SUPERBUBBLE BLOWOUT

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Abstract

Superbubbles form when the winds and supernova explosions from massive stars in an OB association sweep out a large cavity in the interstellar gas. When a superbubble grows large enough, it begins to interact with the stratification of the galactic disk, possibly blowing entirely out of the disk into the halo. I review the structure of superbubbles, and give analytic estimates of when they will blow out, and how large they will be when they do. I then discuss a computational model of blowout, emphasizing the features that cannot be studied analytically such as Rayleigh-Taylor instabilities. I review recent work extending the simple blowout models by examining interactions between bubbles and the effects of magnetic fields. Finally, I review observations of the blowout phenomenon on all scales, ranging from tiny—the explosions resulting from the impact of Comet Shoemaker-Levy 9 on Jupiter—to huge—the growth of the superbubbles generated by starburst galaxies into the intergalactic gas. I emphasize the importance of observations of edge-on disk galaxies, which show a correlation between the star-formation rate and the thickness and activity of the disk.

1 Introduction

Consider an OB association, where ten to a thousand massive stars have formed in a small region. The most massive stars have strong stellar winds, high ionizing luminosities, and will become supernovae (SNe) within a few million years of the formation of the association. Even less massive stars will become SNe within 50 million years of the formation of the association. Most OB associations remain gravitationally unbound, with stellar dispersion velocities of as high as 25 km s^{-1}, but the effects of winds, SN explosions, and radiation expand out far faster than the stars.

The winds and SN blast waves sweep out a cavity in the interstellar gas known as a superbubble ([32], [8], [4]) Figure 1 shows the structure of a typical superbubble ([7], [54], [31]). Winds and SN

Figure 1: Structure of typical superbubble before blowout, showing freely expanding winds and blast waves, inner termination shock, hot shocked gas, contact discontinuity, cold, dense shell, and outer shock.

blast waves freely expand until they reach an inner termination shock. The kinetic energy of the expanding gas is converted to thermal energy, producing a hot, shocked region. The pressure of this region drives a shock into the surrounding interstellar gas, sweeping it up into a shell. The central association photoionizes the inner edge of the shell, while the rest of the shell is dense enough to radiatively cool. The temperature of the hot, shocked region is held down to a few million degrees by conductive evaporation off the swept-up shell.

Superbubbles grow large enough that the global structure of the interstellar medium (ISM) becomes important. In our own galaxy, the disk appears to have multiple components with scale heights ranging from 100 pc for the classical HI layer, through 500 pc for the extended Lockman layer ([25]), to a kpc or more for the high-altitude ionized gas first noted by Reynolds [39]. Magnetic fields and cosmic rays may dominate the pressure supporting this stratified distribution [6]. This review considers the development of superbubbles as they interact with stratified density distributions in dwarf and spiral galaxies. (This topic has also recently been carefully reviewed by Bisnovatyi-Kogan & Silich [2], with a focus on analytic and semi-analytic methods). In the next section, analytic models are described, while § 3 describes numerical gas dynamical models. In § 4 observations of the blowout phenomenon at all scales are described, and some open questions are described in § 5.

2 Analytic Treatments

The most basic question to ask is when will a superbubble blow out of a stratified ISM—that is, when will it accelerate until it reaches a uniform halo or intergalactic medium? A dimensional analysis calibrated by the semi-analytic model of Mac Low & McCray [27] can give the answer (see Koo & McKee [24] for a similar treatment). The relevant scales for this problem are the mechanical luminosity of the OB association L_m, the scale height of the density distribution H, and the midplane density

ρ_0, and pressure P_0. The time scale is then the time for a spherical superbubble to reach dimensions comparable to a scale height [7],

$$t_1 \sim H^{5/3}(\rho_0/L_m)^{1/3}. \tag{1}$$

The sound speed at the midplane $c_s = (\gamma P_0/\rho_0)^{1/2}$ gives a velocity scale. This can be compared to the velocity of the superbubble when it reaches a scale height,

$$v_1 = \frac{3}{5}\frac{H}{t_1}. \tag{2}$$

The Mach number of the superbubble when it reaches a size comparable to a scale height $M_1 = v_1/c_s$ determines whether a superbubble will ultimately blow out or be pressure-confined by the external medium.

