A THREE-DIMENSIONAL STUDY OF STRAIGHTENED GALACTIC

[Signature: James Smith]

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Disclaimer

The work presented in this thesis is entirely my own, with the following qualifications:

- **Chapter 5** is based on the paper “Three-Dimensional Simulations of a Starburst-Driven Galactic Wind”, which is published in the *Astrophysical Journal* (Cooper et al. 2008, ApJ, 674, 157). While this work was published in collaboration with Geoff Bicknell, Ralph Sutherland, and Joss Bland-Hawthorn, the text, and analysis of the data upon which it is based, is my own work. The simulations presented in the chapter were designed, implemented and performed by myself. The fractal cube from which the inhomogeneous disk was created, as well the broadband cooling fractions that I used to estimate the X-ray emission in the simulations, were provided by Ralph Sutherland.

- **Chapter 6** is based on the paper “On the Three-Dimensional Interaction of a Supersonic Wind with a Non-Spherical Radiative Cloud”, which will shortly be submitted to the *Astrophysical Journal*. While this work will be published in collaboration with Geoff Bicknell, Ralph Sutherland, and Joss Bland-Hawthorn the text was written by myself. The design, implementation, execution and analysis of the simulations are my own work.

The PPMLR code, with which the above work was performed, is based upon the VH-1 code written by the numerical astrophysics group at the University of Virginia, and was further developed at the Australian National University by Ralph Sutherland, Curtis Saxton, Stuart Midgley, and Geoff Bicknell to run on multiple processors, have improved treatment of radiative shocks, and to account for the radiative cooling of gas (see Chapter 4 for more details). I adapted this code to be applicable to the specific problems investigated in Chapters 5 and 6.

Jackie L. Cooper

August 20, 2008
To my Gran and my Pa,
who both passed away while this thesis was written.
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Abstract

Galactic winds are a ubiquitous phenomenon in starburst galaxies, and play an important role in galactic feedback processes via the transport of metals and energy. I have performed a series of three-dimensional hydrodynamical simulations of a starburst-driven wind forming in an inhomogeneous disk in order to better understand how the host galaxy’s interstellar medium impacts the structure and evolution of the outflow, and to determine the physical mechanism behind the formation of the filamentary optical emission and spatially correlated soft X-rays. These global simulations were followed up by a series of high resolution three-dimensional simulations of the interaction of a supersonic wind with a single radiative cloud, where the evolution of a cloud with two different geometries (fractal and spherical) is investigated. The aim of these simulations is to ascertain the effect of the assumed numerical resolution on the results of the global model (e.g. X-ray emission) and investigate the importance of radiative cooling on a filament’s survival.

The introduction of an inhomogeneous disk leads to differences in the formation of a wind, most noticeably the absence of the “blow-out” effect seen in homogeneous models. A wind forms from a series of small bubbles that propagate into the tenuous gas between dense clouds in the disk. These bubbles merge and follow the path of least resistance out of the disk, before flowing freely into the halo. Filaments are formed from disk gas that is broken up and accelerated into the outflow. These filaments are distributed throughout a biconical structure within a more spherically distributed hot wind. The distribution of the inhomogeneous interstellar medium in the disk is important in determining the morphology of this wind, as well as the distribution of the filaments. In the global simulations, I find that soft X-ray emission arises from gas that has been mass-loaded from clouds in the disk, as well as from bow shocks upstream of clouds, driven into the flow by the ram pressure of the wind, and the interaction between these shocks.

The detailed study of the interaction of a single cloud with a supersonic wind has revealed that the ability of the cloud to radiate heat is crucial for its survival, allowing it to remain cool, suppressing the transverse expansion seen in the adiabatic case. A radiative cloud experiences a lower degree of acceleration and has a higher relative Mach number to the flow, diminishing the destructive effect of the Kelvin-Helmholtz instability on the cloud. While an adiabatic cloud is destroyed over a short period of time, a radiative cloud is broken up via the Kelvin-Helmholtz instability into numerous small, dense cloudlets, which are drawn into the flow to form a filamentary structure. The
The degree of fragmentation is highly dependent on the resolution of the simulation, with the number of cloudlets formed increasing as the Kelvin-Helmholtz instability is better resolved. Nevertheless, there is a clear qualitative trend, with the filamentary structure still persistent at high resolution. The geometry of the cloud effects the speed at which the cloud fragments; a wind more rapidly breaks-up the cloud in regions of least density. A cloud with a more inhomogeneous density distribution fragments faster than a cloud with a more uniform structure (e.g. a sphere).

The study of an individual cloud interacting with a supersonic wind confirms the result of the global simulations of a starburst-driven wind: Hα emitting filaments can be formed from clouds accelerated into a supersonic outflow by the ram-pressure of the wind. Based on the resolution study, I conclude that bow shocks around accelerated gas clouds, and their interaction, are the main source of the soft X-ray emission observed in these galactic-scale winds.
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Now you shall know the truth,  
No matter how bleak, how black;  
If the white track leads to death,  
Heroes will not turn back.

It is better to climb the ridge  
And stare on chasms of air,  
Or stroke from the sea-cliff’s edge  
The sea’s dark strangling hair,

Than to run like a rat for cover  
When truth comes storming by.  
Better than huddling over,  
The sinking coals of a lie.

To climb to the barren peak,  
Where the shape of truth must show.  
And no man, strong or weak,  
Can hide his head in the snow.

– Douglas Stewart

from

“The Fire on the Snow” (1941)
1. Introduction

In 1963, Lynds & Sandage reported the existence of ionized gas along the minor axis of the irregular galaxy M82. In light of this discovery, they proposed that a powerful explosion, of unknown origin, had expelled material from the nuclear region of the galaxy. In the following decades, the origin of the ionized gas in M82 remained the subject of much debate. Solinger et al. (1977) proposed a model where M82 is an inter-loper in the M81 group, interacting with an extensive, dusty cloud that is scattering light from the galaxy. In this model, no expulsion of gas needs to be invoked and M82 is simply a normal spiral galaxy. Not long after, Axon & Taylor (1978) observed line profiles in M82, that are similar to those observed in the expanding Crab nebula. This could not be easily explained by a model requiring the scattering of light. They also observed line widths in the filaments that were significantly narrower than those in the host galaxy, an observation easily explained by a model in which the gas is expanding. The evidence for an explosion in M82 was mounting. In 1985, Chevalier & Clegg proposed a model in which an outflow could be driven from a galaxy by the combined energy of supernovae in high star forming regions. M82, being the prototype starburst galaxy, would be a perfect platform to observe these galactic-scale winds. In 1988, Bland & Tully detected the wind-like kinematics observed by Axon & Taylor (1978), but on a significantly larger scale, and showed that the filaments in M82 are in fact superposed onto a diffuse polarised halo, thus confirming the galactic wind hypothesis.

Over 40 years since their discovery, we now know that galactic winds are ubiquitous in starburst galaxies, powered by their characteristically high star formation rates. The major products of this star formation are large OB stars, which end their short lifetimes in large supernova explosions, making starburst galaxies the perfect breeding ground for these supernova-driven outflows. Galactic winds have now been observed in all nearby, edge-on starburst galaxies, and are detected by the presence of enhanced minor-axis emission and double-peaked emission line profiles, typical to those of an expanding shocked shell (Lehnert & Heckman, 1996). While detection is more difficult, winds have been inferred in less inclined galaxies using absorption line techniques, and are also seen in galaxies at high-redshifts (e.g. Veilleux et al., 2005).
Introduction

The prevalence of galactic winds makes them an important phenomenon on many levels. Not only is the study of their nature and structure of interest, but the impact of the outflow on the host galaxy, its interstellar medium (ISM) and the surrounding environment need to be considered. Galactic winds are in particular thought to have an impact on dwarf galaxies, whose shallow potential wells may enable the winds to easily escape, transporting the galaxy's ISM out into the intergalactic medium (Dekel & Silk, 1986). On the other hand, the gravitational potential of a more massive galaxy may prevent the ISM from escaping, with the gas falling back into the plane of the galaxy. This would replenish the ISM of the galaxy and possibly fuel additional star formation. Another consequence of galactic winds is the transport of metals out of the host galaxy, which may play an important role in the chemical evolution of galaxies (Martin et al., 2002). They are also thought to be a primary source of metals in the intracluster medium, and may contribute to the heating of the intergalactic medium (Veilleux et al., 2005).

The complex nature of starburst winds makes multi-wavelength observations necessary in order to gain a better insight into their structure, with observations being made at optical, infrared (IR), ultraviolet (UV), X-ray and radio wavelengths. The morphology of the outflow can vary with wavelength. In M82, the Hα emission in the wind appears filamentary and is often limb-brightened. In the infrared (e.g. Engelbracht et al., 2006), observations reveal a filamentary system that extends several kiloparsecs along the minor axis. Although the IR emission is in part spatially correlated to the Hα emission, it is more extended both radially and vertically and has a wider opening angle. The distribution of the filaments also differs between galaxies. For example, the wind in M82 has a biconical structure (Shopbell & Bland-Hawthorn, 1998), while NGC 3079 is more egg-shaped (Veilleux et al., 1994). At X-ray wavelengths, Chandra observations have revealed increasing detail in starburst winds. The most striking result of these observations is the correlation between the X-ray and Hα emission on both small and large scales (e.g. Strickland & Stevens, 2000; Cecil et al., 2002; Strickland et al., 2002, 2004a), which suggests a physical relationship with the filamentary gas. Observations of M82 at ultraviolet (UV) wavelengths (Hoopes et al., 2005) also reveal a filamentary structure, which is well correlated with the Hα emission, suggestive of outflowing dust from the galaxy.

Despite the insight observations have provided into starburst winds, the physical mechanisms behind the emission, and how the observations at different wavelengths relate to each other is still not well understood. An excellent way of studying these outflows is through the use of hydrodynamical simu-
lations, which allow the entire outflow at all temperatures to be investigated. Over the past few decades, numerous hydrodynamical simulations have been made of these winds (e.g. Tomisaka & Ikeuchi, 1988; Tomisaka & Bregman, 1993; Suchkov et al., 1994; Strickland & Stevens, 2000). These simulations follow the formation of a wind in a variety of different environments and initial conditions. Until recently, computational limitations required these simulations to be two-dimensional and have a homogeneous ISM distribution. This hindered their ability to realistically model the interaction between the cool disk gas and the hot expanding wind. In order to explain the observational properties of a starburst-driven galactic wind, a model needs to investigate the impact of the wind on the clumpy interstellar medium. Indeed, these earlier simulations failed to form significant filamentary structures. Another limitation of these models is their inability to model more complex morphologies, such as asymmetries in the outflow. Low numerical resolution in the simulations also leads to overestimates in the calculated X-ray luminosities, as discussed by Strickland & Stevens (2000).

To overcome these limitations, a global model that incorporates a more realistic multiphase interstellar medium is needed. Towards that goal, I have performed a series of three-dimensional hydrodynamical simulations of a galactic wind in an inhomogeneous interstellar medium. Following from the work of Strickland & Stevens (2000), this model consists of a two part gravitational potential, described by a stellar spheroid and a disk, but includes a more realistic log-normal density distribution for the warm ISM. This allows us to follow the evolution of a starburst-driven wind as it interacts with clouds in the galaxy's ISM. Using this model I can gain a better understanding of how observations probe the structure of a starburst wind, with the three-dimensional nature of the simulations allowing the entire structure of the wind to be studied. By focusing on the inner region of the outflow, I can investigate at high numerical resolution the origin of the filamentary Hα emission and its relationship to the X-ray emitting gas.

In this thesis, I present the first three-dimensional model of a starburst-driven galactic wind. These simulations allow the evolution and structure of an outflow to be studied in greater detail than was previously possible. In Chapter 2, I provide an overview of the current literature, including a discussion on the formation of winds in starburst galaxies, as well as an overview on the observations of starburst winds and their inferred morphology and kinematics at various wavelengths. In Chapter 3, I review the previous hydrodynamical models of these objects and discuss some of the limitations and considerations that must be taken into account when designing a model of a starburst wind.
In Chapter 4, I discuss the PPMLR (Piecewise Parabolic Method with a Lagrangian Remap) code used in this thesis, and some of its key features that allow the realistic evolution of the gas to be simulated. In Chapter 5, I present the results of the first three-dimensional model of a starburst-driven wind. I discuss the effect of the inhomogeneous ISM on the evolution of the wind, and propose an origin for the filamentary Hα and spatially correlated X-ray emission. In Chapter 6, I build upon the global simulations presented in Chapter 5 and simulate the interaction of a single radiative cloud with a hot supersonic wind. I investigate the role of radiative cooling in the survival of the filamentary gas, and test the validity of the mechanisms proposed for the origin of the Hα and X-ray gas. I also perform an extensive resolution study in order to determine the impact of the assumed numerical resolution in the global simulations in Chapter 5. In Chapter 7, I summarise the conclusions and discuss the possible future directions of this work.
2. Starburst-Driven Winds

2.1 The Formation of a Wind

Winds are observed throughout the universe, from small-scale stellar winds to the colossal outflows in distant galaxies. The formation and evolution of a wind has been the subject of numerous analytical and computational studies, with the basic physics and structure thought to be well understood. The galactic-scale winds, which are the topic of this thesis, are considered to be analogous to a stellar wind-blown bubble, the physics of the which have been well studied and are discussed below.

2.1.1 Stellar Wind-Blown Bubbles

Massive O and B type stars are able to blow out a bubble of hot gas via their strong stellar winds. An excellent example of a wind-blown bubble occurs near the edge of the HII complex N44 in the Large Magellanic Cloud (Nazé et al., 2002). N44F is a bright circular HII region at the north west rim of N44, and is connected to the main nebula by a bright filament of gas (see Fig. 2.1). The bubble appears as a double ring structure, whose kinematics show to be expanding into the surrounding medium, that is well matched to accepted theory.

The phases of the evolution of a wind-blown bubble are similar to those seen in a supernova shell, and have been investigated in detail by Castor et al. (1975) and Weaver et al. (1977). The first phase is an initial period of expansion that lasts only a short period of time, and is followed by another short period of adiabatic expansion. The third phase of the evolution covers a significant fraction of the lifetime of the bubble, and has thus been the topic of numerous studies. Figure 2.2 shows the structure of a wind-blown bubble in this so called “snow-plow” phase, where the surrounding interstellar gas is swept-up into the wind. This phase is typically characterised by 4 different zones:

(a) The Stellar wind - A hypersonic wind is blown by the central star with
Fig. 2.1: Hubble Image of the stellar wind-blown bubble N44F (CREDIT: NASA, ESA, Y. Nazé [University of Liège, Belgium] and Y.-H. Chu [University of Illinois, Urbana]).

Fig. 2.2: Structure of a stellar wind-blown bubble in the “snow-plow” phase of its evolution.
2.1 The Formation of a Wind

velocity \(v_\ast\) and density

\[
\rho_w(R) = \frac{\dot{M}_w}{4\pi R^2 v_\ast},
\]

where \(R\) is the radius of the wind and \(\dot{M}_w\) is the mass loss from the star. As the wind expands, it encounters a shock at radius \(R_1\), with the energy of the gas being partially converted to thermal energy.

(b) The shocked stellar wind - This region occupies a large percentage of the volume of the bubble and is comprised mainly of shocked stellar wind material, but is also mixed with a small amount of interstellar gas evaporated from region (c). Energy is added to this region at a rate of \(\dot{E} = \frac{1}{2} \dot{M}_w v_\ast^2\).

(c) A shocked shell of interstellar gas - The ambient interstellar gas is swept-up by the wind as it expands. As radiative losses in this gas are high, it quickly collapses into a thin dense “shell”. As noted above, evaporation from this shell is the predominant source of mass in region (b). However, the mass loss from region (c) is in effect negligible as the shell continues to sweep up the surrounding interstellar gas. The mass-gain \(\dot{M}_b\) of region (b) via evaporation from region (c) is given by

\[
\dot{M}_b = \frac{16\pi}{25} \frac{M_c T_b^{5/2}}{k} R_s,
\]

where \(M_c\) is the mass of the shocked shell, \(R_s\) is the radius of the contact discontinuity separating the shocked stellar wind and the shocked interstellar gas, \(T_b\) is the temperature of the shocked stellar wind, and \(k(T) = CT^{5/2}\) is the thermal conductivity, with \(C = 1.2 \times 10^{-6}\) erg cm\(^{-1}\) K\(^{-7/2}\) (Spitzer, 1962).

