical solution. The Kompaneets model (dash-dotted line) expands most rapidly and assumes a more elongated shape than the other models. Its more rapid evolution means that it has already blown out of the atmosphere in the two lower panels. The thin shell approximation (dashed line) remains close to the inner boundary of the shell of swept-up mass in the numerical solution. The closeness of the thin shell and numerical results occurs since the thin shell model tracks the motion of the swept up mass. The numerical solution is also prone to a Rayleigh-Taylor instability at late times, when the upper shell is accelerating rapidly. We note that the Rayleigh-Taylor instability would be more pronounced if cooling was allowed in the shell (MacLow et al. 1989). An important difference between the models is that the Kompaneets model is more highly collimated before blowout than the other two models, since the vertical acceleration is unhindered by inertial effects, and occurs very rapidly.

3. Magnetohydrodynamic Model

Due to the inertial effects mentioned above, the numerical hydrodynamic and thin shell results cannot produce highly collimated bubbles that meet the aspect ratio of the W4 superbubble, even though the less realistic Kompaneets model can do so. From H α observations of the ionized shell (Dennison, Topasna, & Simonetti 1997), we measure an aspect ratio $\frac{z_{\text{top}}}{r_{\text{max}}} \simeq 3.3$, where z_{top} is the distance from the star cluster to the top of the bubble, and r_{max} is the maximum half width of the bubble. We have attempted a variety of atmospheric models in the numerical and thin shell models, and find that neither a steeper nor shallower profile than the exponential stratification can explain the high collimation of the W4 superbubble.

We address this issue by carrying out magnetohydrodynamic (MHD) simulations. A vertical (along z) magnetic field provides the necessary external pressure at large heights to confine the bubble to a narrow width. Figure 2 shows the evolution of the bubble in an exponential atmosphere with an initial vertical magnetic field $B_z = 3 \mu\text{G}$. At the latter time, the aspect ratio of the bubble matches the observed aspect ratio of the H α shell.

4. Discussion

Although the Kompaneets model can provide a highly collimated bubble that matches the aspect ratio of the W4 superbubble, more realistic hydrodynamic

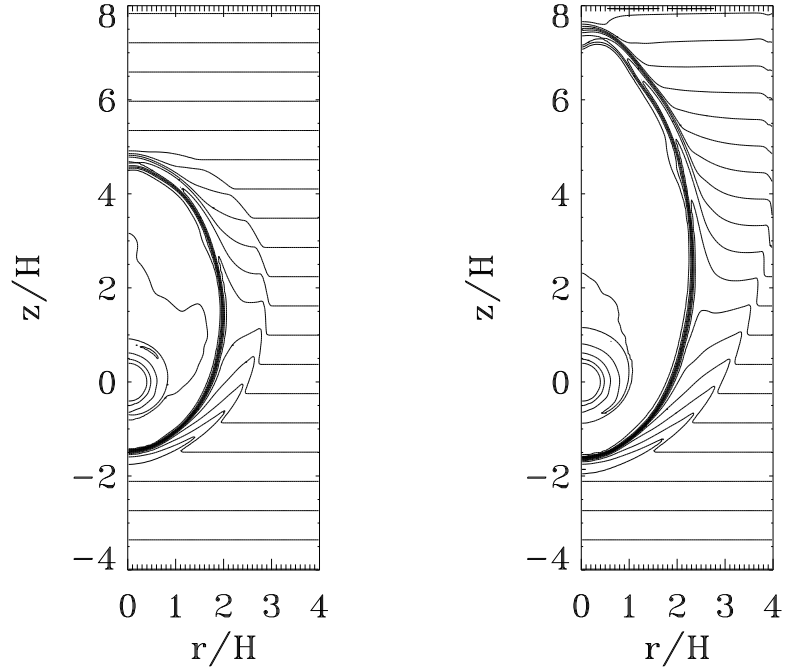


Figure 2. MHD model. Density contours of the expanding superbubble in an exponential atmosphere with an initially vertical magnetic field $B_z = 3 \mu\text{G}$. Dimensionless times are 5.35 and 6.77, where the unit of time is the same as in Fig. 1.

models predict wider bubbles than observed in W4, due to their proper accounting of inertial effects. However, a numerical model which includes a vertical magnetic field of a few μG strength can achieve the required collimation. We believe that such a field can also suppress the potential Rayleigh-Taylor instability in the accelerating upper shell, thereby explaining why the observed $\text{H}\alpha$ shell of the W4 superbubble does not appear to be breaking up. Although a purely vertical field is an idealization and is not supported by Faraday rotation data, we point out that even an initially horizontal magnetic field can produce a significant vertical component through the action of the Parker instability (e.g., Basu, Mouschovias, & Paleologou 1997). More realistic magnetic field geometries such as these remain to be explored.

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