The actual calibration of this criterion must be done using semi-analytic techniques. Kompaneets [22] showed that a blast wave in a zero-pressure, exponential atmosphere will always blow out. The thin-shell approximation that he used can be adapted to the present problem. The assumptions used are that the shell of swept-up gas is thin and that the interior pressure acting on it is uniform everywhere. The latter assumption is equivalent to assuming that the sound speed in the interior is far greater than the expansion velocity of the shell. Mac Low & McCray [27] divided the shell up into a number of segments and numerically integrated the equations of motion of the shell in an arbitrary, finite-pressure, stratified atmosphere to find its shape and expansion velocity. They find that if a bubble has $v_1/c_s > 5$ it will blow out of an exponential atmosphere.

When the shell begins to accelerate upward, it becomes Rayleigh-Taylor unstable, as the rarefied interior effectively supports the dense shell. Numerical models discussed in the next section show that the shell then fragments and releases its internal pressure. The subsequent evolution has been analytically modeled by Koo & McKee [24]. They assume that once the bubble has lost pressure, the shell in the plane of the disk conserves momentum, following a two-dimensional snowplow equation of motion. It comes to a halt at a maximum radius

$$\frac{R_{\max}}{H} \sim 1.4\left(\frac{L_{38}}{P_{04}H_{100}^2 c_{s,6}}\right)^{1/6}, \tag{3}$$

where $L_{38} = L_m/(10^{38}\ \mathrm{erg\ s^{-1}}$, $H_100 = H/(100\ \mathrm{pc})$, $P_{0,4} = P_0/(10^4\ \mathrm{dyne\ cm^{-2}})$, and $c_{s,6} = c_s/(10^6\ \mathrm{cm\ s^{-1}})$. The shell then contracts under the influence of the external ISM pressure to an equilibrium radius maintained by the balance between the external pressure and the ram pressure of winds and SN blast waves from the central OB association, given by

$$\frac{R_{\mathrm{eq}}}{H} \sim 1.1\left(\frac{L_38}{P_{0,4}H_{100}^2 v_{w,8}}\right)^{1/2}, \tag{4}$$

where the effective velocity of the winds and blast waves v_w is scaled as $v_{w,8} = v_w/(10^8\ \mathrm{cm\ s^{-1}})$. Koo & McKee [24] find that if $R_{\mathrm{eq}}/H > 1$ then the expanding winds and ejecta will freely escape in nearly all directions, producing a spherical superwind, while if $R_{\mathrm{eq}}/H \leq 1$ the expanding gas is confined in a chimney and ejected primarily vertically.

Hot gas travelling at high speed up a chimney or over a disk will excite Kelvin-Helmholtz instabilities in the walls of the chimney or the surface of the disk. The chimney case has been considered in particular detail by Shull, Slavin, & Begelman [46] following an initial suggestion by Begelman & Fabian [1]. The result of the Kelvin-Helmholtz instabilities is a mixing layer where hot and cold gas are mixed together. The cold gas is heated and collisionally ionized in this layer, producing a region of relatively high density gas with temperatures near the peak of the radiative cooling curve. The resulting ionizing radiation photoionizes the inner walls of the chimney, producing ion abundances in reasonable agreement with those observed by Reynolds [39], [40] and others (e.g. [30]) in the diffuse, high-altitude ionized gas. This is one reason for believing that, in fact, the Reynolds layer may be the photoionized walls of superbubble chimneys.

3 Numerical Models

Modelling the development of superbubbles in any but the simplest situations require numerical models. Here I briefly describe some models of Rayleigh-Taylor instability in superbubble shells, and then consider models of the global structure of the ISM showing superbubble structure in context, and models of superbubbles in the presence of magnetic fields.

For my own numerical work, I used ZEUS, a general purpose, astrophysical MHD code, developed by M. Norman and students at the Laboratory for Computational Astrophysics of the National Center for Supercomputing Applications. This code is publically available by registration with lca@ncsa.uiuc.edu (Also see their WWW page at `http://zeus.ncsa.uiuc.edu:8080/lca_home_page.html`). It is a second-order code employing Van Leer [52], piecewise-linear, monotonic, advection, an Eulerian moving grid, and constrained transport algorithms for field advection [48], [49].