(d) The ambient interstellar gas - The surrounding gas into which the bubble expands.

The outflow continues to expand into the ambient gas as it further evolves. However, if the density gradient of the surrounding gas decreases, or the bubble becomes more luminous, the wind may accelerate, with the dense shell breaking up via the Rayleigh-Taylor instability (Weaver et al., 1977).

2.1.2 Superbubbles and Superwinds

While observations of bubbles blown by the wind of a single massive star are relatively rare (Naze et al., 2002), winds formed in regions of high concentrations of O and B type stars are more common. OB associations are star clusters containing large fractions of O and B type stars, and are found in regions...
of high star formation. An expanding structure that arises from these regions is commonly known as a superbubble (e.g. Chu & Mac Low, 1990; Dunne et al., 2003; Pidopryhora et al., 2007). In general, a superbubble can be treated as a very large wind-blown bubble, and follows a similar evolutionary pathway. The formation and evolution of a superbubble has been studied in depth by many authors in the past (e.g. Tomisaka & Ikeuchi, 1986; Mac Low & McCray, 1988; Mac Low et al., 1989; Norman & Ikeuchi, 1989), and more recently by, for example, Arthur (2008).

Initially, a hot cavity of gas is created by the collective stellar winds from the OB stars, with the outflowing bubble ultimately powered by the energetic supernovae that form as the massive stars reach the end of their short lifetimes (McCray & Kafatos, 1987). Figure 2.3 (see Heckman et al., 1990) illustrates the structure of a superbubble in two of its evolutionary phases, based on the simulations of Tomisaka & Ikeuchi (1988). Panel (a) shows the wind in the superbubble phase of its evolution. In this phase, the wind has been expanding into a dense stratified disk that has a scale height $SH$, with the surrounding disk gas being swept-up into a dense shell $S$. Similar to the internal structure of a stellar-wind bubble (Fig. 2.2), the interior to the dense shell surrounding the superbubble is made up of a freely expanding wind $FW$ and shocked wind material $SW$, which are separated by a wind shock $WS$. After the bubble has expanded to a few disk scale heights in size, the dense shell of swept-up disk gas begins to fragment via the Rayleigh-Taylor (RT) instability and the wind will “blow-out” of the shell, the physics of which have been studied in detail by Mac Low et al. (1989). At this point the superbubble is said to become a “superwind” (Panel b) that freely expands into the ambient gaseous halo $GH$. As
the wind expands, it sweeps up and shock heat clouds $SC$ in the halo, forming bow shocks $BS$ upstream of each cloud’s position. A second shell of diffuse halo gas forms as the tenuous ambient halo gas is swept-up by the wind (e.g. Strickland & Stevens, 2000).

### 2.2 Winds in Starburst Galaxies

Winds also form on galactic scales, with the best known example being the outflow in the starburst galaxy M82. Many galaxies which play host to a galactic-scale wind are known to contain both a starburst and an active galactic nucleus (AGN), with the mechanism that powers the wind ambiguous. However, while some galactic winds are known to be powered by active galactic nuclei (e.g. IC 5063; Morganti et al., 2007), starbursts are often considered to be the dominant mechanism, being sufficiently energetic to drive the outflows in many galaxies (e.g. NGC 1482; Veilleux & Rupke, 2002). The structure of a starburst-driven wind is similar to that of the superbubbles discussed above; an excellent review of their physics and evolution is given in Veilleux et al. (2005). Many hydrodynamical models have been made of these objects and are discussed in Chapter 3. In the following sections, I give an overview of the known properties of starbursts, and discuss the observational characteristics of a galactic-scale wind.

#### 2.2.1 Starbursts

A starburst is characterised as a region of high star formation that is unable to sustain its current star formation rate for a significant fraction of the Hubble time (see Gallagher, 2005, for review). The major product of the star formation is large O and B type stars that have short life times, which end in violent supernova explosions. Together, the supernovae are able to power an outflow (Chevalier & Clegg, 1985). In the local universe, an excellent example of a starburst is 30 Doradus in the Large Magellanic cloud, which is the site of intense star formation (e.g. Walborn et al., 1999). However, starbursts are also found on galactic scales (Rieke et al., 1980). The star formation is often circumnuclear, but can occur throughout the galaxy disk (e.g. NGC 4631; Golla & Wielebinski, 1994). The triggering mechanism for a galactic-scale starburst is still not completely understood, but tidal interactions are thought to be a necessary criterion (Larson & Tinsley, 1978). For example, while NGC 1569 is known to be a relatively isolated galaxy, Mühle et al. (2005) find evidence in NGC 1569’s halo for the interaction with a large body of neutral hydrogen, and suggest that the
starburst may have been triggered by the interaction of the galaxy with an intergalactic HI cloud. On the other hand, some authors have suggested that galaxy interactions are in fact poor starburst triggers (e.g. Bergvall et al., 2003).

M82 has long been studied as the prototypical example of a starburst galaxy, and thus has perhaps the best understood properties and star formation history (e.g. Rieke et al., 1980; Lugten et al., 1986; O'Connell et al., 1995; Förster Schreiber et al., 2003; Mayya et al., 2004; Smith et al., 2006). It is located in the M81 group of galaxies, at a distance of $\sim 3.1$ Mpc, (Solinger, 1969) and is interacting with its nearest neighbours M81 and NGC 3077 (Yun et al., 1994; Chynoweth et al., 2008). This interaction is known to have had a considerable impact on the galaxy. For example, the tidal interaction between M81 and M82 is thought to have truncated the disk in M82, causing the fall-off observed in M82's rotation curve at large radii (Sofue, 1998). The interaction is also thought to be the triggering mechanism for the extreme starburst seen in the center of the galaxy (Fig. 2.4). Förster Schreiber et al. (2003) investigated the starburst in M82 in great detail and determined that M82 has in fact undergone two different starburst episodes. Their proposed star formation history for M82 is illustrated in Figure 2.5 and summarised below:
Fig. 2.5: Schematic of the star formation history in M82 from Förster Schreiber et al. (2003). The top three panels show the galaxy orientated from the top, illustrating the bar of the galaxy, while the bottom panel has been rotated to present the galaxy edge-on in order to show the galactic wind.
(i) Approximately 100 million years ago, the tidal interaction between M82 and M81 caused the ISM in M82 to experience large-scale torques and loss of angular momentum. The infall of material into the central regions of the galaxy results in a marked increase in star formation in the central kiloparsec of the galaxy.

(ii) Around 8-10 Myr ago, M82 underwent its first starburst episode, with the star formation being the most enhanced within the central few tens of parsecs. This star formation was rapidly exhausted.

(iii) Around 4-6 Myr ago, a second starburst episode was triggered by bar induced resonances in the disk. This burst was also short lived and mainly confined to the circumnuclear region of the galaxy.

(iv) Today, the starburst-driven outflow in M82 has broken out of the disk, appearing in the optical as the spectacular filamentary system seen along the minor axis of the galaxy. This outflow may have played a role in triggering the second starburst through feedback processes.

Since their discovery, starbursts have been characterised as regions of intense star formation. However, improved imaging of these regions over the last decade or so has revealed that they are in fact made up of numerous super star clusters (SSC) (e.g. O'Connell et al., 1995; Watson et al., 1996; Hunter et al., 2000; Melo et al., 2005; Westmoquette et al., 2007a,b). These massive star clusters are typically young, compact and have high luminosities (Ho, 1997). The starburst in M82 is known to contain at least 197 SSC's, with more possibly hidden behind dark lanes in the disk (Melo et al., 2005). These clusters have radii of approximately $5.7 \pm 1.4$ pc, and have high masses and surface densities. Smith et al. (2006) find that 86 of these clusters reside in a single region, with a major component on M82's wind centered over it. This relationship of the outflow with the SSC's is also seen in NGC 1569 (Westmoquette et al., 2008). In this galaxy, the outflow appears as 4 different bubbles that originate near the main clusters in the starburst, but are thought to have yet to "blow-out" and expand freely into the surrounding medium. The major super-shell's present in the outflow appear to be each associated with a young massive cluster.

2.2.2 Optical Observations of Starburst Winds

The most famous feature of a starburst-driven wind are the filaments that manifest themselves at optical wavelengths. These filaments were first imaged in M82 by Lynds & Sandage (1963), and were subsequently shown by Axon
& Taylor (1978) and Bland & Tully (1988) to have line profiles similar to those observed in the Crab nebula (e.g. Hα line splitting) indicating that the filamentary material is indeed outflowing. With further observations of M82 and other winds (e.g. McCarthy et al., 1987; Heckman et al., 1987, 1990), the premise of winds powered by bursts of star formation was generally accepted. While the filaments are often seen in the light of Hα, they are also detected in observations of other emission lines, such as NII, OII, and OIII. For example, the wind in NGC 1482 is more visible in NII than in Hα (Veilleux & Rupke, 2002), while the filaments in the outflow in the Circinus galaxy are seen in OIII (Veilleux & Bland-Hawthorn, 1997).

The outflow in M82 is the best known and studied example of a starburst-driven wind (Fig. 2.6). However, it is also an extreme example resulting from to the nature of the starburst by which it is powered: the starburst in M82 consists of approximately 197 known luminous super star clusters, whereas the starbursts in NGC 1569 and NGC 253 are known to consist of only 45 (Hunter et al., 2000) and 4 (Watson et al., 1996) respectively. Consequently, there exists a large body of literature relating to the starburst in M82 and its outflow, and as such I will use it as an illustrative example of a starburst wind. Early
observations of the outflow were significantly extended upon by Shopbell & Bland-Hawthorn (1998) who studied the outflow in great detail. They found the outflow to have an asymmetric bipolar structure, in which the northern wind extends to a distance of approximately 3.5 kpc along the the minor axis. These filaments display a chaotic structure that fans out at a large opening angle. Conversely, the southern wind extends to only approximately 2 kpc, and the filaments are more collimated than those observed in the northern outflow. The filaments in both northern and southern outflows are particularly bright in the inner 1 kpc region. Hα emission has also been observed at a distance of ~ 11 kpc from the galaxy plane (Lehnert et al., 1999), and is known to be connected to the main superwind emission by a bridge of soft X-ray emission (Stevens et al., 2003).

Ohyama et al. (2002) imaged the outflow using the Subaru telescope and revealed additional structure, such as “shell and loop-like” structures in each filament. They break down the emission into two distinct components: a ridge component (i.e. the filamentary emission) and a diffuse component associated with dust scattered light in the halo. A schematic for their proposed structure of the outflow is given in Figure 2.7. In this model, the filaments are thought to lie on the surface of a pair of cylinders and are limb-brightened in the optical. Indeed, neither Shopbell & Bland-Hawthorn (1998) or Ohyama et al. (2002) find evidence that the filaments are volume-filled. While Ohyama et al. (2002) attribute the morphology of M82 to be that of a pair of cylinders, other authors suggest that it can be better described as a pair of cones arranged as a funnel (e.g. McKeith et al., 1995; Shopbell & Bland-Hawthorn, 1998). McKeith et al. (1995) find that the profile is cylindrical to a height of z < 300 pc, flaring out to become conical after a height of z > 300 pc. They suggest that the sudden shift in morphology is a result of the wind breaking-out of the disk and then expanding freely into the halo. The velocity of the filaments is known to be in the range of 500 - 800 km s⁻¹ (Shopbell & Bland-Hawthorn, 1998; Greve, 2004) and is thought to increase with distance above and below the disk. Greve (2004) also detect rotation in the outflow, which decreases with greater distance from the disk. At a height of 500 pc, the outflow is rotating slowly with a velocity of ~ 50 km s⁻¹ and will likely take around 10 million years to complete a single rotation.

While M82 has a classic hourglass shape, the morphology of galactic winds can vary. Figure 2.8 shows a selection of starburst-driven winds from the study of Strickland et al. (2004a), where pink is the Hα emission, blue is soft X-ray emission, and green is I-band starlight. It can be immediately seen that the morphology of the outflow differs from galaxy to galaxy. Like M82, the out-
Fig. 2.7: Proposed schematic of the structure of the emission in the outflow in M82 from Ohyama et al. (2002).
flows in NCG 253, NGC 1482, and NGC 4945 all have an hourglass-like appearance, although not on the same scale as the wind in M82. On the other hand, NGC 3079 has a more bubble-like appearance, with the entire western hemisphere of the outflow obscured by dust (Veilleux et al., 1994). The “bubble” is arranged into 4 distinct bundles that emerge from a CO ring in the disk (Cecil et al., 2001). At greater heights these filaments become less defined and appear as a “spray of loops and arches” that seem to be falling back into the galaxy. The outflow velocity of the filaments in NGC 3079 is of the order of \( v = 1500 \text{ km s}^{-1} \), which is significantly faster than the velocity of the filaments in M82. It is likely that the differing morphology between winds is related to nature of the ISM of the host galaxy into which the wind flows, producing tilts and asymmetries. The starburst itself is also likely to play a role, with its size and strength affecting the appearance and kinematics of the outflow. For example, the circumnuclear starburst in M82 produces a collimated outflow, while the outflow in the disk wide starburst in NGC 4631 appears to be emanating from the entire disk (Strickland et al., 2004a).

While considerable effort has gone into observing the filaments in starburst winds, their origin remains unclear, with a commonly accepted theory being that this material is cool disk or halo that has been entrained into the outflow (e.g. Suchkov et al., 1994). The ionization mechanism of the filaments is also of interest. Photoionization is thought to be an important ionizing mechanism in many winds (e.g. M82, NGC 253), with the incident radiation from the starburst ionizing the cool neutral gas in the outflow. Shock-ionization is also an important process and may dominate at greater heights and/or in fast flowing gas (Veilleux et al., 2005).

### 2.2.3 X-Ray Observations of Starburst Winds

Over the past few decades, starburst galaxies have been the target of numerous X-ray observations. Early studies (e.g. Einstein, EXOSAT, Ginga) revealed diffuse X-ray emission along the minor axis of the galaxy, which was considered to be associated with the superwind seen at optical wavelengths (e.g. Watson et al., 1984; Fabbiano, 1988; Schaaf et al., 1989; Fabbiano et al., 1990; Tsuru et al., 1990). As well as providing compelling evidence for the presence of soft X-ray emission in galactic winds, they also provided an early indication for the correlation with the H\(\alpha\) emission (Watson et al., 1984). With the launch of ROSAT, increasing detail was inferred in many known winds (e.g. Bregman et al., 1995; Heckman et al., 1995; Dahlem et al., 1996; Moran & Lehnert, 1997; Ptak et al., 1997; Strickland et al., 1997; Pietsch et al., 1998, 2000). These obser-
Fig. 2.8: Composite images of various galactic winds from Strickland et al. (2004a,b). Pink is Hα, Blue is X-ray emission and green is I-band starlight.

Observations further revealed the morphology of the X-ray gas to be similar to that of the optical filaments. For example, Strickland et al. (1997) found the emission to vary between the north and south winds, an asymmetry seen in the Hα gas. Filamentary structure also began to be observed in the soft X-ray emission (e.g. Pietsch et al., 2000).

More recently, higher resolution X-ray observations using XMM-Newton (e.g. Pietsch et al., 2001; Stevens et al., 2003; Bauer et al., 2007; Ranalli et al., 2008) and Chandra (e.g. Strickland et al., 2000; Prestwich et al., 2001; Smith & Wilson, 2001; Cecil et al., 2002; Martin et al., 2002; Strickland et al., 2002, 2004a; Strickland & Heckman, 2007) have provided a greater understanding of the morphology and properties (e.g. metallicity) of many winds. They also confirmed the hinted at correlation between the diffuse soft X-ray emission and the filaments, further revealing that this relationship is in fact a prevalent feature of galactic winds. For example, the correlation can be clearly seen in the bottom right panel of Figure 2.9, which shows the optical filaments (red) in the outflow in NGC 3079 and the related soft X-ray emission (blue) (Cecil et al., 2002).

