The Magnetic Collimation of Bipolar Outflows I: Adiabatic Simulations

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Abstract

The collimation of an isotropic, non-magnetic protostellar wind by an ordered magnetic field in the ambient medium is investigated using self-consistent magnetohydrodynamic simulations in two-dimensions. The strong protostellar wind inflates a low density bubble in the ambient medium. The growth of this bubble is confined along the direction of the ambient magnetic field when the gas pressure in the interior drops to the level of the magnetic pressure at the surface. For typical molecular cloud conditions, collimation of the protostellar wind into a bipolar outflow occurs on timescales of $10^4 - 10^5$ yrs. When a self-consistent model for a magnetically supported cloud is used as a more realistic initial condition, the wind blown bubble can "blowout" along diverging field lines in the direction of the steepest density gradient.

Subject headings: ISM: jets and outflows - radio lines: molecular: circumstellar - stars: pre-main-sequence

1 Introduction

Observations have firmly established that energetic mass outflows are a ubiquitous consequence of the late stages of star formation (see Lada 1985; 1988; Welch *et al* 1985; and Snell

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1987 for recent reviews). Normally such outflows are identified by the presence of high velocity wings in molecular emission line observations in regions associated with deeply embedded infrared sources and classical T Tauri stars. High resolution mapping of these regions has revealed that the outflow is usually collimated into two oppositely directed (bipolar) streams. The length to width ratio of most sources lies between one and six, with the average value being 2.4 (Lada 1985). In addition to these poorly collimated molecular bipolar outflows, some star forming regions are the source of protostellar jets: small scale, high velocity, highly collimated ionized outflows which are observed at optical wavelengths (Mundt 1985, Mundt *et al* 1987). A prototypical example of a mass outflow from a star forming region is the source L1551-IRS5 which has been extensively studied at multiple wavelengths (see, *e.g.* Moriarty-Shieven *et al* 1987 and references therein). This source contains both a bipolar outflow and a protostellar jet emanating from a deeply embedded infrared source.

With the wealth of observational data available, a detailed *kinematic* picture of bipolar outflows is emerging. Currently, the observational data is consistent with a model in which the molecular emission arises in a dense shell of ambient molecular gas swept up by a strong protostellar wind. Herbig-Haro objects and water masers are thought to be associated with the interface between the dense shell and the cavity evacuated by the high velocity wind. Recently, direct observation of velocity neutral atomic (Lizano *et al* 1988) and molecular (Koo 1989) protostellar winds have been reported.

While the evidence for this kinematic model of bipolar outflows is compelling, the theoretical understanding of their *dynamics* is still rudimentary. Fundamental questions such as what drives the outflow, what collimates it, and what are the consequences of the outflow on the star formation process and the parent molecular cloud as a whole are yet to be fully resolved. For example, although a consensus is emerging that magnetohydrodynamic (MHD) processes are most likely responsible for driving these outflows, it remains controversial as to whether they are launched by the protostar itself (Hartmann and MacGregor 1982, Draine 1983, Shu *et al* 1988) or its surrounding accretion disk (Pudritz and Norman 1983; Uchida

and Shibata 1985, Königl 1989). For these reasons, we have begun a comprehensive project (Stone 1990) to apply realistic numerical simulations to further our understanding of the dynamics of mass outflows from star forming regions. In this paper, we report on self-consistent MHD simulations we have performed which focus on the question of the collimation of bipolar outflows. In particular, we examine the possibility that an isotropic protostellar wind may be collimated by an ordered magnetic field in the ambient medium.

The idea that magnetic fields might contribute to the collimation of protostellar outflow is not new. For instance, in a paper primarily concerned with interpreting the collimation of bipolar outflows as due to anisotropic density and pressure distributions in the ambient medium, Königl (1982) suggested the possibility that large scale ordered magnetic fields could also provide collimation. There is considerable observational evidence to support this conjecture. Magnetic field strength measurements near bipolar outflows reveal that these fields are strong enough to be dynamically important (Heiles 1987). Perhaps the most compelling piece of evidence, however, is the observation that more than 70% of the outflows are aligned within 30° of the ambient magnetic field direction as determined by optical polarization studies (Strom and Strom 1987). Moreover, when protostellar disks are resolved, their minor axes are usually aligned with the local magnetic field direction, suggesting that the ambient magnetic field in these regions is determining the orientation of the disks (*e.g.* through magnetic braking effects, Mouschovias and Paleologou 1980) and the direction of the subsequent outflow. In this paper, we will perform a detailed investigation of this suggestion with the aid of numerical simulations. The central question which we will address, therefore, is: can magnetic stresses in the ambient medium alone produce the observed degree of collimation in bipolar molecular outflows from star forming regions?