3.1 Blowout Models

The questions that a gas dynamical model of superbubble blowout can hope to answer are where the shell mass goes, how big a hole can be produced, how much of the enriched interior is ejected, and what fraction of the energy remains in the disk of the galaxy. Additional information on the morphology and kinematics of the blowout may also be gleaned for direct comparison with observations.

In Mac Low, McCray, & Norman [28], models in exponential and Gaussian atmospheres were presented. Actual galactic disks probably lie somewhere between these two extremes, but their structure remains poorly known. The Milky Way disk apears to consist of a combination of a thin Gaussian layer and a thicker exponential disk [25], but the blowout phenomena observed should be some combination of those observed for linear and exponential atmospheres, as confirmed by Michaelis, Samland, & Hensler in these proceedings.

These models show the characteristic morphology of Rayleigh-Taylor instabilities in a blowout: dense clumps of shell connected by less dense arches expanding into the decreasing density external medium (see Garcia-Segura & Mac Low [16] for another example of this behavior in the context of Wolf-Rayet stellar wind bubbles). Most of the mass of the shell remains in the plane. In the case of the Gaussian blowout, only five percent of the shell mass participates in the blowout, with the rest remaining in the cylinder coasting to rest in the plane. Typical clump velocities are 75 km s^{-1}, with the hot gas moving much faster. The cylindrical shell at a time $t = 6t_1$ has a radius of $2H$ and a height of $3 - -4H$.

Several caveats need to be given. Large clumps are seen along the axis, which are caused by the assumption of cylindrical symmetry. In three dimensions, the Rayleigh-Taylor instability produces dense spikes. However, the assumption of symmetry suppresses all the spikes except the central one, allowing only rings to form. As a result, the central spike is exaggerated. The treatment of the hot interior is quite approximate. In reality most of the mass comes from conductive evaporation off the shell walls [7], but this effect was not included in the computations. Instead, roughly the correct amount of mass was fed in from the center, reproducing the gross behavior of the interior, but not the full density structure. As a result, this and similar models (such as that presented by Michaelis et al. in these proceedings) cannot address the interior temperature or kinematics quantitatively.

3.2 Global Structure

An illustrative, though difficult, project has been undertaken by a few groups. This is to directly model the large-scale behavior of the ISM including the effects of star-formation and evolution as well as that of gas-dynamics. Rosen & Bregman ([43], [42]) present models done assuming that both stars and gas can be treated as fluids, with a star-formation rate dependent on the local density, and an energy-injection rate tied to the stellar density either uniformly or in the form of isolated, supernova-like explosions. They include the vertical component of galactic gravity to study the behavior of the violent ISM in a disk. (Passot, Vázquez-Semadeni, & Pouquet [34] have presented similar models including magnetic fields but neglecting stratification.)

Although the neglect of magnetic fields and the assumption of continuum equations of motion for the stars are severe handicaps, the results are nonetheless quite suggestive. Large, irregular, superbubble-like structures can be seen to form and break out of the disk. At lower energy-injection rates these structures are isolated, rarely reach the halo, and do not significantly disturb the disk. As the energy-injection rate increases, they become more frequent, cover more of the area of the disk, and start to cause it to thicken, until at high energy-injection rates virtually all the cold gas is contained in the interacting walls of these structures in a very thick, hot, disk. This sequence of disk structures appears to reflect the observed correlation of disk thickness with star formation rate (Rand, these proceedings, [35]) as I will discuss below.

3.3 Magnetic Fields

A parallel development is the addition of magnetic fields to superbubble models in relatively simple galactic atmospheres. Tomisaka [50] used a hybrid atmosphere that attempts to include the Lockman and Reynolds layers as smooth distributions of gas with different exponential or Gaussian scale heights, in the first three-dimensional models of magnetized superbubbles in a stratified disk. Mac Low & Norman [29] extended their study by examining several different energies and magnetic field strengths. Mineshiga, Shibata & Shapiro [33] performed two-dimensional models, assuming slab symmetry, effectively modeling bubbles blown by linear energy sources rather than point sources. As shown by Mac Low et al. [28] linear bubbles will blow out slightly faster than normal ones, but, in the unmagnetized case, otherwise behave similarly to the normal point source bubbles.