Starburst-driven winds have also been the subject of many X-ray surveys (e.g. Read et al., 1997; Strickland et al., 2004a,b; Ott et al., 2005a,b; Grimes et al., 2005). Strickland et al. (2004a) imaged numerous starburst winds at both X-ray and Hα wavelengths (Fig. 2.8). Despite the varying morphologies of the winds in their sample, they again observed the spatial correlation between the two gaseous species. While these surveys, along with observations of individual galaxies, have provided a wealth of data on the X-ray properties of many
winds, below I will focus on the morphology of the outflows in 4 well known and studied starburst galaxies, which are depicted in Figure 2.9:

(a) M82 - Diffuse soft X-ray emission (red) is observed along the minor axis of the galaxy, with harder point sources (blue) seen in the starburst region. This emission is asymmetric (e.g. Strickland et al., 1997, 2004a), with the northern outflow extending ~ 14 kpc and the southern outflow ~ 7.5 kpc (Stevens et al., 2003). This emission appears filamentary and coincides with regions of Hα emission (e.g. Strickland et al., 2004a). There is also evidence for the outflow interacting with HI streamers in the halo (Yun et al., 1993), with the X-rays in the northern wind extending to the “cap” seen in Hα observations (Stevens et al., 2003).

(b) NGC 1569 - Martin et al. (2002) imaged NGC 3079 in ultra soft (0.3-0.7 keV; red), soft (0.7-1.1 keV; green), and hard (1.1-6.0 keV; blue) X-ray bands. They found the diffuse X-ray halo emission to be comprised of multiple lobes, with the southwest arm being more limb-brightened than the other lobes, possibly due to an interaction with known molecular clouds in the vicinity. These features were also observed in an earlier observation by Heckman et al. (1995), who detected diffuse emission in the halo to a distance of ~ 12 kpc in the soft ROSAT (0.1-2.4 keV) band. Curiously, Martin et al. (2002) also detect X-ray emission throughout the wind volume in the ultra soft band, which they attribute to the hot wind material itself.

(c) NGC 253 - As with M82, the wind in NGC 253 is observed as a well collimated outflow of diffuse soft X-ray emission (red) along the minor axis of the galaxy (e.g. Strickland et al., 2000, 2002; Bauer et al., 2007). Again this emission has a filamentary structure (e.g. Pietsch et al., 2000), which is well correlated to the Hα emission, out to a distance of ~ 900 pc in the southeastern direction and ~ 450 pc in the northwestern direction (Strickland et al., 2000). A notable feature is the luminous soft X-ray emitting ridge along the northern limb (Strickland et al., 2002).

(d) NGC 3079 - The spatial correlation between the soft X-ray emission (blue) and the Hα filaments (red) is particularly apparent in the outflow in NGC 3079 (Cecil et al., 2002). While a counter bubble is not seen in the optical, most likely due to its obscuration by the disk, evidence for its existence can be seen at soft X-ray wavelengths. The emission is known to have an X-shaped morphology centered on the starburst nucleus (Pietsch et al., 1998; Cecil et al., 2002; Strickland et al., 2004a); the bubble is considered to be at least partially volume-filled (Cecil et al., 2002).
Fig. 2.9: Chandra images of the winds in (a) M82, where red represent the soft X-ray emission in the halo and blue represents harder X-ray emission in the starburst region (CREDIT: NASA/CXC/JHU/D.Strickland); (b) NGC 1569, where red represents the ultra-soft X-rays, green soft X-rays, and blue hard X-rays (CREDIT: NASA/CXC/UCSB/C.Martin et al.); (c) NGC 253, where red is the soft X-ray emission (CREDIT: NASA/SAO/CXC); and (d) NGC 3079, where red is Hα emission and blue is soft X-ray emission (CREDIT: NASA/CXC/STScI/U.North Carolina/G.Cecil).
Proposed Origins for the X-ray Emission

The origin of the X-ray emission is a question of particular interest. Understanding its origin is the motivation behind several hydrodynamical models discussed in Chapter 3. The nature of the physical mechanism(s) behind the emission could have an impact on observational constraints of, for example, the metallicity and energetics in a starburst-driven wind. While the diffuse hard X-ray emission is somewhat constrained, having been observed to be more luminous in the starburst region itself (e.g. Strickland & Heckman, 2007), the origin of the soft X-rays is less certain. Strickland et al. (2002) discussed several models for the origin of the soft X-ray emission, relating in particular to their Chandra observations of NGC 253. A detailed discussion on the plausibility of each model can be found in their paper; the main features are summarised below:

(i) **Cooling radiation from the wind** - If the cooling time of the wind is less than the age of the outflow, it is possible that it may cool to emit at soft X-ray energies. Strickland et al. (2002) rule out this model as it cannot reproduce the observed X-ray morphology, nor explain the correlation to the Hα gas.

(ii) **Shocked clouds in the halo** - Preexisting clouds in the halo (e.g. HI clouds) may be shock heated to emit at Hα temperatures as they are overrun by the wind. Soft X-rays could arise from bow shocks upstream of the Hα emitting clouds, naturally explaining the observed correlation. This model would also explain asymmetries in the wind (Strickland et al., 2002), but cannot produce filaments that trace back to the starburst region (e.g. Cecil et al., 2002).

(iii) **Shocked disk gas carried into the halo** - Hα emission arises from shock heating or photoionization of disk gas that is transported by the wind into the halo. X-rays could arise from bow shocks, conductive interfaces, or the thermal mixing of the gas.

(iv) **Hot swept-up shell of halo gas** - If the cooling time of the swept-up shell is less than the age of the bubble, it may cool to form a thin radiative shell. Again this model is unable to account for the correlation with the Hα emission.

(v) **Swept-up thick disk and shocked wind** - In this model, the swept-up shell cools to form a thin shell that emits at Hα temperatures, with soft X-rays arising near the shell due to thermal conduction evaporating and the mixing of material from the shell into the hot wind fluid it surrounds.
Fig. 2.10: The prototypical starburst-driven wind in M82 seen at various wavelengths. Red represents mid-infrared emission from *Spitzer*, blue is soft X-ray emission from *Chandra*, and orange is Hα emission from *Hubble*. (CREDIT: X-ray: NASA/CXC/JHU/D.Strickland; Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht).

In reality, it is likely that a combination of mechanisms is responsible for the production of soft X-rays.

2.2.4 Observations at Other Wavelengths

While much attention has been paid to starburst winds in the optical and X-ray regimes, they have also been studied at numerous other wavelengths, e.g. molecular, ultraviolet, infrared, radio (see Veilleux et al., 2005, and references therein). At UV and IR wavelengths, there is again a strong correlation to the filamentary Hα emission and soft X-ray gas in M82. This is considered to be an indicator of the presence of dust in the outflow. For example, in ultraviolet observations, the filaments can be distinguished from a more diffuse UV background, and UV emission is also present in the Hα “cap” at a distance of ~ 11 kpc in the northern outflow of M82 (Hoopes et al., 2003).

At mid-IR wavelengths, the filamentary structure of the outflow in M82 is
striking and is extremely well correlated with the Hα and soft X-ray emission in the superwind region of M82 (Engelbracht et al., 2006). This correlation can be clearly seen in the composite Hα (orange) / soft X-ray (blue) / infrared (red) image of M82’s galactic wind in Figure 2.10. However, the mid-IR emission extends beyond the wind region defined by the Hα and X-ray gas, being more radially and vertically extended. It also appears to originate from all parts of M82’s disk. Engelbracht et al. (2006) suggest that some mechanism, prior to the current starburst episode, may have expelled dust from the disk into the halo, and that M82’s galactic wind is currently flowing into this dusty medium.

The morphology of a starburst-driven wind is highly dependent upon the wavelength at which it is observed. While the nature of the IR and UV emission, and the origin of the dust in the outflow, is a question of interest, it is beyond the scope of this work. Determining the mechanism for the formation of the filamentary optical emission, as well as the spatially correlated X-ray emission, is one of the major motivations behind this thesis, and is investigated in detail in Chapters 5 and 6. I also study the effect of inhomogeneities in the ISM of the host galaxy on the morphology and kinematics of an outflow.
3. HYDRODYNAMICAL SIMULATIONS

3.1 Previous Starburst Wind Models

Galactic Winds are complex multiphase objects that consist of gas ranging in temperature from a few tens to over a million degrees, making hydrodynamical simulations a valuable tool for studying the evolution and dynamics of these outflows and for developing a better understanding of the physics that govern them. While observations have provided many insights into the kinematics and structure of these wind, many questions have arisen which cannot be adequately answered by the observations alone. For example:

(i) What is the origin of the filaments seen at optical wavelengths in starburst-driven winds?

(ii) What is the origin of the soft X-ray emission and what is its relationship to the optical filaments?

(iii) What are the energetics of the outflow? Where is the energy stored, e.g. in the cool filamentary gas or the hot wind material? How efficient is the starburst in powering the outflow? Do starburst winds contribute appreciably to the heating the intergalactic medium?

(iv) Can galactic winds efficiently remove the ISM of galaxies? Is the outflow energetic enough for the wind material to be transported into the intergalactic medium or will it fall back into the plane of the galaxy, replenishing the ISM and fueling additional star formation (e.g. feedback)?

(v) Are galactic winds a significant source of the chemical enrichment of the intracluster medium? Can the metal enriched supernovae ejecta from the starburst escape the gravitational potential of the host galaxy?

Over the last few decades, hydrodynamical simulations have been used by many authors to provide estimates to these important questions, as well as improve our understanding of the formation and evolution of galactic winds. With improvements in computational technology and resources becoming more
readily available, models of galactic winds have become more detailed and complex. Early simulations were necessarily two-dimensional and had poor computational resolution, while later simulations built upon early models, but were at considerably higher resolution, included additional physics and employed more rigorous computational methods. Nevertheless, early simulations of starburst-driven winds provided many important insights into the overall structure and evolution which have been reproduced in all global simulations to date. For example, the wind always takes on the classical snow-plow structure as it expands into the ambient medium (see Section 2.1.2).

Most simulations of starburst-driven winds have adopted a global approach, simulating the formation of a wind from the plane of the galaxy and evolving into the surrounding medium. The starburst is typically modelled as a single large central source, having either a single large instantaneous injection of energy or a more gradual continuous deposition. However, a few simulations utilise stellar evolution models to produce a more realistic time-dependent es-
3.1 Previous Starburst Wind Models

An estimate of the star-formation history of the starburst (e.g. Suchkov et al., 1994). A gravitational potential for the galaxy and a homogeneous density distribution for the ISM is usually assumed, with later models adopting a two component gravitational potential to model both the disk and halo of the galaxy (e.g. Strickland & Stevens, 2000). While there have been many models of starburst-driven winds, which have been designed to investigate various aspects of their nature, such as the X-ray emission from different X-ray observatories (e.g. Tomisaka & Ikeuchi, 1988 [Einstein]; Tomisaka & Bregman, 1993 [Ginga]; Strickland & Stevens, 2000 [ROSAT]) and the transport of the ISM and metals into the IGM (e.g. D'Ercole & Brighenti, 1999; Mac Low & Ferrara, 1999; Dubois & Teyssier, 2008), the numerical strategies and results of a selection of several important studies are highlighted below.

3.1.1 Tomisaka & Ikeuchi 1988

In 1986, Tomisaka & Ikeuchi modeled the formation of a superbubble powered by the supernovae produced in OB associations. This work was soon followed by their early model of the formation of a galactic-scale bipolar outflow from a starburst nucleus (Tomisaka & Ikeuchi, 1988). These simulations were two-dimensional in nature and assumed the gravity of the stellar component to be dominant, ignoring the self-gravity of the gas. The density of the gas was modeled by a King distribution (eq. [3.1] and [3.2]), where $\rho_*$ and $\phi_*$ are the stellar density and potential respectively, $\omega$ is the radial distance from the center, $\rho_c$ is the central density, and $r_c$ is the core radius:

$$\rho_*(\omega) = \frac{\rho_c}{[1 + (\omega/r_c)^2]^{3/2}}, \quad (3.1)$$

$$\phi_*(\omega) = -4\pi G \rho_c r_c^2 \ln \left\{ (\omega/r_c) + [1 + (\omega/r_c)^2]^{1/2} \right\} \frac{\omega}{r_c}. \quad (3.2)$$

Tomisaka & Ikeuchi achieved radial force balance in their model by taking the azimuthal velocity to be a fraction of the keplerian velocity as described by equation 3.3, where $e = 1$ when the gravitational forces are azimuthal:

$$v_\phi(r) = \left( e^2 r \frac{\partial \phi_*}{\partial r} \right)^{1/2}. \quad (3.3)$$

This leads to the following expression for the density of an isothermal interstellar medium:

$$\rho(r, z) = \rho_0 \exp \left[ -\frac{\phi_*(\omega) - e^2 \phi_*(r) - (1 - e^2) \phi_*(0)}{c_s^2} \right], \quad (3.4)$$
where $c_s$ is the three-dimensional random velocity of the clouds. The starburst occurs in a defined region, with energy and mass deposited continuously into each cell of the starburst region.

Their simulations were designed to test the formation of a galactic scale wind under a variety of different conditions. The main results of their work are summarised below:

(a) **Effect of the mass-loss rate** - By increasing the amount of gas deposited into each cell of the defined starburst region, Tomisaka & Ikeuchi found an increase in the density of the shocked wind material, as well as an increase in the width of the free-wind region of the outflow.

(b) **Effect of the density distribution** - The introduction of an artificial plane stratified density distribution resulted in the outflow having a smaller vertical size and rounder appearance to a wind that forms in their standard density distribution. However, these differences were not significant. The density stratification lead to the formation of a bipolar outflow.

(c) **Effect of the ambient density** - An increase in the ambient density resulted in the slower expansion of the outflow (Fig. 3.1). The resultant bubble is structurally the same as that of a bubble expanding into a medium of lower ambient density.

(d) **Effect of the supernova rate** - Lowering the supernova rate (i.e. decreasing the energy injected by the starburst) resulted in the formation of an outflow that has the same structure and shape as an outflow powered by a more energetic starburst, but with a slower expansion rate. If the supernova rate is too low, most of the energy is radiated away and the bubble fails to break-out of the disk.

(e) **Comparison with a Single Explosion** - An outflow powered by a single powerful burst of energy is able to sufficiently power an outflow which initially expands faster than an outflow powered by the continuous deposition of energy. However, rapid cooling in the outflow results in temperatures that are too low to explain the X-ray emission observed in starburst-driven winds.

(f) **X-ray emission** - Tomisaka & Ikeuchi also determined the X-ray emission from their simulations in the *Einstein* Observatory HRI band (0.2 - 4 keV). They found X-ray luminosities in the $L_x = 10^{39} - 10^{40}$ erg s$^{-1}$ range. At low heights, the X-rays arise from the free-wind region, but at high $z$ arise from shocked wind material.
3.1 Previous Starburst Wind Models

3.1.2 Tomisaka & Bregman 1993

Tomisaka & Bregman (1993) modeled the formation of a starburst-driven wind over a 50 Myr period with the intent of providing a better understanding of the X-ray observations from Ginga. They adopted a similar approach to Tomisaka & Ikeuchi (1988) using a modified King model to describe the stellar density and gravitational potential (eq. [3.1] and [3.2]). As with Tomisaka & Ikeuchi (1988) they assume the azimuthal velocity to be a fraction of the keplerian velocity $v_{\text{rot}}$, but introduce the factor $e = e_{\text{rot}} \exp \left[ -\frac{z}{Z_d} \right]^2$ to produce slower rotation in the halo than the disk, i.e.

$$e = e_{\text{rot}} \exp \left[ -\frac{z}{Z_d} \right]^2,$$  \hspace{1cm} (3.5)

where $e_{\text{rot}} = 0.9$ and $Z_d = 5 \text{ kpc}$. This factor was introduced to compensate for the weak gravitational forces at large distances that result from the density distribution given in equation (3.4). However, note that Sutherland & Bildfell (2007) show that $e$ cannot be a function $z$ (see Section 5.2.1). Tomisaka & Bregman introduced a hot hydrostatic isothermal halo with initial density $\rho_{\text{hi}} = 2 \times 10^{-3} \text{ cm}^{-3}$. They also account for the radiative cooling of the gas, and include artificial viscosity for numerical stability at the shock front.