To answer this we shall be concerned primarily with reproducing the morphology of these sources, in particular the observed typical length to width ratio of 2.4 and the formation of a dense shell of material swept up by a low density high velocity wind. Thus, we do not attempt to provide detailed kinematic modeling of specific sources here. Moreover, we do

not address the mechanism responsible for the wind here; in Stone and Norman (1991a) we report on simulations which study the generation of a hydromagnetic wind from magnetic accretion disks. We also note that magnetic collimation of an isotropic wind by external fields may have relevance in other astrophysical systems, for example the asymmetries observed for some planetary nebula, novae, and supernovae remnants, or the dynamics of galactic "superbubbles" (Tomisaka 1990; Ferrière, MacLow, and Zweibel 1991).

The organization of this paper is as follows. In §2, we review previous hydrodynamic studies of wind blown bubbles in non-magnetic media. From these studies, we can make specific predictions of the differences we expect for our MHD calculations. In §3 we describe the setup and parametrization of our numerical simulations. In §4, we discuss our results, while in §5 we summarize these results and present our conclusions.

2 Wind Blown Bubbles

The hydrodynamic growth of wind blown cavities (bubbles) in the interstellar medium has been studied extensively. Weaver *et al* (1977) were the first to examine in detail the evolution of such bubbles generated by strong stellar winds from early type stars. Although we expect bubbles evacuated by protostellar winds to differ considerably from hot star winds (particularly in the thermodynamic state of the wind), we nonetheless find many of their previous results useful, as summarized below.

Weaver *et al* found that the evolution of the bubble is analogous to that of a supernova shell (Spitzer 1978): there is an initial free expansion phase, an intermediate adiabatic expansion phase, and a late isothermal expansion phase (often called the "snowplow" phase) during which radiative cooling in the interior of the bubble significantly affect the dynamics of the flow. During the intermediate adiabatic phase, the bubble is energy-driven, while in the later isothermal phase it is primarily momentum-driven. Because the density of the swept-up ambient medium surrounding the bubble is much higher than in the interior, radiative losses

cause it to collapse into a thin shell during the adiabatic expansion phase even though the stellar wind still conserves energy. When generated by multiple supernovae and powerful stellar winds from OB associations, these bubbles can grow to sizes rivaling the thickness of the galactic disk (termed "superbubbles"). MacLow *et al* (1989) used the ZEUS code (upon which the ZEUS-2D code used here is based) to simulate the dynamics of superbubbles in the stratified galactic disk.

Since the initial free expansion phase is short lived, in the following we focus on the intermediate adiabatic expansion phase. If the ambient medium is uniform, Weaver *et al* found that the adiabatic energy driven expansion phase of the spherical bubble can be described by a similarity solution, just as for the case of supernova shells. The solutions differ, however, in that for the wind blown bubble there is a continuous injection of energy from the central source, whereas in the case of a supernova, the entire reservoir of energy is deposited essentially instantaneously. These authors found that the radius and internal pressure of the bubble are given by:

$$R = \left(\frac{250}{308\pi}\right)^{1/5} L_W^{1/5} \rho_\circ^{-1/5} t^{3/5}, \tag{1}$$

$$p = \frac{7}{(3850\pi)^{2/5}} L_W^{2/5} \rho_\circ^{3/5} t^{-4/5}, \tag{2}$$

where L_W is the mechanical luminousity of the wind, and $\rho_\circ$ is the density of the ambient medium. The mechanical luminousity L_W is determined by the observed terminal velocity V_W and mass loss rate $\dot{M}_W$ of the wind, so that

$$L_W = \frac{1}{2} \dot{M}_W V_W^2. \tag{3}$$

Königl (1982) extended this solution to plane stratified external density distributions of the form $\rho(z) = \rho_\circ z^{-m}$, where $0 \leq m < 3$; in this case the bubble does not remain spherical, but elongates in the direction of the steepest density gradient.