Early results include the demonstration that magnetic fields can prevent blowout of bubbles and absorb energy that would otherwise be ejected from the disk. The swept up shells remain thick and low-density, and so do not efficiently radiatively cool. Ferrière, Mac Low & Zweibel [14] gave semi-analytic models of magnetized superbubble shells in homogeneous atmospheres, and Tomisaka [51] performed two-dimensional numerical calculations, both of which describe the state of the shells in some detail. The outer shocks of the superbubbles decay more quickly, but travel faster, driving Alfvén waves high into the halo.

4 Observations

Over the last five years, blowouts have moved from a theoretical construct proposed as an explanation for isolated observations, to a phenomenon that has been observed at all scales. In this section I give a brief review of blowout observations on scales ranging from tiny (hundreds of km) to huge (hundreds of Kpc), with the emphasis on the medium and large scales most directly related to superbubbles.

4.1 Tiny

In the summer of 1994, clear examples of the blowout of an explosion in an exponential atmosphere were observed by nearly every observatory in operation, during the impacts of D/Comet Shoemaker-Levy 9 on Jupiter. The explosions were small enough that these were actually examples of weak blowouts with adiabatic shells [55], [26]. However, they propagated through more then ten scale heights of atmosphere between the explosion sites and circumjovian space, compared to the two or three scale heights typical for the galactic case, emphasizing the expansion and acceleration processes inherent in a blowout.

Observation and modeling of these blowouts taught a number of interesting lessons. The incoming comet fragments produced a hot path to space at an angle to the vertical. The high sound speed in this path allowed fast propagation of the upward moving blowout shock wave [55], producing a fast blowout in the direction of the hot gas [5], [9]. The rising plumes of accelerated gas cooled adiabatically and fell ballistically [56], coming down again and hitting the top of the jovian atmosphere supersonically. Horizontal velocity remains unaffected by a vertical shock, so the shocked plume material continued to spread horizontally even after falling, producing the observed large, dark spots. Plume heights were observed to be nearly constant, despite the varying sizes and kinetic energies of the impactors [18] which appears to be explainable by similarity arguments [57] similar to those given here in § 2. Finally, the plumes were observed to bounce several times after hitting the atmosphere, until their energy was all lost to radiative cooling.

4.2 Small

On galactic scales, isolated bubbles and supernova remnants are occasionally observed to break out of regions of dense gas into rarefied cavities such as would be created by old superbubbles. These structures can also be thought of as blowouts, though the density gradients in these cases may be much sharper than in a galactic disk. An example of this sort of structure in the LMC is discussed by Chu in this volume. Some ultracompact H II regions have also been interpreted as blowouts from molecular clouds into the diffuse atomic medium (e.g. [10], [17], [15]).

4.3 Medium

One of the earliest observations of possible blowouts, that triggered much of the theoretical work on these structures, was of H I "worms" [19]. These are linear structures lying perpendicular to the galactic disk, especially within the solar circle. They were revealed by applying a median filter to observations of total H I emission in order to filter out the more uniform foreground and background emission. Outside the solar circle, these structures more frequently appear as complete shells rather than linear holes through the disk. This has been suggested to be a consequence of the increasing scale height of the galactic disk at greater radii [31], [27]. The physical reality of the worms has been confirmed by showing that they correspond to linear structures seen in the infrared, in the IRAS survey of the galactic disk [23]. What remains unknown is whether these holes are actually "chimneys" that connect to the halo (Norman & Ikeuchi 1989) or merely superbubbles that have blown out of the dense plane of the disk, but are still confined by the Lockman layer [20], [27].

The Large Magellanic Cloud provides a good laboratory for examining structures such as these, since the disk can be seen more or less face-on, it is far enough that large structures can be imaged easily without having to cover huge swaths of sky, yet it is close enough to be able to achieve reasonable resolution on these structures. The supergiant shell LMC-2 has been interpreted as a blowout through the back side of the LMC disk by Wang & Helfand [53]. Another supergiant shell, LMC-4, also shows some evidence of blowing out in observations of UV absorption lines, although the evidence remains inconclusive [12].

Giant H II regions in more distant galaxies may also drive superbubbles large enough to blow out of their disks. One well studied example where blowout may be occurring is the H II region NGC 2363 in the galaxy NGC 2366. Roy et al. [45] used a Fabry-Perot spectrometer to observe O III line profiles best interpreted as an expanding shell. They also noted that the line appeared to have an extremely broad plateau. Roy et al. [44] used echelle observations to show that the plateau was about 1000 km s^{-1} broad. They took this to be evidence against a blowout explanation for the high-velocity gas, because the inclination angle of the galaxy is significant, and the central bubble is smaller than the region showing emission from high-velocity gas. However, once a blowout reaches low density regions, it will expand out quasi-spherically, producing high-velocity gas in most directions over a region much broader than the source shell in the plane of the disk, so this may well be a blowout after all.