They performed a series of two-dimensional, cylindrically symmetric simulations with various ISM conditions, switching to a courser grid to follow the evolution of the outflow at later times. They describe the initial formation of the wind, where a spherical bubble is produced and driven along the minor axis of the galaxy, sweeping-up ambient gas as it expands. The swept-up gas...
is shocked as it is pushed into the surrounding medium and forms a shell of radiatively cooling gas around the hot bubble. The evolution of this bubble at 5 Myr and 10 Myr epochs is shown in Figure 3.2. By 10 Myr, the wind has begun to flow into the low density halo, and starts to accelerate upwards leading to the fragmentation of the surrounding cool dense shell. At later times, the structure and dynamics of the outflow are determined by the extended low density medium into which it is expanding. By altering the density and pressure of the isothermal halo, Tomisaka & Bregman found that the expansion of the outflow in the vertical direction is sensitive to the halo density, but less so to the halo pressure. On the other hand, expansion in the radial direction is sensitive to both, expanding at a faster rate into a halo of higher pressure or lower density.

In order to compare the estimated X-ray emission from their model to observations from Ginga, Tomisaka & Bregman estimated the X-ray emission in the Ginga LAC band (~ 1.56-8.265 keV). They also calculated the predicted X-ray emission in the Einstein Observatory HRI band (~ 0.284-1.56 keV) and in the 0.155-24.8 keV band. They found that their calculated X-ray luminosities are comparable to those reported in the outflow in M82 of $L_x \sim 4 \times 10^{39}$ erg s$^{-1}$ by Tsuru et al. (1990) in the 2-10 keV energy band. In the HRI band, they found the luminosity to remain constant across all models at $L_x \sim 5 \times 10^{40}$ erg s$^{-1}$, but to decrease in the LAC band from $L_x \sim 3 \times 10^{39}$ erg s$^{-1}$ to $L_x \sim 1 \times 10^{39}$ erg s$^{-1}$ for models with a smaller mass-loss rates. They propose the origin of the X-rays in the soft HRI band to be from accumulated halo or intergalactic matter, while they suggest that the X-rays in the hard LAC band could possibly arise from the material ejected by the starburst.

3.1.3 Suchkov et al. 1994

Suchkov et al. (1994) improved upon the work of Tomisaka & Ikeuchi (1988) and Tomisaka & Bregman (1993) by considering the evolution of a starburst wind into a two-component interstellar medium consisting of a distinct disk and halo. They adopt the same spherically symmetric stellar component, but make an allowance for a dark matter contribution. The density of the stellar spheroid component is given by

$$\rho_{\text{tot}} = \frac{\rho_1}{[1 + (R/r_{c1})^2]^{3/2}} + \frac{\rho_2}{[1 + (R/r_{c2})^2]},$$

where $\rho_1$ and $r_{c1}$ are the central density and core radius of the stellar component, and $\rho_2$ and $r_{c2}$ are the central density and core radius of the dark halo component. The corresponding gravitational potential is $\phi = \phi_1 + \phi_2$, where $\phi_1$
is given by equation (3.2) and $\phi_2$ by

$$
\phi_2 = -4\pi G \rho_2 r_{c2}^2 \left\{ 0.5 \ln \left[ 1 + \left( \frac{R}{r_{c2}} \right)^2 \right] + \frac{\tan^{-1}(\frac{R}{r_{c2}})}{\frac{R}{r_{c2}}} - 1 \right\}.
$$

The initial density distribution of the gas is the same as that used by Tomisaka & Ikeuchi (1988) (eq. [3.4]), with the interstellar gas consisting of a dense rotating disk of cool dense gas and a static halo of hot tenuous gas. The halo does not rotate in order to reduce the collimating funnel produced by the density distribution.

They considered 4 different models, each with varying interstellar gas properties, and mass and energy deposition rates:

(a) Model A1 has a continuous time-dependent mass and energy deposition rate based on a Leitherer et al. (1992) stellar population model, and displays a similar development to the outflow in the model of Tomisaka & Ikeuchi (1988). However, they found the wind to be collimated by the dense disk, with disk material being dragged out by the wind to form the extended walls of a biconical cavity. Disk and halo material is also swept-up to form a shell that surrounds the bubble of hot gas.

(b) Model A2 differs from A1 by considering a higher central density and a larger disk thickness. It also incorporates the gravitational field from a thin
exponential disk. The presence of a thicker disk results in the wind breaking out of the disk obliquely, rather than perpendicular as seen in all other models. Despite this, at later times the wind displays a similar morphology to the outflow in A1, but with the hottest gas occupying a smaller central region.

(c) Model B1 utilises the same continuous energy and mass deposition rates as Tomisaka & Ikeuchi (1988) of $M = 1 \, M_\odot \, \text{yr}^{-1}$ and $\dot{E} = 10^{50} \, \text{erg} \, \text{yr}^{-1}$. Due to the higher energy injection rate, the expansion of the wind is more rapid and results in more energetic outflow dynamics.

(d) Model B2 is characterised by a tenuous ISM which is unable to provide the same degree of confinement to the wind as the thicker disk in the other models. In this model, the shocked, swept-up disk gas is torn to shreds and drawn into the wind, allowing Suchkov et al. to briefly look at the interaction of the wind with a cloud of gas.

As with Tomisaka & Bregman (1993), Suchkov et al. estimated the X-ray emission in 3 different bands (0.1-0.7, 0.7-2.2, and 1.6-8.3 keV), allowing them to draw conclusions about the origin of the soft and hard X-ray emission in starburst winds. The first two bands approximate the soft X-ray emission, which was found to originate from shocked disk and halo gas, and not from the wind itself, while the hard X-ray emission in the 1.6-8.3 keV band was found to arise from the wind material itself. However, they conclude that this is an unlikely origin for the hard X-ray emission based on observations of M82, which show the soft and hard luminosities to be of the same order of magnitude, whereas their models predict smaller hard X-ray luminosities. Based on their models, they propose that the line-emitting gas, seen as the filaments in starburst-driven winds, may form from disk gas that is drawn out from the disk, with shocked clouds being a significant contributor to the thermal soft X-ray emission.

3.1.4 D’Ercole & Brighenti 1999

D’Ercole & Brighenti (1999) took a slightly different approach to the models discussed above, and similarly to Mac Low & Ferrara (1999), focused on modelling the galactic winds from dwarf starburst galaxies. They assume an homogeneous ISM and neglect the self-gravity of the gas. The gravitational potential in their model consists of two parts: A spherical quasi-isothermal dark matter halo and a thin stellar disk. The dark matter halo is described by equation (3.1), with the halo being truncated at a radius of 20 kpc. The stellar component is
described by a Kuzmin’s disk, which has surface density:

\[ \Sigma_*(R) = \frac{r_* M_*}{2\pi (R^2 + r_*^2)^{3/2}} \]  

where \( r_* \) is the radial scale-length and \( M_* \) is the total stellar mass. The gravitational potential from this density distribution is given by:

\[ \Phi_*(R, z) = -\frac{G M_*}{\sqrt{R^2 + (r_* + |z|)^2}}. \]

The starburst was assumed to be an instantaneous burst of star formation, which injects energy into the ISM over a period of 30 million years. Two different starburst strengths were considered, having energy injection rates of the order \( \dot{E} = 10^{39} \text{ erg s}^{-1} \) and \( \dot{E} = 10^{40} \text{ erg s}^{-1} \) respectively. The second was chosen to have a mechanical power similar to that of the starburst in the dwarf starburst galaxy NGC 1569.

In order to investigate the effects of dark matter and thermal conduction, D’Ercole & Brighenti performed four simulations: (i) a standard simulation, (ii) a simulation in which the ISM was replaced with a hot intracluster medium, (iii) a simulation in which dark matter and the rotation of the gas was removed, and (iv) a simulation identical to (iii), but which includes the effects of thermal conduction. In particular, they looked at the efficiency of an outflow in transporting the ISM and metal enriched supernovae ejecta out of the galaxy, as well as the implied X-ray emission from the wind.

D’Ercole & Brighenti followed the evolution of the wind in their standard model over a period of 500 million years (Fig. 3.4). Again they report the formation of a wind with a classical snow-plow structure, where the bubble sweeps-up the ambient ISM as it expands. The shape of the outer shell of swept-up gas changes as the wind evolves, and takes on a bipolar structure at late times. They found that the rate of expansion of the bubble was dependent on the strength of the starburst, with the bubble evolving more slowly and having more difficulty breaking out of the gravitational potential of the galaxy in models with a weaker starburst. The inclusion of thermal conduction in one of the models altered the density and velocity of the outflow; as the velocity of the wind is lower and the density of the hot gas increases when conduction is considered. In all models, the shell fragments via Rayleigh-Taylor instabilities as the bubble is accelerated due to a steepening in the density gradient. This results in the formation of “filamentary” structures. At late times the outflow begins to collapse back into the galaxy, eventually recovering a “normal” ISM.

They found that galactic winds are not efficient at removing the ISM from dwarf galaxies and that a galaxy is able to recover a normal ISM after a period
of $\sim 100$ Myr. In the absence of a dark matter halo, the ISM returns to normal at a faster rate. On the other hand, they found that dwarf galaxies are better able to transport the enriched stellar ejecta into the intergalactic medium. This is particularly true for their simulations that employed a more powerful starburst. In contrast to Suchkov et al. (1994), they found the majority of the soft X-ray emission to arise from broadened contact discontinuities that may mimic thermal conduction and/or the turbulent mixing of the gas. D’Ercole & Brighenti suggest that the shocked shell in their models may be too slow to emit at X-ray temperatures, as seen by Suchkov et al. (1994), due to the comparably lower energy injection rates they employed.
3.1.5 Strickland & Stevens 2000

The most recent major attempt at globally modeling the galactic-scale winds from starburst galaxies was by Strickland & Stevens (2000). Their main focus was investigating the X-ray emission and energetics of the outflow. They use a similar approach to Tomisaka & Bregman (1993) and Suchkov et al. (1994) and adopt an ISM that consists of a cool disk and and a hot halo, which is in rotating hydrostatic equilibrium. They consider two different ISM distributions, a “thick disk” model and a “thin disk” model. The gravitational potential of the thick disk model consists of a stellar spheroid and is described by a modified analytic king model given by equation (3.2). For the thin disk model, a Miyamoto & Nagai (1975) disk potential (eq. [3.10]) is added in order to more accurately reproduce M82’s rotation curve, where $M_{\text{disk}}$ is the mass of the disk, and $a$ and $b$ are the radial and vertical scale heights respectively:

$$\Phi(r, z) = -\frac{GM_{\text{disk}}}{\sqrt{r^2 + (a + \sqrt{r^2 + b^2})^2}}. \quad (3.10)$$

The ISM is assumed to be supported predominantly by rotation (eq. [3.3]), and as with Tomisaka & Bregman (1993) the rotational velocity is decreased above the plane of the galaxy (eq. [3.5]).

The density distribution of the warm and hot ISM is of the form:

$$\rho(r, z) = \rho_0 \exp \left[ -\frac{\Phi_{\text{tot}}(r, z) - e^2\Phi_{\text{tot}}(r, 0) - (1 - e^2)\Phi_{\text{tot}}(0, 0)}{c_{\text{s}}^2} \right], \quad (3.11)$$

where the density $\rho$ is different for the disk and halo, $\rho_0$ is the initial density of the disk or halo, $\Phi_{\text{tot}}$ is the sum of the gravitational potentials of the stellar spheroid and disk, and $c_s$ is the sound sound speed of the disk or halo. In order to simulate the turbulent pressure support seen in the disks of real galaxies, Strickland & Stevens increase the isothermal sound speed of the gas in the disk, imposing a minimum allowed temperature in the disk of $T_{\text{disk}} = 6.5 \times 10^4$ K.

Strickland & Stevens considered three different starburst scenarios: (i) a single instantaneous burst of total mass $M_{\text{tot}} = 10^8 \, M_\odot$, (ii) a weaker single instantaneous burst of total mass $M_{\text{tot}} = 10^7 \, M_\odot$, and (iii) a starburst with the same total mass as (i), but with a more complex star formation history spread out over a 10 Myr period. For their thick disk models the starburst region is assumed to be a sphere of radius 150 pc, while a cylinder of radius 150 pc and height 60 pc was adopted for the thin disk models.

They account for the effects of mass ablation from clouds that have been overrun by the wind, and have added material to the flow (e.g. ablation), by
Fig. 3.5: Logarithm of the number density in the thin disk model of Strickland & Stevens (2000) showing the evolution of a wind over a 9.5 Myr interval.

a process known as “mass-loading”. This process was previously investigated by Suchkov et al. (1996) who determined that a central mass-loading rate of \( \dot{M} = 5 M_\odot \text{yr}^{-1} \) is best able to reproduce the observed X-ray luminosities observed in M82. In their simulations, Strickland & Stevens consider two different hydrodynamical scenarios:

(a) **Central mass-loading**- Assumes that the majority of the cloud material exists within the starburst region itself. Following the approach of Suchkov et al. (1996), they increase the mass deposition rate from 1 \( M_\odot \text{yr}^{-1} \) to 5 \( M_\odot \text{yr}^{-1} \).

(b) **Distributed mass-loading**- Assumes that the clouds are distributed throughout the disk. This scenario was simulated by fixing a constant maximum mass-loading rate over the entire grid. Each cloud is assumed to have the same size, density, and temperature. At each time step, the local Mach number \( M \) and the cloud mass-loading rate \( \dot{q} \) is calculated:

\[
\dot{q} = \begin{cases} 
Q \times M^{4/3} & \text{if } M < 1.0 \\
Q & \text{if } M \geq 1.0 
\end{cases} \tag{3.12}
\]
where

\[ Q = a \left( \frac{\rho_w v_w k T_c \rho_c^2}{\mu m_p \rho_c^3} \right)^{1/3}, \]  

(3.13)

and \( \rho_w \) and \( v_w \) are the density and velocity of the surrounding flow; \( \rho_c, T_c, \) and \( v_c \) are the density, temperature, and velocity of the clouds; and \( a \) is a constant of order unity. The above condition for distributed mass-loading is based on the assumption that a supersonic wind will destroy a cloud more quickly than a subsonic wind, where the cloud will slowly lose material via Rayleigh-Taylor and Kelvin-Helmholtz instabilities. The mass-loading is set to end when all the cloud’s mass has been removed and the cloud is in effect “destroyed”.

In all, they performed twelve simulations: seven utilizing the thick disk ISM and five using the thin disk ISM. These simulations were designed to investigate the effects of central and distributed mass-loading, the properties of the interstellar medium, the star formation history, and the computational resolution on the resultant outflow. The evolution of the wind in all their simulations follows a similar pattern, with the wind initially appearing to have the standard structure of a superbubble (see Section 2.1.2). By 5 Myr the wind has blown out of the disk and the dense superbubble shell fragments under the Rayleigh-Taylor instability. At this stage, the spherical reverse shock separating the shocked wind and the free-wind region becomes elongated. A new shell is formed as halo gas is swept-up into the outflow. As the outflow evolves, the fragments of the original dense shell are carried out of the disk.

The extensive parameter study allowed them to investigate the effect of properties of the starburst and the host galaxy’s ISM on the resultant outflow. They confirm the result of D’Ercole & Brighenti (1999) and find that smaller energy injection rates result in a slower evolution of the expanding bubble, but with an overall structure similar to that of a bubble powered by a more powerful starburst. A slower evolution was also observed when the starburst was modeled by the gradual deposition of mass and energy. The inclusion of mass-loading to the model altered the dynamics and structure of the bubble: Central mass-loading slows the growth rate of the bubble and alters the internal structure, but the overall global features remain the same as in the non-mass-loaded models. Distributed mass-loading results in an increase in the density of the gas in the free-wind and shocked wind regions. In addition, the reverse wind shock seen in the classic snow-plow structure is absent.

The thin disk utilized in some of their simulations also altered the evolution and morphology of the outflow. The thiner disk provides less confinement to the wind than the thicker disk, with the wind breaking out of the disk at an
Fig. 3.6: Isodensity contours ($\Delta \log p = 0.1$) with velocity field from the $Z = 10 \, Z_\odot$ model of Tenorio-Tagle et al. (2003). Each panel has a size of $100 \times 1000$ pc, and (from bottom to top) is at time $t = 1.79 \times 10^5, 4.82 \times 10^5, 1.05 \times 10^6, 1.39 \times 10^6$ years.

earlier time. As a result, the wind fans out at a larger opening angle, and possesses a larger free-wind region and a smaller dense shell of swept-up disk gas. The fragmentation of this thin shell results in fewer dense fragments, which are mixed into the ISM at an earlier time than in the thick disk models. They found that the thicker disk was able to provide a greater degree of collimation to the wind than the thinner disk. However, the opening angles of the outflow are still far too large when compared to the opening angles observed in the wind in M82, a problem which is characteristic of all global simulations of starburst-driven winds to date.