If the ambient medium is magnetized, we also expect that the growth of the bubble during the intermediate adiabatic expansion phase will no longer be spherical, but that

expansion will occur more easily along field lines than across them. Physically, we expect the bubble to begin to deviate substantially from spherical expansion when the internal pressure decreases to a value comparable to the magnetic pressure at the equator in the ambient gas, $p_B = 9B_\circ^2/32\pi$ where $B_\circ$ is the (uniform) magnetic field strength in the ambient medium (an additional factor of 9/4 has been included in the magnetic pressure to account for the additional stresses induced by the exclusion of the field from the cavity, Königl 1982). Equating the magnetic pressure to the internal pressure of the bubble given by the hydrodynamical solution (eq. [2]) allows us to predict the collimation time

$$\left(\frac{t_{coll}}{10^4\mathrm{yrs}}\right) = 22\left(\frac{B_\circ}{30\mu\mathrm{G}}\right)^{-5/2}\left(\frac{L_W}{\mathrm{L}_\odot}\right)^{1/2}\left(\frac{n_\circ}{10^3\mathrm{cm}^{-3}}\right)^{3/4}. \tag{4}$$

Substitution of the collimation time into eqs. [1] and [2] allows us to estimate the radius and internal pressure of the bubble when magnetic collimation begins to become significant.

Using a perturbation analysis, Königl also was able to predict the asymptotic behavior of a wind blown bubble in a magnetic ambient medium. At early times, when $p \gg p_B$, the bubble's growth is nearly spherical and is given by the hydrodynamic solution, except for a slight eccentricity introduced by the non-isotropy of the Lorentz forces. At late times ($t \gg t_{coll}$), the bubble is collimated into a cylindrical shape. Königl predicts the axial and radial dimensions of the bubble ($Z_\circ$ and $R_\circ$ respectively) should evolve in time according to

$$Z_\circ(t) \propto t^{2/(2-m)}, \qquad R_\circ(t) \propto t^{-m/(4-2m)}, \tag{5}$$

so that

$$\frac{Z_\circ}{R_\circ} \propto t^{(4-m)/(4-2m)}. \tag{6}$$

Computing the exact structure of the bubble and surrounding shell at intermediate times ($t \sim t_{coll}$) is difficult with analytic methods. In this paper, we study by means of self-consistent numerical simulations the growth of wind blown bubbles in a magnetized ambient medium. We follow the evolution of the bubbles from the early hydrodynamic phase (described by the analytic solution eqs. [1] and [2]), through the collimation phase, to the late time, non-isotropic growth regime predicted by Königl (eqs. [5] and [6]). These simulations therefore

provide a unified picture of the growth and evolution of magnetically collimated bubbles. Moreover this approach allows us to include a more realistic representation of the ambient conditions encountered in molecular clouds.

To simplify the problem in this first analysis, we assume that both the wind and ambient gas are adiabatic. However, once radiative cooling in the interior of the bubble becomes important, the subsequent dynamics can be strongly affected. In §3 we argue that radiative cooling will become important first in the shocked ambient gas, causing it to collapse into a thin shell. The collimation of the bubble will be unaffected by such a process. However, we also show in §3 that radiative cooling will become important in the *shocked* protostellar wind on a timescale comparable to the collimation time of the bubble. Thus, a more realistic treatment of the thermodynamic evolution of the protostellar wind is an important extension to this work, and in a future communication (Stone and Norman 1991b) we present calculations including the effects of cooling in both the wind and ambient medium.

Finally, we remark that the growth of wind blown cavities in a magnetic medium has been considered in other contexts. For example, Ferrière, MacLow and Zweibel (1991) recently studied the expansion of a superbubble into a uniform magnetic field including cooling. Previous studies of explosions in magnetic media (*e.g* Heiligman 1980 and references therein) used a quasi one-dimensional analysis that only considers the effect of the magnetic pressure part of the Lorentz force term on the dynamics.