4.4 Large

Several years ago, layers of ionized gas well over a kpc thick were revealed in deep Hα images of several edge-on spiral galaxies, including NGC 891 [37] and NGC 4631 [38], [21]. ionized gas in our own galaxy. Searches for other galaxies with similar structure by Pildis, Bregman, & Schombert [35] and by Rand (this volume) has led to a result that I consider extremely important to understanding the structure of our own galaxy.

A global indicator of the energy input from massive star formation, such as the far infrared surface brightness, directly predicts the thickness of the diffuse ionized gas (see the summary tables given in Dettmar 1995 and Rand, this volume). The galaxies with the most apparent star formation have thick layers with filaments and structures reminiscent of the most energetic simulations of Rosen & Bregman [42], less active galaxies show occasional plumes or filaments of ionized gas, but no coherent layer, while the least active galaxies had no detected extraplanar Hα emission from ionized gas. Models of the vertical structure of the Milky Way disk no longer have to fit just one object, but a statistical ensemble of them.

4.5 Huge

The extreme case of a galaxy with active star formation is a starburst galaxy, where large regions of the galaxy have massive star formation rates more typically seen only in giant H II regions such as 30 Doradus. In dwarf galaxies, starbursts can be sufficiently energetic to control the evolution of the interstellar medium. De Young & Heckman [11] showed that the superbubble resulting from a starburst will eject most of the ISM in more spherical dwarf galaxies, but will blow out the minor axis first in more flattened dwarves.

An example of a dwarf galaxy undergoing the initial stage of this process is Holmberg II [36]. H I observations show holes with diameters up to 1.7 kpc in a gaseous disk with a scale height of about 625 pc, agreeing well with models that predict a diameter of $1.5 - -2H$. Ionized gas traced by Hα emission fills the smaller holes, but only outlines the big shells, again suggesting that they might have blown out, losing much of their interior gas.

Larger starburst galaxies drive strong galactic winds that can blow huge bubbles in the surrounding intergalactic medium. These objects are reviewed by Heckman in this volume, so I will not discuss them further.

5 Open Questions

The existence of superbubbles and their basic properties and behavior in a stratified disk now seem reasonably well established. The big open questions now shift to their interactions with each other and with the disks and halos of galaxies.

It is clear that the Reynolds layer is ionized by O stars in the galactic disk—no other energy source is powerful enough [41]. However, the origin of the layer and its influence on the development of superbubbles remains unclear. Is the Reynolds layer sufficiently homogeneous to confine superbubbles, preventing them from breaking through to a hot galactic halo? As was seen in the cometary case, if a path of hot gas out to the halo exists, superbubbles intersecting it will follow it out. Or is the Reynolds layer actually just the walls of large superbubbles, appearing as a homogeneous layer due mainly to our position deep within the disk?

Evidence for the interaction of neighboring superbubbles is starting to be found (e.g. [13], [47]). These observations support the picture seen in models such as those by Rosen & Bregman [42] of a bubbling or boiling disk, in which superbubbles expand not into a homogeneous stratified medium, but into the remnants of previous superbubbles. How does this modify the structure of superbubbles, and of the galactic disk?

Magnetic fields play an important role in determining the structure of superbubbles; if the strength of the random field is actually as strong as suggested by , they may dominate the structure. They may prevent the formation of dense, cold shells, and might even prevent the blowout of supershells that otherwise could. What strengths of ordered and random fields will prevent blowout of a superbubble of given strength? If superbubbles manage to blow out anyway, can they stretch magnetic field lines and set up a geometry that will drive a galactic wind as suggested by Breitschwerdt, Völk, & McKenzie [3].

Finally, the big question: can theories of the structure of the ISM predict the observed correlation between star formation rate and thickness of the ionized gas layer observed in Hα? Now that we have a laboratory with systems in different states, we can use it to more tightly constrain our theories than we could when we only try to compare to the conditions in our own Galaxy.

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