In both thick and thin disk models, the calculated soft X-ray luminosities are higher ($L_x = 10^{40} - 10^{41}$ erg s$^{-1}$) than those inferred from ROSAT observations of starburst driven winds ($L_x = 10^{39} - 10^{41}$ erg s$^{-1}$). However, they suggest that the X-ray luminosities may have been overestimated due to low resolution and their assumption of solar metallicity. In general, the thick disk models were more X-ray luminous than the thin disk models, radiating $\sim$5-20% of the mechanical energy of the starburst, whereas in the thin disk models less than 1% of the mechanical energy was found in the X-ray gas. They found that the interstellar medium is the most important factor in determining the amount of X-ray emission, followed by the starburst's power, and the mass-loading of the wind. They suggest that the soft X-ray emission may originate from a mixture of shocked gas and from the intermediate temperature interface between the
hot and cold gas. While this interface is most likely the result of numerical diffusion caused by insufficient resolution of the gas, they suggest that it may mimic the effects of shock-heating, turbulent mixing layers, or a conductive or photo-evaporative interface. They agree with the conclusion of Suchkov et al. (1994) that the hard X-ray emission arises from the starburst region itself, with a smaller contribution from the free-wind and shocked-gas.

Strickland & Stevens also considered the energetics of the wind and the ability of the outflow to transport mass out of the galaxy. They found that the majority of the energy injected by the starburst resides in the hot gas, with only a small fraction found in the cool disk gas. In all models, this energy was efficiently transported out of the disk of the galaxy. As such, they suggest that galactic winds may be good sources for the heating of the intergalactic medium. However, they found that the winds in their study were unable to transport a significant fraction of the ISM to a height above $z = 1.5$ kpc, in agreement with the result of D’Ercole & Brighenti (1999) that galactic winds are inefficient at removing the ISM of galaxies.

3.1.6 Tenorio-Tagle, Silich & Muñoz-Tuñón 2003

While most attempts to model the observed structure of starburst-driven winds have utilised a global approach, simulating the formation of the wind from a central source in the disk of the galaxy, Tenorio-Tagle et al. (2003) focused on modeling the outflow produced by a few super-star clusters. Optical, radio, IR and UV observations of starburst nuclei have revealed that they are made up of numerous young compact SSC’s. For example, the starburst region in M82 is known to be made up of over 100 super-star clusters arranged in a flattened disk of radius 150 pc (Shopbell & Bland-Hawthorn, 1998). Tenorio-Tagle et al. investigated the effect that a few of these clusters in the starburst region would have on the internal structure of an expanding super-galactic wind. This is in contrast to approach adopted by the authors discussed above, who assume that the mass and energy deposition arise from a single large central source.

Their simulations were two-dimensional and incorporate radiative cooling using the Raymond et al. (1976) cooling law scaled to 2 different metallicities ($3$ and $10 Z_\odot$). The SSC’s, each with radius 5 pc, were arbitrarily placed, in two different configuration: (i) three SSC’s with two positioned at 60 and 90 pc respectively from the central SSC, and (ii) two SSC’s positioned 30 and 60 pc from the symmetry axis. The deposition rate of energy at each time-step from each SSC is $\dot{E} = 10^{41}$ erg s$^{-1}$. The simulations assume that the superbubble has
already formed, and has broken out of the disk and evacuated the area around the SSC’s. Only the free-wind region of the outflow is modelled.

In contrast to a wind forming from a single large starburst region, Tenorio-Tagle et al. found that each SSC produces its own high velocity \( v = 1000 \text{ km s}^{-1} \) stream. The interaction between these streams results in the formation of multiple reverse shocks, each with a high pressure region immediately following the shock. The density and temperature is at its highest where the reverse shocks are perpendicular to the SSC streams. Where the cooling is fast enough, the reverse shocks acquire a standing location, with narrow, dense filaments forming as the temperature drops behind the shocks (Fig. 3.6). The drop in temperature is greatest at the base of the outflow, where the density and cooling are greatest, resulting in the outflow of the dense filaments at speeds of several hundred \( \text{km s}^{-1} \). They suggest that these filaments may be easy targets for UV radiation produced in the SSC, and upon cooling and recombination are likely to become photoionized, providing an origin for the optical emission seen in starburst-driven winds. In addition, these filaments consist of a variety of “loops and twists” that present a large cross-section to the wind and would appear to be enveloped by soft X-ray emission as they are struck by the free wind.

Another result of their simulations is the self collimation of the wind. The outflow in M82, is known to be highly collimated to approximately 500pc above the plain of the galaxy (e.g. Götz et al., 1990). However, most galactic wind simulations provide little collimation to the outflow, with both the base of the outflow growing to unrealistic dimensions and the wind fanning out at too large opening angles. Tenorio-Tagle et al. found that there was a high degree of collimation when the SSC’s were placed in a preferential plane. In this scenario, the formation of the standing oblique reverse shocks provides a natural collimating mechanism for the filaments. They suggest that a wider outflow would result when the SSC’s have differing mass and energy injection rates. The results of Tenorio-Tagle et al. (2003) will be discussed further below.

### 3.2 Motivation for New Work

As noted earlier, improvements in computational technology has led to an increase in the complexity of simulations of starburst winds. While many of the global properties of the winds seen in early simulations have held, such as the snow-plow structure of the bubble as it expands into the ambient gas, other results have been shown to be model dependent. For example, Suchkov et al. (1994) find the soft X-ray emission to arise predominantly from shocked
gas in the outflow, while D'Ercole & Brighenti (1999) find the shocked gas to not contribute appreciably to the X-ray emission, with the majority arising as the interface been the cool ISM and hot wind. Clearly the initial assumptions made and the numerical method utilised by the model can have an impact on the results and the subsequent conclusions. The limitations of earlier models are discussed below, as well as some of the considerations that must be made when constructing a model of a starburst-driven wind.

**Numerical Resolution** - The assumed numerical resolution of the simulation can affect the hydrodynamics of the gas in the outflow. From the mid 1990’s, increases in the resolution of the two-dimensional simulations began to reveal finer and finer structure in the gas as hydrodynamical instabilities were better resolved. Strickland & Stevens (2000) looked at the effect of the numerical resolution in their study and found that it had the greatest impact on the coolest gas, which becomes more fragmented at higher resolution. Since it is the cool $T = 10^4$ K gas that emits at optical wavelengths, an investigation into the filaments found in starburst winds must sufficiently resolve this gas in order to draw meaningful conclusions concerning its origin and dynamics. On the other hand, an investigation into the energetics of the outflow and the transport of mass and metals out of the galaxy requires a large spatial range to be considered in order to follow the evolution of the wind to late times. Without the use of an adaptive mesh code, this necessitates a sacrifice in numerical resolution. While this is unlikely to have a significant effect on the hottest gas in which the majority of the energy and metals is likely to be stored, insufficient resolution in the cool disk gas may effect estimates of the escape fraction of the ISM.

**The Interstellar Medium** - All global simulations of starburst winds to date have investigated the evolution of the wind in a homogeneous ISM. However, the ISM is known to be multiphase, consisting of gas that ranges from cool molecular clouds to hot million degree gas. Tenorio-Tagle et al. (2006) investigated the evolution of a wind through a clumpy medium and found that the wind flowed around the dense clouds. However, a wind that forms in an homogeneous disk must force its way out of the dense gas, resulting in the formation of a dense shell as disk gas is swept-up by the outflow. Thus, the interaction of a wind with an homogeneous disk does not provide an accurate reflection of the dynamics of these objects. The interaction of the wind with each dense cloud must also be considered. A cloud overrun by a wind is destroyed by hydrodynamical instabilities with its mass mixed into the surrounding flow (e.g. Klein et al., 1994; Mellema et al., 2002). In order to account for this additional material, simulations in an homogeneous ISM must include the mass-loading of the wind as employed by Suchkov et al. (1996) and Strickland & Stevens (2000).
However, these models have shown that the assumed location of the mass-loading (i.e. central or distributed) can alter the morphology and kinematics of the outflow. Natural mass-loading via an inhomogeneous ISM removes this uncertainty, and potentially leads to the formation of with winds with more complex morphologies (e.g. tilted outflows).

Filamentary Optical Emission - The formation of significant filamentary structures that are morphologically similar to those observed at optical wavelengths has been a problem in many models. Many authors attempt to explain this emission as the fragments left over from the dense shell of swept-up disk gas after it has been broken up by the Rayleigh-Taylor instability. However, the dense shell fragments typically do not originate in the starburst region, as is observed in starburst winds. Tenorio-Tagle et al. (2003) reported the formation of long dense filamentary structures in their model. However, these filaments are launched at considerable velocities of a several hundred km s\(^{-1}\), whereas the velocity gradient of the filaments in M82 is known to be more gradual, reaching higher speeds at larger distances above the galactic plane. Any model of a starburst wind must be able to explain the morphology and kinematics of these filaments which are a prominent feature of these winds.

Base Confinement and Wind Collimation - The narrow base of the outflow is another observational feature of starburst winds that simulations have had difficulty reproducing. With the exception of Tenorio-Tagle & Munoz-Tunon (1997) and Tenorio-Tagle & Munoz-Tunon (1998) who designed their simulations to prevent this expansion, the base grows to unrealistic dimensions (\(>\ 1000\) pc) as the wind expands. However, the base of the outflow in M82 is known to have a diameter of only \(\sim\ 400\) pc. Achieving the degree of collimation observed in M82's wind of \(\theta \sim 30^\circ\) has also been a significant problem, with all global simulations resulting in the wind fanning out with opening angles in excess of \(\theta \sim 100^\circ\). Tenorio-Tagle et al. (2003) were able to produce a self-collimating outflow, but this result did not encompass the entire bulk of the outflow and is dependent on the position of the SSC's powering the outflow. The mechanism(s) which prevent the expansion of the base and provide the needed collimation of the outflow are still unknown, but the nature of the ISM in the host galaxy is likely to play a role.

The Starburst - How the starburst that powers the outflow is modeled is also an important consideration. While early models typically utilised a single instantaneous burst, later models considered a more gradual deposition of energy or made use of stellar evolution models to take the star formation history of the starburst into account, with less energetic and more gradual injection histories having been shown to slow the expansion of the outflow. In reality, a starburst
Motivation for New Work

is known to be made up of multiple luminous super star clusters, whose star formation history affects the evolution of the outflow. The position of the SSC's (e.g. ring or disk) may also affect the morphology of the outflow. Tenorio-Tagle et al. (2003) took a step forward and considered the effect of multiple sources of energy in the starburst. However, these simulations were not global, focusing only on the inner free-wind region of the outflow, making it difficult to obtain an accurate picture of the overall effect on the evolution and structure of the wind. A global simulation in which the starburst region is made up of multiple SSC's, each with their own star formation history, would be ideal.

Magnetic Fields, Thermal Conduction, and Photoionization - While D'Ercole & Brighenti (1999) briefly considered the effects of thermal conduction in an outflow, its importance, along with that of magnetic fields and the photoionization from the incident radiation from the starburst, is still not well understood. Photoionisation is known to play a role in the ionisation of the filaments in many starburst-driven winds (Veilleux et al., 2005) and the incident radiation from the starburst may also lead to the photoevaporation of the gas (Tenorio-Tagle et al., 2006). While magnetic fields may help to stabilise the filaments against hydrodynamical instabilities. However, few (if any) global hydrodynamics studies of galactic winds have included these processes in their simulations.

3.2.1 New Global Model of a Starburst Wind

With the above considerations in mind, the global simulations of a starburst-driven wind presented in Chapter 5 consider the evolution of the entire outflow, but focus on the inner 1 kpc region of the galaxy in order to retain a good numerical resolution of 2 pc per cell. The model has the following main features:

- Fully three-dimensional, allowing the evolution and kinematics of the entire outflow to be more realistically studied.

- Incorporates a multiphase interstellar medium, consisting of a hot homogeneous halo and a warm inhomogeneous disk, enabling the interaction of the wind with clouds of disk gas to be investigated. This also allows for the natural addition of mass to the outflow via the hydrodynamical destruction of the disk clouds.

- The scale-height of the disk is determined by both the sound speed of the warm gas and turbulent velocity of the clouds (see eq. 5.4). This removes the need to impose artificially high temperatures on the disk gas
to achieve reasonable disk scale heights, as required by other authors (e.g. Strickland & Stevens, 2000).

- The starburst is modeled as a cylindrical region in the center of the galaxy disk, where mass and energy are continuously injected at a rate proportional to the density in each computational cell. This effectively creates individual super-star clusters in regions where the density is highest (i.e. disk clouds present in the starburst region).

The effects of magnetic fields, thermal conduction, and photoionization have not been considered at this time. See Section 5.2 for a complete description of the numerical method.

The aim of this work is to investigate the evolution and morphology of a starburst and its outflow interacting with a multiphase ISM, as well as to determine the origin of the optical emitting filaments and the X-ray emission. As a result of the limited spatial range, the evolution of the entire outflow is only followed for a period of approximately 1 Myr. Therefore, a study of the energetics and the transport of the ISM and metals in the enriched hot gas has not been attempted. After the outer edge of the wind has left the computational grid, the evolution of the free-wind region of the outflow can still be studied over a larger period of time. This allows the formation and evolution of the filaments to be studied in detail at a reasonably high resolution.
4. The PPMLR Code

The three-dimensional hydrodynamical simulations presented in this thesis were performed using the PPMLR code described here. PPMLR is based on the VH-1 hydrodynamics code developed at the University of Virginia (Blondin, 1995), which is in turn based on the PPM (Piecewise Parabolic Method) scheme described by Colella & Woodward (1984). The VH-1 code has been further modified in the Research School of Astronomy and Astrophysics at the Australian National University by the inclusion of thermal cooling, the elimination of numerical shock instabilities, and the parallelisation of the code (see Sutherland et al., 2003a,b; Saxton et al., 2005). In the following sections, I give a brief overview of the the PPM scheme that forms the basis of PPMLR, and discuss the major modifications that have made to the original VH-1 code.

4.1 PPM with a Lagrangian Remap

The VH-1 hydrodynamics code utilises the piecewise parabolic method developed by Colella & Woodward (1984), which is a high-order extension of Godunov’s (1959) method for solving the equations of ideal inviscid compressible fluid flow:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \] (4.1)

\[ \frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) + \nabla \rho = \mathbf{F}, \] (4.2)

\[ \frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \varepsilon \mathbf{u}) + \nabla (\rho \mathbf{u}) = G + \rho \mathbf{u} \cdot \mathbf{F}, \] (4.3)

where Equations 4.1-4.3 are written in conservative Eulerian form, \( \varepsilon = u^2/2 + (\gamma - 1)^{-1}p/\rho \) is the total specific energy, \( \rho \) is the mass density, \( p \) is the pressure, and \( \mathbf{F} \) and \( G \) are the momentum and energy source terms (Blondin, 1995). Note that the energy source term \( G \) is used to represent cooling in PPMLR, but is not used in VH-1. A key advancement of the PPM advection scheme over other methods (e.g. MUSCL; see Woodward & Colella, 1984) is the use of parabolae for the basic interpolation within each zone. The quadratic interpolation allows for a more accurate calculation of the fluid variables. While Colella & Woodward describe two different schemes for solving these equations, one based
Fig. 4.1: The Riemann problem with a discontinuity at \( x=0 \), with pressure and velocity \( p_1 \) and \( u_1 \) on the left of the discontinuity, and \( p_2 \) and \( u_2 \) on the right.

on a Eulerian coordinate system and the other Lagrangian, VH-1 and PPMLR make use of the Lagrangian method. For full details see Colella & Woodward (1984), and Blondin (1995) for a description of its use in VH-1.

An important feature of the PPMLR code is the Lagrangian remap step, where the Riemann problem is solved on a Lagrangian grid and the fluid variables mapped back to a fixed Eulerian grid. In this step, the second-order accuracy of the code is sacrificed in zones where shocks are present. However, the solution maintains the representation of the discontinuity over 1 or 2 zones, which is a significant benefit of using the PPM advection scheme. The advantage of using a Lagrangian remap in the calculation is that, while a second interpolation must be performed, the first-order treatment of the discontinuities is simpler and less computationally expensive than in the Eulerian method.