3 Numerical Simulations

To compute the structure of a wind blown cavity inside a dense, magnetized ambient gas, we solve the equations of ideal MHD in cylindrical geometry with the ZEUS-2D code. The algorithms and test problems used in this code are described in detail in Stone and Norman 1991c,d; and Stone *et al* 1991.

In this initial study, we ignore radiative transfer effects, so that both the ambient

medium and the wind are adiabatic and are described by a gamma-law equation of state with $\gamma = 5/3$. We model the ambient molecular gas in one of two ways. In the first, we assume ambient medium is initially isothermal with a sound speed $C_\circ$ and a density distribution which is plane stratified according to

$$\rho(z) = \frac{\rho_\circ}{[1 + (z/a)^2]^{m/2}} \qquad \text{for } 0 \leq m \leq 2, \tag{7}$$

where a is an arbitrary core radius used to smooth the density distribution near the equator; here we choose $a = 0.25$ pc. For the case $m > 0$, we compute the gravitational potential of the ambient gas so that it is in hydrostatic equilibrium by balancing the gradients of the pressure and gravitational potential in the axial equation of motion. The ambient magnetic field is taken to be of uniform strength $B_\circ$ parallel to the Z axis.

Alternatively, as a more realistic model of the ambient medium we adopt the models of magnetically supported self-gravitating molecular clouds given by Tomisaka *et al* (1988). In particular, we take "case 1e", a magnetic cloud in equilibrium at critical mass with a central density enhancement of approximately 30.

In both cases the stellar wind is assumed to be isotropic, non-magnetic and steady. It is modeled by continuously adding mass into a small spherical source region with specific internal energy $\epsilon_W = C_\circ^2/\eta$, and at a rate such that the desired mechanical luminosity L_W is produced, *i.e.* $\dot{M}_W = L_W/\epsilon_W$. The value of η is arbitrary, for this study we choose $\eta = 0.01$. This method of modeling a steady wind has been used successfully in previous studies of the hydrodynamic formation of twin exhaust jets (Norman *et al* 1981)

The computational grid is typically chosen to contain 256 axial by 128 radial zones. Figure 1 diagrams the problem setup. We assume axial and equatorial symmetry along the inner Z and R boundaries, while both the outer boundaries are outflow. The physical size of the wind source region R_W is computed from the analytic hydrodynamic solution assuming that at the start of the calculation, $t = t_\circ$, the internal pressure in the bubble is $p_\circ = (\rho_\circ C_\circ^2/\gamma + 9B_\circ^2/32\pi)/\eta$. The values of $t_\circ$ and R_W then follow from eqs. [1] and [2]

respectively. By choosing $\eta \ll 1$, we guarantee the internal pressure of the bubble greatly exceeds the sum of the gas and magnetic pressure in the ambient medium, so that the initial evolution will be described by the hydrodynamic solution. For the case of plane stratified ambient medium with $m > 0$, we must additionally ensure $R_W \ll a$ initially. The physical size of the computational grid is chosen to be about $10 - 100$ R_W in each direction. In order to adequately resolve the wind source region, we use logarithmic grid spacing in each direction, with 5 to 10 zones contained within the source region.

We choose the same values for the particle number density $n_\circ$ and temperature $T_\circ$ in the ambient medium for all runs, so that the only free parameters in the problem are the magnetic field strength $B_\circ$ and wind luminosity L_W. To match conditions in molecular clouds, we choose $n_\circ = 10^3$ cm^{-3}, $T_\circ = 30$K, $B_\circ = 30 - 50\mu$G, and $L_W = 0.1 - 1.0$ L$_\odot$. Table 1 lists the values of the parameters used for each of the runs performed in the uniform density ambient medium and the predicted collimation time in each case. The values for the plasma β parameter ($\beta \equiv 8\pi p/B^2$) implied by these field strengths are $\beta = 0.1 - 0.04$. Note these low values of β derive from the low temperature of the molecular gas and not due to extraordinarily high magnetic field strengths. For the case in which the initial conditions are given by the more realistic model of a molecular cloud given by Tomisaka *et al* we scale the dimensionless solution by the fiducial values $n_\circ = 10^3$ cm^{-3}, $p_\circ = 4.14 \times 10^{-12}$ dynes, and $L_W = 0.1$ L$_\odot$, which leads to a grid size of $(Z, R) = (1.0, 0.67)$ pc. mhe magnetic field strength is then determined by the given value of $\beta = 1$ measured at the surface for this model.