PPMLR uses Godunov's method for the temporal advancement of zone averaged variables based on the fluxes through the boundaries of each zone. The main advantage is that the true solution is well approximated even when the solution is not smooth (Woodward & Colella, 1984). Godunov's method works by determining the zone-averages of the fluid variables based on their value in the previous time step and the fluxes into the zone. The fluxes are calculated by finding a solution to the Riemann problem.

The one-dimensional Riemann problem with a discontinuity at \( x=0 \), pressure and velocity \( p_1 \) and \( u_1 \) on the left of the boundary, and \( p_2 \) and \( u_2 \) on the
**Fig. 4.2:** When $p_1 > p_2$, the 4 possible solutions to the Riemann problem shown in Figure 4.1 are: (a) a rarefaction and a shock wave are produced; (b) two rarefaction waves are produced; (c) a vacuum is generated in the middle of two rarefactions, bounded by contact waves at $C_1$ and $C_2$; and (d) two shock waves are produced.

right, is shown in Figure 4.1. For $p_1 > p_2$ there are 4 possible solutions to the Riemann problem, which are depicted in Figure 4.2 (see Toro, 1999):

(a) A rarefaction and a shock wave, separated by a contact discontinuity, are produced when the difference between the velocities $u_1$ and $u_2$ is sufficiently small.

(b) Two rarefaction waves, separated by a contact discontinuity, are produced when the pressure difference is small.

(c) A vacuum is generated in the middle of two rarefaction waves when the velocities $u_1$ and $u_2$ are directed away from each other. Two contact waves $C_1$ and $C_2$, with velocities $S_1$ and $S_2$ respectively bound the vacuum region. The condition $S_1 \leq S_2$ must hold in order for this solution to occur.

(d) Two shocks, separated by a contact discontinuity, will be produced if the velocities $u_1$ and $u_2$ are large enough and directed towards each other.

In order to ensure that the solution to the Riemann problem in one zone does not interfere with the solution in the next, the Courant condition is imple-
mented (see Blondin, 1995). The limiting condition

$$\Delta t < \frac{\Delta x_i}{u_w \mid_{\text{max}}}$$  \hspace{1cm} (4.4)$$

is imposed in order to keep the time step $\Delta t$ sufficiently small, where $\Delta x_i$ is the width of a cell and $u_w \mid_{\text{max}}$ is the maximum wave speed in any zone.

In the PPMLR code, Godunov’s Method is implemented on a Lagrangian grid, where the cell boundaries move with the velocity of the gas. In a Lagrangian coordinate system, the one-dimensional Euler equations have the form:

$$\frac{\partial \tau}{\partial t} = \frac{\partial u}{\partial m},$$  \hspace{1cm} (4.5)

$$\frac{\partial u}{\partial t} = -\frac{\partial p}{\partial m} + g,$$  \hspace{1cm} (4.6)

$$\frac{\partial E}{\partial t} = -\frac{\partial}{\partial m} (p u) + u g,$$  \hspace{1cm} (4.7)

$$\frac{\partial x}{\partial t} = u,$$  \hspace{1cm} (4.8)

where $\tau = 1/\rho$ is the specific volume, $m = \int \rho dx$ is the mass coordinate, and $g$ is the body force per unit mass (e.g. gravity). Integrating over a time step in one mass zone, these equations become:

$$\int_{m_{i-1/2}}^{m_{i+1/2}} \tau^{n+1} \, dm - \int_{m_{i-1/2}}^{m_{i+1/2}} \tau^n \, dm = \int_{t^n}^{t^{n+1}} (u_{i+1/2}^* - u_{i-1/2}^*) \, dt,$$  \hspace{1cm} (4.9)

$$\int_{m_{i-1/2}}^{m_{i+1/2}} u^{n+1} \, dm - \int_{m_{i-1/2}}^{m_{i+1/2}} u^n \, dm = -\int_{t^n}^{t^{n+1}} p_i^{1+1/2} \, dt + \int_{t^n}^{t^{n+1}} p_i^{1-1/2} \, dt$$

$$+ \int_{m_{i-1/2}}^{m_{i+1/2}} \left[ \int_{t^n}^{t^{n+1}} g \, dt \right] \, dm,$$  \hspace{1cm} (4.10)

$$\int_{m_{i-1/2}}^{m_{i+1/2}} E^{n+1} \, dm - \int_{m_{i-1/2}}^{m_{i+1/2}} E^n \, dm = -\int_{t^n}^{t^{n+1}} (p^* u^*)_{i+1/2} \, dt + \int_{t^n}^{t^{n+1}} (p^* u^*)_{i-1/2} \, dt$$

$$- \int_{m_{i-1/2}}^{m_{i+1/2}} \left[ \int_{t^n}^{t^{n+1}} v \, g \, dt \right] \, dm,$$  \hspace{1cm} (4.11)

where $u^*$ and $p^*$ are the velocity and pressure at the zone boundaries (contact discontinuities). To calculate the zone-averaged values in each cell, the flux across the zone boundaries must be determined, i.e.

$$\int_{t^n}^{t^{n+1}} u_{i+1/2}^* \, dt, \hspace{1cm} \int_{t^n}^{t^{n+1}} p_{i+1/2}^* \, dt, \hspace{1cm} \int_{t^n}^{t^{n+1}} p_{i+1/2}^* u_{i+1/2}^* \, dt.$$  \hspace{1cm} (4.12)

A Riemann solver is used to calculate $u^*$ and $p^*$ (e.g. Toro, 1999). Once these values are known, the fluxes can be determined and the zone averages of the variables $\tau$, $u$, and $E$ calculated in each cell. The variables are then interpolated back onto the original Eulerian grid.
4.1.1 Multi-Dimensional Solution

The method described above is for a one-dimensional problem. For a multi-dimensional problem, such as the simulations described in this thesis, the problem is solved using dimensional splitting (see Toro, 1999, pp 539-555). This technique involves solving the one-dimensional problem in each coordinate direction. In PPMLR, for a three-dimensional problem, this is done by performing orthogonal sweeps in the x, y, and z directions of the computational grid. For example, in the x-sweep the one-dimensional problem is solved in the x-direction of the grid. The sweeps are performed in the order of x, y, z, z, y, x in order to retain the second-order accuracy in time of the one-dimensional solution.

4.2 Modifications to PPMLR

Over the last several years, the PPMLR code used in this work has undergone a number of advancements intended to improve its performance and increase the realism of the simulations. Overall, it has been reorganised to increase efficiency and has also had improvements made to its Riemann solver. In particular, three main modifications have been made to PPMLR that make it stand apart from its predecessor: (i) the inclusion of radiative cooling within the code, (ii) improved treatment of radiative shocks, and (iii) the implementation of MPI (Message Passing Interface) to allow computation over multiple processors in large-scale simulations.

4.2.1 Inclusion of Radiative Cooling

Both the PPM scheme described by Colella & Woodward (1984) and the subsequent VH-1 code did not take into account the radiative cooling of the gas; the simulations performed using these codes are adiabatic. While there are scenarios where an adiabatic solution is adequate (e.g. relativistic jets), it is likely to be an important consideration in many astronomical phenomena, such as the starburst-driven winds simulated in this thesis. Radiative cooling was thus implemented into the PPMLR code by way of a non-equilibrium (NEQ) cooling function $\Lambda(T)$. See Sutherland et al. (2003a) for full details of the set-up and modification of the energy equation.

The NEQ cooling function was obtained from the one-dimensional time-dependent plasma modeling code MAPPINGS III (Sutherland & Dopita, 1993)
and describes an isobaric plasma cooling from high $T \sim 10^{10}$ K temperatures over 1024 logarithmic intervals to a temperature of $T \sim 10^3$ K. The resulting table is used for interpolation in each cell of the computational grid. For fast $v \gtrsim 150$ km s$^{-1}$ shocks, the NEQ function is a good approximation to the actual cooling function, while for slower shocks additional calculations, which take into account the ionization fractions of the cooling gas, need to be made in order to obtain accurate cooling rates.

If the cooling timescale were used to limit the integration time step, the latter would become unacceptably small. Therefore, in PPMLR the energy equation is split and the cooling part is integrated using a second order semi-explicit Runge-Kutta integrator.

### 4.2.2 Improved Treatment of Radiative Shocks

One particular problem with VH-1, and the PPM scheme in general, is the appearance of the so called "striping instability" in regions of strong shocks aligned with the computational grid, which appears as alternating stripes of density fluctuations following the shock front. Sutherland et al. (2003b) characterise this instability as being initially caused by small errors in the pressure that inevitably cause a flux of mass, from high to low pressure, parallel to the shock front. Over time, mass accumulates in regions of low pressure, slowing the shock and further reducing the pressure in each of the cells. Whereas, in the adjacent cells, the density is relatively low and the pressure high. The growth of the instability continues as the slower advance of the shock front further enhances the observed pressure differential. Colella & Woodward (1984) noticed this effect and attempted to compensate for it using multiple dissipation methods with varying success. In order to eliminate the instability from the PPMLR code, a "Local Oscillation Filter" was designed and added to the code (see Sutherland et al., 2003b, for full details).

When performing a calculation, PPMLR does orthogonal sweeps of the computational grid in the x, y, and z directions. The local oscillation filter works by using additional information obtained from the previous orthogonal sweep. As discussed in Section 4.1, the second-order accuracy of the code is sacrificed in zones where shocks are present, with the interpolation in the cells being piecewise linear, rather than piecewise parabolic. Thus, in shock capturing regions, the cells are "flattened" during the initial x-sweep of the computational grid. In the next sweep, the local oscillation filter searches for, and flags, the flattened cells that have a specific pattern of density fluctuations, extending over at least 5 Lagrangian cells and having at least three vertices. This pattern is indicative
if the presence of the "striping instability". Once the solution has been mapped back to the Eulerian grid, the zone averages of the flagged vertex cells are reassigned a new value. In subsequent sweeps, the flagged cells from the previous sweep are marked as potential candidates for smoothing, with the net effect of the smoothing in each sweep resulting in the elimination of the instability from the simulation.

4.2.3 Computation via Multiple Processors

While the PPMLR code has been optimised for efficiency, large two- and three-dimensional simulations are still computationally expensive, being somewhat difficult (or impossible) to perform using a single computer within a reasonable time frame. In order to perform such computationally demanding simulations, it is necessary to divide the computation over a number of different processors. This ability was implemented into the PPMLR code through the use of MPI, which allows the different processors to communicate with each other. A description of this implementation can be found in Appendix A of Saxton et al. (2005).

In a large two-dimensional simulation, the computational grid is divided up into a number of sub-grids of equal size along the y-axis, so that a global grid of dimension I×J cells will be divided up into \( N \) sub-grids of size I×(J/N) cells, where \( N \) is the number of processors. For a three-dimensional simulation, the division is done along the z-axis of the computational grid. In this case a global grid of size I×J×K cells will be divided up into \( N \) sub-grids of size I×J×(K/N) cells. For example, the simulations presented in Chapter 5 were performed using a computational grid of size 512×512×512 cells, divided over 128 processors, each responsible for a sub-grid of size 512×512×4 cells.

In a three-dimensional simulation, the time-averaged fluid variables are first calculated in each cell of the sub-grids during the x- and y-sweeps of the computational grid. As no sub-grid interfaces are encountered during these sweeps, there is no need to communicate the flux information between the processors. The grid is then transposed using a call to MPI, so that the z-sweep can be performed without encountering any sub-grid interfaces. No information is lost during this transform. After the z-sweep, the grid is transposed back into its original orientation. At output time steps, each processor writes out the evolved variables on its sub-grid to a single file. These files are then assembled to obtain the full solution over the entire computational grid. This method allows the required computational resources (e.g. memory) to be spread out over multiple processors, improving the speed and efficiency of the simulation.
5. THREE-DIMENSIONAL SIMULATIONS OF A STARBURST-DRIVEN GALACTIC WIND

5.1 Introduction

The best studied starburst-driven wind is the outflow in M82, which is clearly visible in the light of $\text{H}$, displaying a vast filamentary system extending several kpc along the minor axis of the galaxy (Shopbell & Bland-Hawthorn, 1998). These filaments lie on the surface of a mostly hollow structure and rotate in the same direction as the disk (Greve, 2004). As with other galactic winds (e.g. NGC 253: Sugai et al., 2003), the wind in M82 is asymmetric, with the northern outflow more chaotic than the southern outflow. The filaments can be traced to the nuclear region and display both shell and loop-like structures (Ohyama et al., 2002). The formation of these filaments is currently not well understood, but they are thought to be either disk or halo gas that has been entrained into the outflow.

The morphology of galactic winds can vary. Outflows often display asymmetries, varying degrees of collimation and may be tilted with respect to the minor axis. While many outflows are limb-brightened (e.g. NGC 3079; Veilleux et al., 1994), the optical filaments can also fill the volume rather than remain confined to the surface of the biconical outflow (Veilleux & Bland-Hawthorn, 1997). The host galaxy itself plays an important role in determining the morphology of a wind, with its size and structure affecting the degree of collimation (Strickland & Stevens, 2000) and expansion of the outflow (Strickland et al., 2004a; Grimes et al., 2005; Martin, 2005).

Recent Chandra observations have revealed increasing detail in the X-ray emission from galactic winds. One of the most striking results of these observations is the close spatial relationship with the $\text{H}$ emitting gas (e.g. Strickland & Stevens, 2000; Strickland et al., 2002, 2004a; Cecil et al., 2002; Martin et al., 2002; Grimes et al., 2005; Ott et al., 2005b), suggesting a close physical connection. Thus, a successful model of a galactic wind needs to explain this relationship. Strickland et al. (2002) provide a summary of several theories for the origin of
the X-ray emission that could explain this correlation. These mechanisms involve shocked disk or halo gas that has been swept up into the wind, in the form of dense clouds or shells (also see Section 2.2.3).

As discussed in Chapter 3, numerous simulations have been made of starburst winds (Tomisaka & Ikeuchi, 1988; Tomisaka & Bregman, 1993; Suchkov et al., 1994, 1996; D’Ercole & Brighenti, 1999; Tenorio-Tagle & Munoz-Tunon, 1998; Strickland & Stevens, 2000; Tenorio-Tagle et al., 2003). Suchkov et al. (1994) performed two-dimensional, axisymmetric simulations of a starburst wind in an isothermal ISM, with varying densities and temperatures. They concluded that the Hα filaments form from disk gas that has been entrained into the flow and that the X-ray emission most likely arises from shocked disk and halo gas. More recently, Strickland & Stevens (2000) performed a series of simulations, focusing on the energetics and X-ray emission from the wind. As with Suchkov et al. (1994), their simulations were two-dimensional and axisymmetric with an isothermal ISM. They found that a large fraction of the soft X-ray emission in their model comes from shock-heated ambient gas and from the interfaces between cool dense and hot tenuous gas. While these simulations provide some insight into the origin of the X-ray and Hα emission, the homogeneous nature of these models and their symmetry renders them incapable of forming significant filamentary structures, limiting their ability to constrain the emission processes.

In order to improve upon previous models and to gain a better understanding of the origin of the Hα filaments and X-ray emission, we have performed a series of three-dimensional simulations of a galactic wind in an inhomogeneously distributed interstellar medium (ISM). The introduction of inhomogeneity is important as the interstellar medium in a galaxy disk is highly complex in all its phases (see for example Elmegreen & Elmegreen, 2001, and references therein). Inhomogeneity is also crucial in the development of a wind, as energy from massive stars formed in dense molecular clouds in the starburst region may be radiated away before a wind could form. A wind is more likely to develop from the kinetic energy from stellar winds adjacent to the diffuse gas surrounding the clouds.

The inhomogeneous structure of the ISM is also likely to affect the distribution of filaments throughout the wind, producing asymmetric and tilted outflows. It is likely that the size and strength of the starburst itself plays an important role in determining the morphology. Many starburst galaxies, such as M82 and NGC 3079, contain circumnuclear starbursts, with their resultant outflows being strong and violent (Shopbell & Bland-Hawthorn, 1998; Veilleux et al., 1994). Other starbursts are weaker and have less prominent outflows.
An example is NGC 4631, which is currently undergoing a disk-wide starburst (Strickland et al., 2004a).