It is instructive to compare important timescales in the problem as we have set it up. For instance, we note that the free fall time for a uniform cloud of density $\rho_\circ$ is $\tau_{ff} = \sqrt{3\pi/32G\rho_\circ} = 1.7 \times 10^6$ yrs. The results of our simulations show that the timescale for the growth of the bubble as predicted by eq. [4] is much shorter than the free fall time (*e.g.* $t_{coll} \ll \tau_{ff}$). It is therefore acceptable to ignore the gravitational collapse which should occur for a uniform density, isothermal molecular cloud, as we have done here. Furthermore, we

note that the radius of a 100 $M_\odot$ cloud with density $\rho_\circ = m_H n_\circ \approx 1.6 \times 10^{-21}$ gm cm^{-3} is about 1.0 pc. Since the typical masses observed for molecular cloud cores are $M \approx 100$ $M_\odot$, then once the linear scale of the wind blown bubble exceeds 1.0 pc, we would expect it to begin to reach the edge of a real molecular cloud core and begin to "blowout". Therefore, our assumption of a uniform ambient medium is strictly applicable only while the length of the bubble does not exceed 1.0 pc.

Finally, in order to assess the importance of radiative losses to the dynamics of the bubble, we estimate a cooling time in the following way. Define the cooling time t_c as the time it takes for the gas to radiate away its internal energy, which from dimensional arguments gives

$$t_c \sim \frac{kT}{n\mathcal{R}(T)} \tag{8}$$

where n is the particle number density, T the gas temperature and $\mathcal{R}(T)$ is the per particle cooling rate. Observations of the *unshocked* neutral component (region *(a)* defined in Figure 1 of Weaver *et al*) of high velocity protostellar winds (Koo 1989) indicate that they are cold ($T \sim 100$ K). Moreover, this region drives the growth of the bubble primarily be the action of its large kinetic rather than internal energy. Thus radiative cooling for this componant of the bubble is negligable to the dynamics. However, the high velocities observed for these winds ($v \gtrsim 100$ km s^{-1}) implies the *shocked* protostellar wind and ambient gas (regions *(b)* and *(c)* defined by Weaver *et al* respectively) can reach temperatures of $T \sim 10^6$ K. Using the cooling function of MacDonald and Bailey (1981) we estimate the cooling rate at this temperature to be $\mathcal{R} \sim 10^{-22}$ erg cm^3 s^{-1}, which gives a cooling time of

$$t_c \approx 4 \times 10^4 \left(\frac{T}{10^6 \text{ K}}\right) \left(\frac{n}{1 \text{ cm}^{-3}}\right)^{-1} \text{yrs.} \tag{9}$$

Thus, we expect cooling to affect the denser ambient gas first (region *(c)*), causing it to lose pressure support and collapse into a thin shell. In addition, comparison of the cooling time (eq. [9]) with the dynamical times listed in Table 1 shows that cooling can be important even in the shocked wind (region *(b)*) if the density there is $n \gtrsim 1$ cm^{-3}. In this region, the growth

of the bubble is driven by a large internal energy and pressure, therefore radiative cooling in this region will strongly affect the dynamics of the bubble. Studies of the collimation of non-adiabatic protostellar winds will therefore be an important extension to this work.

4 Results

In this section we report on the results of our simulations to study the magnetic collimation of wind blown bubbles in molecular clouds, using three types of initial conditions. First, we study the evolution of such bubbles in a uniform ambient medium (using $m = 0$ in eq. [7]). Secondly, we study the asymptotic growth of bubbles in plane stratified media (using $m = 1$ and $m = 2$ in eq. [7]). And finally, we consider the more realistic scenario of the growth of a bubble in a magnetically supported equilibrium configuration as computed by Tomisaka *et al* (1988).

4.1 Uniform Density Ambient Medium

Figure 2 shows the results for Run C at t/t_{coll}=0.25, 1.0 and 5.0; the other runs give nearly identical results at the same times. In each frame of this figure, the solid lines are density contours while the dashed lines are representative magnetic field lines. These frames trace the evolution of the system as the protostellar wind evacuates a low density bubble in the ambient medium, and drives an MHD shock wave ahead of it. At early times, $t \ll t_{coll}$, the bubble and shock are quasi-spherical, and the layer of compressed ambient gas between the shock front and contact discontinuity at the bubble's surface is quite thin. At intermediate times, $t \sim t_{coll}$, the bubble has swept up a magnetic energy comparable to its thermal energy, and it begins to be collimated into a prolate shape aligned with the ambient magnetic field. In contrast to the bubble, the shock surface becomes oblate due to the higher propogation speed of compressive MHD waves perpendicular to $\mathbf{B}$ ($\sqrt{C_\circ^2 + V_A^2}$, where V_A is the Alfvén velocity) versus parallel to it ($C_\circ$). At late times, $t \gg t_{coll}$, the bubble expands only along the magnetic field lines, and drives a quasi planar compound MHD shock front

attached to the bubble apex. The shape of the MHD shock at late times is slightly concave which is quite different from the shape of ordinary HD bow shocks. This unusual shape for bow shocks in MHD has been studied in detail by Hundhausen, Holzer and Low (1987); it is a consequence of the progression of shock wave families (acoustic to fast magnetosonic) with increasing polar angle required in MHD flows. As pointed out by Ferrière, MacLow, and Zweibel (1991), the strong kink in the magnetic field lines at the bow shock implies a significant jump in the tangential velocity there due to magnetic "tension" forces. In fact, it is the non-isotropic magnetic tension part of the Lorentz force, acting on the bubbles surface, which ultimately leads to collimation. Thus, the collimation of a wind by a magnetic media is an intrinsically multi-dimensional problem in which all terms in the Lorentz force must be accounted for; one-dimensional analyses which consider the effects of only the magnetic pressure cannot be used to follow the evolution into the collimation regime.

Figure 3 plots the length to width ratio Z/R for the bubble (where the surface of the bubble is defined by the contact discontinuity) versus the dimensionless time t/t_{coll} for each of the four runs listed in Table 1. Beyond the collimation time, the axial ratio of the bubble grows nearly linearly in all cases. The linear growth in the ratio Z/R results from a linear growth of $Z_\circ(t)$ while $R_\circ(t)$ reaches a limiting size and stagnates. This behavior agrees in detail with the asymptotic scaling laws (eqs. [5] and [6]) derived by Königl. We also note that the functional form of the axial ratio of the bubble is independent of the parameters $B_\circ$ and L_W, indicating the expansion is self-similar in nature, just as in the hydrodynamic case. The small discrepancies and wiggles between curves in this figure can be attributed to "measurement" errors in determining the precise position of a numerically represented feature (the contact discontinuity) on a discrete mesh.

Also plotted in Figure 3 is the length to width ratio of the shock surface versus dimensionless time. We find that the shock speed in both the axial and radial directions is constant and nearly identical, so that the shock surface grows into an oblate shape only slowly. However, since the radial growth of the bubble (which originally provided the piston

to drive the shock) has been halted, we expect the shock to weaken and dissipate in the radial direction, leaving a quasi-planar MHD shock attached to the bubble apex.

The bubble becomes significantly collimated (*i.e.* length/width ≥ 2) by about $t = 4.0\ t_{coll}$, or 2.8×10^5 yrs for Run C. The velocity of the apex and equatorial radius of the bubble at this time are observed to be 2.4 km s^{-1} and 0.65 km s^{-1} respectively. The sound, Alfvén and fast magnetosonic speeds in the ambient medium for Run C are 0.64 km s^{-1}, 2.1 km s^{-1} and 2.2 km s^{-1} respectively. Thus, the bubble apex is expanding super magnetosonically, and is driving a fast magnetosonic shock, while at the equator the bubble is expanding nearly subsonically.