Tenorio-Tagle et al. (2003) investigated the formation of the emission line filaments by modeling the formation of a wind from several super star clusters. They proposed that kiloparsec long filaments are formed from stationary and oblique shocks. In this chapter we present a different model, which follows a similar approach to that of Strickland & Stevens (2000), but introduces an inhomogeneous disk. We follow the evolution of a starburst-driven wind in different ISM conditions and discuss the effect of the inhomogeneity of the disk on the morphology of the wind. We consider the morphology of the Hα emitting filaments separately and investigate their origin. Finally, the luminosity of the soft and hard X-ray emitting gas is calculated and we suggest an origin for the soft X-ray emission.

5.2 Numerical Model

5.2.1 Description of the Code

The simulations were performed using a PPMLR code (Piecewise Parabolic Method with a Lagrangian Remap), which is based on the method described by Colella & Woodward (1984). The code has been extensively modified (see, for example, Sutherland et al., 2003a,b) from the original VH-1 code (Blondin, 1995). It is a multi-dimensional hydrodynamics code, optimized for use on multiple processors of the SGI Altix computer operated by the Australian Partnership for Advanced Computing (APAC). Thermal cooling has been incorporated, based upon the output from the MAPPINGS III code (see Sutherland & Dopita, 1993; Sutherland et al., 2003b; Saxton et al., 2005), enabling the realistic evolution of a radiatively cooling gas (see Chapter 4 for a more detailed description of the PPMLR code). The simulations discussed in this paper are three-dimensional and utilize cartesian (x,y,z) coordinates. In each cell of the computational grid, the density, temperature, velocity, emissivity and a disk gas tracer are recorded at intervals of 0.01 Myr.

The Gravitational Potential

Following Strickland & Stevens (2000), the gravitational potential used in these simulations consists of a stellar spheroid and a disk. Let \( R = \sqrt{r^2 + z^2} \) be the radius of the stellar spheroid, \( r_0 \) the core radius, \( M_{ss} \) its mass, \( M_{disk} \) the
Fig. 5.1: Fit to the CO rotation curve of M82 (empty squares: Sofue, 1998)

mass of the disk, $a$ its radial scale length, and $b$ its vertical scale length. The potential $\Phi_{ss}$ of the stellar spheroid is described by an analytic King model (eq. [5.1]) and the disk potential $\Phi_{\text{disk}}$ by a Miyamoto & Nagai (1975) model (eq. [5.2]). The total gravitational potential is then the sum of the two components ($\Phi_{\text{tot}} = \Phi_{ss} + \Phi_{\text{disk}}$), where

$$\Phi_{ss}(R) = -\frac{GM_{ss}}{r_0} \left\{ \ln \left[ \frac{(R/r_0) + \sqrt{1 + (R/r_0)^2}}{(R/r_0)} \right] \right\}$$  \hspace{1cm} (5.1)

$$\Phi_{\text{disk}}(r, z) = -\frac{GM_{\text{disk}}}{\sqrt{r^2 + (a + \sqrt{z^2 + b^2})^2}}$$  \hspace{1cm} (5.2)

Whilst these simulations are intended to be applicable to the general class of disk galaxies, we used parameters which are based on the iconic galaxy, M82. Note also that simulations including cooling admit a one-parameter scaling which is described in Sutherland & Bicknell (2007). Within limits the simulations may be scaled to smaller or larger galaxies.

We adopted parameters for the above potential by approximately fitting the rotation curve of M82 (Fig. 5.1); the parameters are summarised in Table 5.1.
Table 5.1. Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellar spheroid mass</td>
<td>$M_{ss}$</td>
<td>$6.0 \times 10^8 , M_\odot$</td>
</tr>
<tr>
<td>Disk mass</td>
<td>$M_{disk}$</td>
<td>$6.0 \times 10^9 , M_\odot$</td>
</tr>
<tr>
<td>Core radius</td>
<td>$r_0$</td>
<td>$350.0 , pc$</td>
</tr>
<tr>
<td>Radial scale length</td>
<td>$a$</td>
<td>$150.0 , pc$</td>
</tr>
<tr>
<td>Vertical scale length</td>
<td>$b$</td>
<td>$75.0 , pc$</td>
</tr>
<tr>
<td>Central halo density</td>
<td>$n_h$</td>
<td>$0.2 , cm^{-3}$</td>
</tr>
<tr>
<td>Average disk density</td>
<td>$n_{d,avg}$</td>
<td>$100.0 , cm^{-3}$</td>
</tr>
<tr>
<td>Halo temperature</td>
<td>$T_h$</td>
<td>$5.0 \times 10^6 , K$</td>
</tr>
<tr>
<td>Average disk temperature</td>
<td>$T_{d,avg}$</td>
<td>$1.0 \times 10^4 , K$</td>
</tr>
<tr>
<td>Starburst radius</td>
<td>$r_{sb}$</td>
<td>$150.0 , pc$</td>
</tr>
<tr>
<td>Starburst height</td>
<td>$h_{sb}$</td>
<td>$60.0 , pc$</td>
</tr>
<tr>
<td>Mass injection rate</td>
<td>$\dot{M}$</td>
<td>$1.0 , M_\odot , yr^{-1}$</td>
</tr>
<tr>
<td>Energy injection rate</td>
<td>$\dot{E}$</td>
<td>$1.0 \times 10^{42} , erg , s^{-1}$</td>
</tr>
</tbody>
</table>

This produces a good fit at the smaller radii used in these simulations. We neglect the contribution of a dark matter halo, since our model only extends to a radius of less than 1 kpc. This is justified because, for example, in the Galaxy where the contribution of dark matter is well constrained at all radii, it is now well established that baryonic matter dominates the potential within the Solar Circle (see Binney, 2005, for review).

The Interstellar Medium

The interstellar medium used in these simulations has two components, a hot isothermal halo and a turbulent warm inhomogeneous disk. As with Strickland & Stevens (2000), the density distribution of the halo is homogeneous and is described by equation (5.3), where $c_{s,h} = \sqrt{kT_h/\mu m}$ is the isothermal sound speed of the hot gas, and $\epsilon_h$ is the ratio of the azimuthal velocity to the Keplerian velocity. In order to obtain a non-rotating halo, which is supported by pressure alone, we adopt $\epsilon_h = 0$.

\[
\frac{\rho_{\text{halo}}(r, z)}{\rho_{\text{halo}}(0, 0)} = \exp \left[ -\frac{\Phi_{\text{tot}}(r, z) - \epsilon_h^2 \Phi_{\text{tot}}(r, 0) - (1 - \epsilon_h^2) \Phi_{\text{tot}}(0, 0)}{\epsilon_h^2 c_{s,h}^2} \right] \tag{5.3}
\]

We follow the same approach as Sutherland & Bicknell (2007) and introduce an ensemble mean density distribution which introduces a turbulence parame-
The introduction of turbulence removes the need to impose artificially high temperatures to achieve reasonable disk scale heights. We discuss the details of this distribution below. In order to construct the warm inhomogeneous disk, we first establish the ensemble mean density distribution. Let $c_{s,d} = \sqrt{kT_d/\mu m}$ be the sound speed of the warm gas, $\sigma_t$ the turbulent velocity dispersion of the clouds, and $e_d$ be the ratio of azimuthal to the Keplerian velocity of the warm gas. As shown by Sutherland & Bicknell (2007), the parameter $e_d$ is strictly constant and cannot be a function of $z$, as implemented by Tomisaka & Bregman (1993) and Strickland & Stevens (2000). While smaller values of $e_d$ would result in a thicker disk (Silich & Tenorio-Tagle, 2001), we adopt $e_d = 0.95$ in all models, in order to produce a gaseous disk with a finite radial extent. Hence the ensemble mean density of warm gas is given by:

$$\frac{\bar{\rho}_\text{disk}(r, z)}{\bar{\rho}_\text{disk}(0, 0)} = \exp \left[ - \frac{\Phi_{\text{tot}}(r, z) - e_d^2 \Phi_{\text{tot}}(r, 0) - (1 - e_d^2) \Phi_{\text{tot}}(0, 0)}{\sigma_t^2 + c_{s,d}^2} \right]$$  \hspace{1cm} (5.4)$$

Figure 5.2 shows density contours of various homogeneous ISM distributions, demonstrating the effect of varying the parameters $\sigma_t$ and $T_d$. The case of $\sigma_t = 0$ km s$^{-1}$ is equivalent to the density distribution used by, for example,
Strickland & Stevens (2000). In this case, the average temperature of the disk must be high \((10^5 - 10^6 \text{ K})\) in order to produce reasonable disk scale-heights (bottom row). However, this scenario is unrealistic as gas at this temperature rapidly cools. The turbulence parameter \(\sigma_t\) allows us to increase the disk scale-height, whilst keeping the temperature at reasonable values. Nevertheless, this parameter cannot be made too large as the turbulence quickly becomes hypersonic, and gas in the disk would be highly dissipative. In these simulations we set the average temperature of the disk gas to be \(T_d = 10^4 \text{ K}\) and we use the cloud velocity dispersions of \(\sigma_t = 60\) and \(75 \text{ km s}^{-1}\) (panels a and b respectively).

Whilst these values are supersonic with Mach numbers of the order of 5-6, they were chosen in order to obtain a reasonable disk thickness without the gas being excessively supersonic and, as noted, to avoid excessively high temperatures. The supersonic turbulence may be driven by star formation; it is also possible that the vertical pressure support is provided by magnetic fields. Note however, that supersonic velocities in gaseous disks are not unknown. For example, the disks in M87 and NGC 7052 are inferred to be supersonic with velocity dispersions \(\sim 200 \text{ km s}^{-1}\) in M87 and up to \(400 \text{ km s}^{-1}\) in NGC 7052 (Dopita et al., 1997; van der Marel & van den Bosch, 1998). Moreover, the concept of supersonic turbulence is not new in the context of starburst galaxies and is a key feature of the simulations of the ISM in such galaxies (e.g. Wada & Norman, 2001, 2007). In particular these papers focus on the production of a log-normal ISM such as has been incorporated into our initial data. Further justification for a log-normal ISM and its relation to supersonic/superalfvenic turbulence, appealing to the work of Nordlund & Padoan (1999) and Padoan & Nordlund (1999) is provided in Sutherland & Bicknell (2007).

The funnel seen in earlier simulations which utilize a similar potential (e.g. Tomisaka & Bregman, 1993) is still present in our model, most noticeably in panels c and f. This is more apparent if one examines the density distribution over a larger spatial range. This is an unavoidable consequence of this type of disk model and one would need to revisit models for the initial data in order to eliminate it in a physically acceptable fashion. This is beyond the scope of this thesis.

A specific inhomogeneous ISM (out of an ensemble of such possible ISMs) is obtained by multiplying equation (5.4) by a fractal distribution, which has log-normal single point statistics and a Kolmogorov density spectrum (see Sutherland & Bicknell, 2007, for further details). The fractal distribution has mean \(\mu = 1.0\) and variance \(\sigma^2 = 5.0\), where the variance measures the concentration of mass within the dense clouds (Fischera et al., 2003; Sutherland & Bicknell,
Fig. 5.3: Initial density distribution through the central y=0 plane in the three main models. (i) The standard model M01 (left panel), (ii) The thicker disk in M02 (center panel), and (iii) The modified cloud distribution in M03 (right panel).

The temperature of the disk clouds is determined by the pressure of the disk gas and the density of the clouds. The maximum temperature of the disk gas is set to be $T_d = 3.0 \times 10^4$ K in order to prevent disk gas from having temperatures near the peak of the cooling function. Gas at temperatures above this limit is replaced by hot halo gas.

In principle, the resulting warm gas distribution is supported in the gravitational potential by a combination of thermal pressure and turbulence. However, we did not impose a turbulent velocity field because the interaction with the wind generated by the starburst dominates in the vertical direction. However, we did find that a value of $e_d = 0.95$ led to some radial inflow so that we compensated for this by adopting $e_d = 1.0$ (i.e. azimuthal velocity equal to Keplerian velocity) for the velocity field only.

The rotation of the disk causes some additional (but unimportant) problems, as the boundary conditions used in the code are unable to handle inhomogeneous gas rotating onto the computational grid. This results in numerical artifacts at the boundaries, with streams of uniform dense gas appearing on the grid as the disk rotates. These artifacts only appear at the external $x$ and $y$ boundaries and do not effect the evolution of the winds produced in the simulations. Nor do they affect the production of the filaments.

We constrain the central density and temperature of the ISM in the disk and halo to be in pressure equilibrium, with $P/k = 10^6$ cm$^{-3}$ K, consistent with the central regions of starburst galaxies (Chevalier & Clegg, 1985). The parameters of the hot halo and warm disk are summarised in Table 5.1.
The Starburst Region

The starburst region of M82 is believed to be a flattened disk (see Shopbell & Bland-Hawthorn, 1998, and references therein). We therefore adopt a cylindrical starburst region of radius $r_{sb}$ and height $h_{sb}$. We inject mass and energy into this region proportional to the initial density $\rho$ (eq. [5.5] and [5.6]) so that regions of the ISM that are likely to contain stars have a higher injection rate of mass and energy. Hence, the mass injection rate per unit volume ($V$) is given by:

$$\frac{dM}{dtdV} = \frac{\dot{M}_\rho}{\int \rho dV}$$

(5.5)

and the energy injection rate per unit volume:

$$\frac{dE}{dtdV} = \frac{\dot{E}_\rho}{\int \rho dV}$$

(5.6)

where the integral $\int \rho dV$ is over the volume of the starburst region. All of the injected energy is in the form of internal energy of the gas.

Mass and energy are injected continuously into each cell of the starburst region over the course of the simulation. The parameters of the starburst region are summarised in Table 5.1.

5.2.2 The Simulations

Three main simulations were performed, each of which was designed to test the formation of a wind in different ISM conditions. The parameters of these simulations are described in Table 5.2. The resolution is $512 \times 512 \times 512$ cells, covering a spatial extent of $1 \text{kpc}^3$. This allows us to follow the initial formation of the wind, with sufficient resolution to investigate the origin of the $\text{H}\alpha$ and some of the X-ray emission. A fourth simulation was performed in order to test the effect of resolution. This simulation uses a smaller computational grid of $256 \times 256 \times 256$ cells, covering the same $1 \text{kpc}^3$ spatial range. The simulations encompass both hemispheres of the wind, with the starburst region at the center of the computational grid. Each simulation covers a time frame of 2 Myr, and thus we consider only initial stages of the evolution of a wind.

1. Model $\text{M01}$ is the standard model, using the parameters given in Table 5.1.

2. Model $\text{M02}$ is the same as M01 except for the turbulent velocity of the clouds, which has been increased to $\sigma_t = 75 \text{ km s}^{-1}$ to produce a thicker disk.
Table 5.2. Simulation Parameters

<table>
<thead>
<tr>
<th>Model</th>
<th>$M_{sb}^{a}$ ($10^6$ $M_\odot$)</th>
<th>$\sigma_t^{b}$ (km s$^{-1}$)</th>
<th>$h_d^{c}$ (pc)</th>
<th>Grid Size (cells)</th>
<th>Spatial Range (pc$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M01</td>
<td>3.44</td>
<td>60</td>
<td>110</td>
<td>$512 \times 512 \times 512$</td>
<td>$1000 \times 1000 \times 1000$</td>
</tr>
<tr>
<td>M02</td>
<td>4.16</td>
<td>75</td>
<td>135</td>
<td>$512 \times 512 \times 512$</td>
<td>$1000 \times 1000 \times 1000$</td>
</tr>
<tr>
<td>M03</td>
<td>3.96</td>
<td>60</td>
<td>110</td>
<td>$512 \times 512 \times 512$</td>
<td>$1000 \times 1000 \times 1000$</td>
</tr>
<tr>
<td>M04</td>
<td>3.36</td>
<td>60</td>
<td>110</td>
<td>$256 \times 256 \times 256$</td>
<td>$1000 \times 1000 \times 1000$</td>
</tr>
</tbody>
</table>

$^a$Mass of the starburst region

$^b$Velocity dispersion of the clouds

$^c$Scale-height of the disk
3. Model **M03** is the same as M01, but with a modified cloud distribution in the disk.