4.2 Plane Stratified Ambient Medium

In order to examine the asymptotic scaling laws (eqs. [5] and [6]) in more detail, we have also performed simulations for a plane stratified ambient medium, using $m = 1$ and 2 in the density distribution (eq. [7]). The two dimensional evolution of the bubble in these cases is similar to that presented in Figure 2 for the uniform ambient medium; the bubble quickly adopts a prolate shape and drives an oblate MHD shock front ahead of it. Eventually the shock front is distorted into a dumbell shaped surface as it runs down the density gradient, however despite the reduced gas pressure at large Z, we find the bubble does not flare and "blowout" owing to the strong lateral magnetic confinement of the uniform strength field. In fact, at no point along the axis of symmetry does the radial width of the bubble exceed the width at the equator.

Figure 4 shows the evolution of the axial lengths of the bubble $Z_\circ$ and $R_\circ$ for both the $m = 1$ and $m = 2$ runs, using a wind luminosity $L_W = 1.0$ L$_\odot$ and magnetic field strength $B_\circ = 35\ \mu$G. In both cases the bubble tip accelerates whereas the equatorial radius eventually decreases, in agreement with the asymptotic scaling relations. Königl has suggested that the acceleration of the apex of the bubble in the axial direction which occurs in a non-uniform

ambient medium might result in the growth of Raleigh-Taylor instabilities. However, we have found no evidence for such instabilities in our simulations. Zelago and Melcher (1969) have shown that a magnetic field tangential to a density interface will suppress the growth of the Raleigh-Taylor instability there. Since the thin shell enclosing the bubble contains a strong tangential magnetic field resulting from the compression of the ambient gas, we suggest this field is suppressing the growth of the instability.

4.3 Magnetically Supported Cloud

The high degree of collimation seen in the $m = 1$ and $m = 2$ simulations presented in the previous section are a direct result of the assumed geometry of the magnetic field. The purely axial and parallel field lines in the tenuous envelope of the molecular cloud are able to strongly confine the radial growth of bubble. However, this assumed field geometry is unrealistic. To discover what bubble shapes are produced in more realistic environments, we have simulated the growth of a bubble within a magnetically supported equilibrium configuration given by Tomisaka *et al.* Figure 5 shows a time sequence of the blowout process, where once again solid lines denote density contours and dashed lines are representative of magnetic field lines. With the assumed fiducial values used to scale Tomisaka's dimensionless solutions given in §3, the times for the three plots are 1.1×10^5 yrs, 2.2×10^5 yrs, and 3.2×10^5 yrs respectively. The evolution is seen to be quite similar to the uniform medium case. The expanding bubble drives an MHD shock ahead of it, forming a layer of dense compressed ambient gas. However, the diverging field lines now allows the wind to flare as it leaves the cloud, forming a dumbbell shaped bubble. The bubble is completely enclosed in a shell of dense material, which has been swept up by the wind; in the equatorial plane the remnant of the initial cloud is a dense torus. Overall, a collimation factor (length/width) of about 3 is produced, which is suggestive of the mean value of 2.4 observed for EMOs. Moreover, the overall morphology of the system (a dense shell swept up by a wind blown cavity) is clearly produced. We also note that the growth of the bubble in the equatorial plane results in a

dense torus of swept up ambient gas. Interestingly, observations of toroidally shaped density distributions around some molecular outflow sources have been reported (Lada 1985; 1988).

Just as in the plane stratified ambient medium, we find the bubble tip accelerates as it runs down the density gradient in the axial direction. However, Figure 5 clearly shows no evidence for the growth of Rayleigh-Taylor instabilities along the bubble surface. We conclude such instabilities are once again suppressed by the strong tangential field in the compressed ambient gas.

5 Summary and Conclusions

We have used ideal MHD simulations and typical parameters for the environment in molecular clouds to model the collimation of protostellar winds by magnetic stresses in the ambient medium. We have demonstrated that

- ambient magnetic fields in molecular clouds alone are capable of collimating protostellar winds into bipolar outflows with characteristics similar to observations. Collimation factors of between 1-6 are easily produced with our models.

- wind bubbles in a uniform density ambient medium collimate along the direction of the magnetic field lines on a timescale given by eq. [4].

- the axial ratio of the bubble Z/R grows linearly in time for $t > t_{coll}$ in a uniform density ambient medium. For plane stratified ambient medium, the bubble tip accelerates, while the equatorial radius eventually decreases, in agreement with previously derived asymptotic scaling laws.

- the acceleration of the bubble tip observed for density stratified ambient media does not result in Rayleigh-Taylor instabilities due to the strong magnetic field in the compressed ambient gas.

Our numerical simulations have allowed us to follow the evolution of wind blown bubbles in magnetic media through all phases of their evolution. Thus, we are able to make contact between the previous analytic work for hydrodynamic bubbles (which is valid for $t \ll t_{coll}$) and the asymptotic scaling of Königl (which is valid for $t \gg t_{coll}$). The bubble evolution proceeds through three distinct phases, as summarized in Figure 6. The first phase is quasi spherical hydrodynamic expansion (for $t \ll t_{coll}$), the second is prolate bubble, oblate shock (for $t \sim t_{coll}$), and the final is prolate bubble and quasi planar shock (for $t \gg t_{coll}$).

We have also followed the growth of a bubble in a realistic model for a molecular cloud, the magnetic equilibrium configuration of Tomisaka *et al* (1988). In this environment, a flaring outflow enclosed within a dense layer of compressed ambient gas is produced, which is suggestive of observed bipolar outflows. For example, the bubble sweeps up a dense torus of ambient gas in the equatorial plane which is similar to observations of some molecular outflow sources.

The present simulations have been confined to axisymmetry. Fully three- dimensional evolution introduces the possibility of a non-axisymmetric magnetic Rayleigh-Taylor instability in which the wind squirts out between flux ropes. This instability may contribute to the shape of galactic superbubbles (Heiles 1987); in the case of bipolar outflows it may increase the mixing and entrainment of ambient gas into the wind. Detailed examination of this possibility must await fully three-dimensional MHD simulations.

The primary shortcoming of the present simulations, however, is the assumption that the wind and shocked ambient gas is adiabatic. We expect the dense ambient gas, for example, to lose energy effectively via optically thin radiative cooling during the dynamical growth of the bubble, causing it to collapse into a thin shell. While this process will not affect the gross dynamics of the bubble (for example the collimation rate), it is vital to include before detailed comparisons of the observed kinematics of bipolar outflows and our simulations can be made. For example, we have found that the strong magnetic field in the compressed shell

of ambient gas suppresses the formation of Rayleigh-Taylor instabilities there. Thus, the formation of Herbig-Haro objects and water masers at the interface cannot be accounted for by this effect, whereas the thermal instability may still be effective. Moreover, given the uncertainty of the thermodynamic state of protostellar winds, it will be important to explore the consequences of radiative cooling in the bubble interior on the dynamics. We will present simulations which include the effects of radiative cooling in both the wind and ambient gas and provide detailed comparison to observations in a future paper.

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Table 1. Parameters for Uniform Density Ambient Medium Runs

Run	$n_\circ$ (cm^{-3})	$L_W/L_\odot$	$B_\circ$ (μG)	t_{coll} (10^4 yrs)
A	10^3	1	30	22
B	10^3	1	50	6.1
C	10^3	0.1	30	7.0
D	10^3	0.1	50	1.9

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Figure Captions

Figure 1. Setup of numerical simulations. The simulations are performed in cylindrical geometry using a uniform or plane stratified ambient medium and a small spherical source region into which mass and internal energy are added continuously. The ambient magnetic field is excluded from the wind source region.

Figure 2. Growth of a magnetically collimated bubble in a uniform density ambient medium. Solid lines are contours of the density, while dashed lines are representative magnetic field lines. The bubble is shown at dimensionless times of 0.25 (top), 1.0 (middle), and 5.0 (bottom).

Figure 3. (TOP) The collimation factor Z/R for the bubble versus dimensionless time for the uniform density ambient medium runs listed in Table 1. (BOTTOM) The ratio Z/R for the shock surface for the uniform density ambient medium runs.

Figure 4. The axial and radial lengths of the bubble (Z and R respectively) are shown as a solid line (for Z) and a dashed line (for R) for the plane stratified ambient medium using $m = 1$ (top) and $m = 2$ (bottom) in eq. [7].

Figure 5. Growth of a magnetically collimated bubble in a self-gravitating magnetically supported cloud at three equally spaced times in the evolution. Solid lines are contours of the density, while dashed lines are representative magnetic field lines.

Figure 6. Schematic diagram of the three phases of the evolution of a magnetically confined bubble observed in our simulations.

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