4. Model **M04** is the same as M01, but has a lower resolution.

The differences between the initial conditions for the three main models are illustrated in Figure 5.3, which shows the initial density distribution through the central y=0 plane. The model M02 was designed to produce a more collimated outflow, while M03 was designed to test the dependence of the morphology on the inhomogeneity of the ISM. A summary of the simulation parameters is given in Table 5.2. The altered ISM distributions result in minor differences in the mass contained within the starburst region (\(M_{\text{eb}}\)) and consequently lead to differences in the distribution of mass and energy injected into the region.

In order to investigate the formation and structure of the filamentary gas, we define the H\(\alpha\) emitting material in the simulations to be gas originating from the disk and whose temperature evolves to being within the range of \(T = 5 \times 10^3\) to \(3 \times 10^4\) K, using a tracer variable to follow disk gas.

### 5.3 Formation of a wind

#### 5.3.1 Evolution, Structure and Morphology

In this section we describe the formation and structure of the wind formed in our main simulation M01, and discuss the effect altering the distribution of the ISM had on the morphology of the outflow. The evolution of the wind in M01 at 6 different epochs (0.5, 0.75, 1.0, 1.25, 1.5, and 2.0 Myr) is depicted in Figure 5.4. Each frame represents the logarithm of the density in the central y=0 plane of the computational grid; this rendering makes much of the structure in the wind obvious. A comparison of the morphology of the outflow at 1 Myr and 2 Myr epochs in the models M01, M02, and M03 is shown in Figure 5.5.

The wind begins as a series of small bubbles originating from the clumpy gas in the starburst region. These bubbles merge as they expand, forming a larger bubble that breaks out of the disk at approximately 0.15 Myr. The introduction of the inhomogeneous disk leads to a marked dependence of the morphology of the wind on the distribution of the ISM, with the initial shape of the outflow determined by the path the wind follows as it interacts with the dense clouds. This results in the asymmetrical morphology seen in all simulations. The thicker disk in M02 acts to slow the development of the outflow,
Fig. 5.4: Logarithm of the density (cm$^{-3}$) through the central y-plane of the wind in M01 at 0.5, 0.75, 1.0, 1.25, 1.5, and 2.0 Myr epochs.

Fig. 5.5: Log-density though the central y-plane illustrating the morphology of the winds in M01 (left), M02 (middle) and M03 (right) at 1.0 Myr (top row) and 2.0 Myr (bottom row).
5.3 Formation of a wind

with the wind breaking out of the disk at approximately 0.2 Myr, somewhat later than the winds in M01 and M03.

It should be noted that the wind does not "blow-out" of the disk as observed in numerous homogeneous simulations (see for example, Mac Low et al., 1989; Strickland & Stevens, 2000, and references within). This is the result of the inhomogeneous nature of the ISM in the disk of our model. Unlike a wind formed in an homogeneous disk, which is forced to push its way out of the dense disk, a wind formed in an inhomogeneous medium follows the path of least resistance, i.e. the tenuous gas between clouds of disk gas. The density of these clouds prevents them from being immediately swept-up by the outflowing hot gas. As a result, the wind does not sweep-up and form a dense shell of disk gas, as is found in the homogeneous case. The formation of such a dense shell has been shown to impede the expansion of the wind until it has reached a sufficient distance from the disk, where the shell begins to fragment under Rayleigh-Taylor instabilities allowing the wind to "blow-out" of the shell. In the inhomogeneous case the wind expands freely into the more tenuous halo gas, which is swept-up to form its own "shell" around the outflow. This shell of swept-up halo gas is also observed in the homogeneous case after their wind has blown-out of the disk and is expanding into the halo. It is unlikely that the presence of a thicker disk in our model would result in the formation of a dense shell of disk gas surrounding the outflow, as any wind formed in such a clumpy medium naturally follows the path of least resistance out of the disk.

By 0.5 Myr (Fig. 5.4; upper left panel), the wind has become more spherical as it propagates into the uniform hot halo. At this stage the structure of the bubble consists of fast \((\dot{v} \gtrsim 1000 \text{ km s}^{-1})\), hot \((T \gtrsim 10^7 \text{ K})\), turbulent gas, surrounded by a slower \((\dot{v} \sim 300 - 400 \text{ km s}^{-1})\), cooler \((T \sim 3 \times 10^6 \text{ K})\), dense shell of swept-up halo gas. Aside from the slower development of the wind in M02 and a slight difference in overall shape, the morphology at this time is similar in all models.

At 1.0 Myr, the wind has begun to flow off the edge of the computational grid. At this stage, in all simulations (Fig. 5.5, upper panels) the outflow resembles the basic structure of a superbubble in the "snow-plow" phase of its evolution (Tomisaka & Ikeuchi, 1988), wherein the bubble is sweeping a substantial amount of the ambient hot ISM. As discussed in Section 2.1, this phase is characterized by 5 zones, which are illustrated in Figure 5.6:

(i) The central injection zone \((T > 5 \times 10^7)\).

(ii) A supersonic free-wind \((T \gtrsim 10^6 \text{ K}, \dot{v} \sim 1000 - 2000 \text{ km s}^{-1})\)
(iii) A region of hot, shocked, turbulent gas ($T \gtrsim 10^7$ K, $v \sim 500-1200$ km s$^{-1}$).

(iv) A cooler, dense outer shell ($T \sim 7 \times 10^6$ K, $v \sim 300 - 400$ km s$^{-1}$).

(v) The undisturbed ambient gas ($T = 5 \times 10^6$ K).

The second and third zones are separated by a wind shock. At this time, the cool, dense disk gas has begun to be accelerated into the wind and is distributed throughout the free-wind region. The amount and distribution of this gas varies between models. Again, the structure of the outflow is heavily influenced by the initial distribution of clouds in the disk. As a result of the thicker disk, the outflow in M02 is still somewhat less extended than the outflow in M01, but displays similar structures, such as the “cavity” to the upper right of the starburst region. In M03, the altered cloud distribution in the disk results in a somewhat different morphology to that of M01, with the outer swept-up shell and wind shock being wider and more flat.

At later times, most of the outer shell has flowed off the computational grid and the shape of the wind shock has taken on a more hour-glass-like appearance. The wind shock appears more asymmetric in the case of M03, while M02 displays similar, but less evolved structure to M01. For example, the arc of dense disk gas to the lower right is evident in both outflows. In all models, disk gas continues to be accelerated into the free-wind. By 2.0 Myr (lower panels), the computational grid is mainly occupied by the free-wind region. At this stage, disk gas that has been swept into the flow forms filamentary-like structures, consisting of strings of clouds with velocities in the range of $v \sim 100 - 800$ km s$^{-1}$ (Fig. 5.9).

In view of the above descriptions at various epochs, it is apparent that inhomogeneities in the disk result in asymmetries on relatively small ($\sim 100$ pc) scales. However, in all models the wind becomes more uniform as it propagates into the homogeneous halo. It is therefore likely that asymmetries on the large scale (e.g. tilted outflows; Bland-Hawthorn & Cohen, 2003) are caused by inhomogeneities in the halo gas, such as the neutral hydrogen cloud enveloping M82 (Yun et al., 1993, 1994).

5.3.2 Base Confinement

A difficulty with previous two-dimensional simulations of starburst winds is their inability to confine the base of the outflow, which expands over the course of the simulations, resulting in unrealistic base diameters (e.g. Tomisaka
5.3 Formation of a wind

& Bregman, 1993; Suchkov et al., 1994; Strickland & Stevens, 2000). For example, the simulations of Strickland & Stevens (2000) resulted in base diameters of the order of 1000 pc, whereas the base of M82’s outflow has been observed to be \(~ 400\) pc (Shopbell & Bland-Hawthorn, 1998). While the base diameter of \(~ 600-800\) pc for M82 observed by Greve (2004) compares more favorably to those found in previous simulations of these winds, it is clear that some mechanism must be in place to prevent the base of the outflow from expanding radially as the wind evolves.

Tenorio-Tagle & Munoz-Tunon (1997, 1998) were able to confine the base of the outflow in their simulations by including the inflow of disk gas onto the nucleus of the galaxy. This resulted in the downward ram pressure of the infalling gas to be greater than the thermal pressure in the central region, preventing the outflow from expanding. However, as noted by Strickland & Stevens (2000), the amount of gas required in this scenario is unrealistic. In our simulations the base of the outflow is well confined, not expanding beyond a radius of \(~ 200\) pc over the 2 Myr time frame (see Fig. 5.4). While it is possible that the size of the base may increase if the simulations were followed to later times, the density of the disk gas (\(~ 100 \text{ cm}^{-3}\)) is large enough to impede the expansion of the outflow along the major axis of the disk.
5.3.3 Wind Collimation

In discussing the degree of collimation of the winds, we refer to the opening angle of the cone defined by the Hα filaments, \( \theta_{H\alpha} \), and the opening angle of the cone defined by the hot wind, \( \theta_{HW} \). Previous simulations of these winds (Tomisaka & Bregman, 1993; Suchkov et al., 1994; Strickland & Stevens, 2000) were unable to collimate the outflowing gas to the degree observed in M82 (\( \theta_{H\alpha} \approx 30^\circ \); Götz et al., 1990; McKeith et al., 1995; Shopbell & Bland-Hawthorn, 1998). In our simulations, the thicker disk in M02 provides the greatest degree of collimation to the outflow with \( \theta_{HW} \approx 100^\circ \), whereas in models M01 and M03 \( \theta_{HW} \approx 160^\circ \).

While the hot wind is poorly collimated when compared to the degree of collimation in M82 defined by the Hα filaments, the morphology of the Hα emitting material in our simulations compares somewhat more favorably. In M02, the filaments are collimated to the greatest extent with \( \theta_{H\alpha} \approx 60 - 70^\circ \). The varying cloud distributions in the disks of M01 and M03 collimate the filaments to different degrees. Both models possess the same disk scale height, yet the filaments in M03, which has a more sparse distribution of clouds, are less collimated (\( \theta_{H\alpha} \approx 80 - 90^\circ \)) than those in M01 (\( \theta_{H\alpha} \approx 70 - 80^\circ \)). However, these values are still far larger than the degree of collimation found in M82 (\( \approx 30^\circ \)).

On the basis of our simulations, we conclude that the amount of gas surrounding the starburst region is an important contributor in determining the degree of collimation of the outflow. In addition, as noted earlier (see Section 5.3.1), it is known that in M82 the extent of the cold gas surrounding the source is much more extended than we have modeled here with a turbulent disk (Yun et al., 1993, 1994). This gas will also have an important additional effect, possibly providing the additional collimation required in M82.

5.4 Filamentary Hα Emission

5.4.1 Formation of the Filaments

Emission line filaments are a dramatic feature in the images of starburst galaxies so that there is a large amount of interest in the mechanism behind their formation. Figure 5.7 shows log-temperature slices through the central \( y=0 \) plane of M01 over the period of 0.75 to 1.75 Myr. The filaments appear as dense clouds of disk gas that has been drawn into the outflow. Since energy is injected into the starburst region proportional to the local density, a signif-
significant fraction of the energy is injected into the dense clouds which appear in the log-normal, fractal distribution. The binding energy of clouds is quickly overcome and the Hα filaments then form from the break up of these clouds, the fragments of which are then accelerated into the flow by the ram-pressure of the wind.

This process is illustrated in Figure 5.7, where at 0.75 Myr (upper left panel) the starburst region is filled with clumped disk gas. Over the next 1 million years, the break-up of the central clouds can be seen, with material being drawn out into strings of dense clouds (lower panels). By 1.75 Myr, the starburst region is almost completely evacuated. The filaments are initially immersed within the turbulent hot gas in the vicinity of the starburst region. As the wind expands, the filaments are accelerated into the free-wind region of the outflow. Gas is also stripped and entrained into the wind from clouds at the edge of the starburst region. (See in particular the panels from 1.15 Myr onwards.)

The filamentary structure can be seen best in Figure 5.8 which shows the three-dimensional structure of the Hα emitting gas at 1 Myr (upper panels) and 2 Myr (lower panels) in M01, M02 and M03. The filaments appear as strings of dense clouds emanating from the starburst region. These filaments form a filled biconical structure inside of the more spherical hot wind, with the filaments distributed throughout this region. A movie of the formation of the filaments in M01 is available online (see Fig. 5.16). At 2 Myr the velocity of the Hα emitting gas in all models falls within the range \( v \sim 100-800 \text{ km s}^{-1} \) (see Fig. 5.9) and increases with height \( z \) above the disk. This is comparable to the velocities observed in M82, at a height of 500 pc, of \( v = 500-800 \text{ km s}^{-1} \) (Shopbell & Bland-Hawthorn, 1998; Greve, 2004). It is possible that lower velocities are not observed in the filaments of M82 because of dust obscuration of the central starburst (de Grijs et al., 2000).

5.4.2 Filament Survival

The interaction of a cloud of dense gas with a supersonic wind has been investigated in the past via numerous two- and three-dimensional simulations (e.g. Sgro, 1975; Klein et al., 1994; Poludnenko et al., 2002; Melioli & de Gouveia Dal Pino, 2004; Melioli & de Gouveia Dal Pino, 2006; Melioli et al., 2005; Marcolini et al., 2005; Pittard et al., 2005; Tenorio-Tagle et al., 2006). A common theme in this work is the issue of the survival of the cloud which is subject to shock disruption. Another effect to consider is the ablation of the cloud as a result of the Kelvin-Helmholtz instability. This is discussed by Klein et al. (1994) and also further below. In adiabatic simulations (Klein et al., 1994; Poludnenko
et al., 2002) clouds are heated and disrupted on a shock-crossing timescale. The heating and expansion of the cloud renders it susceptible to ablation by the surrounding stream. However, as explained by Melioli et al. (2005) cooling effects a dramatic difference to the adiabatic scenario: If the cooling time is short enough (e.g. compared to the cloud-shock crossing time) then the radiative shock driven into the cloud provides a protective high density shell which prevents further disruption.

In view of the importance of cooling, we compare the cooling time to both the cloud-crushing time \( t_{\text{crush}} \approx R_c/v_{\text{sh}} \approx (\rho_c/\rho_w) R_c/v_w \) and the timescale of the Kelvin-Helmholtz instability \( t_{\text{KH}} = R_c(\rho_c + \rho_w)/(v_c - v_w)(\rho_c\rho_w)^{1/2} \), in order to ascertain whether we can expect the clouds to be protected by an enveloping radiative shock.

The cooling time of a \( R_c = 5 \) pc cloud in our simulations is of the order \( 10^{10} \) seconds. This is far shorter than the crushing time of the same cloud \( t_{\text{crush}} \sim 10^{14} \) seconds and the growth rate of the Kelvin-Helmholtz instability \( t_{\text{KH}} \sim 10^{12} \) seconds, for \( v_c \sim 800 \) km s\(^{-1}\). This suggests that a cloud may be accelerated to the velocities found in this study and remain sufficiently stable to ablation. However, we note that the Kelvin-Helmholtz timescale could be shorter for clouds at lower velocities and that mass ablation may occur a faster rate as a
result of the heating of the clouds outer layers by photoionization (e.g. Tenorio-Tagle et al., 2006).

A related issue is whether the clouds can be accelerated to supersonic velocities (based on the internal cloud sound speed). Consider a simple model of a spherical cloud of density $\rho_c$ and radius $R_c$ being driven by a wind of density $\rho_w$ and velocity $v_w$. Let the drag coefficient be $C_D = 1$. Then the theoretical acceleration of the cloud is

$$f_{th} = \frac{3}{8} C_D \left( \frac{\rho_w}{\rho_c} \right) \frac{v_w^2}{R_c}$$

If we take one of our clouds with radius $R_c = 5$ pc and average number density $n_c = 100$ cm$^{-3}$ then the theoretical acceleration of the cloud, by a wind with velocity $v_w = 2000$ km s$^{-1}$ and average number density $n_w = 0.05$ cm$^{-3}$, is $f_{th} = 5 \times 10^{-12}$ km s$^{-2}$. The observed acceleration of a gas cloud in our simulations is $f_{ob} \approx 1.3 \times 10^{-11}$ km s$^{-2}$ – close to the theoretical value. This is physically feasible as a result of the protection by the radiative shell. Nevertheless, this estimate neglects detailed hydrodynamics including the formation of shocks and the ablation of material, which are important in a realistic wind-cloud interaction. Detailed higher resolution simulations of a single cloud impacted by a wind are necessary in order to investigate this problem in sufficient detail (see Chapter 6).

Other previous simulations have also addressed similar situations. For example, Tenorio-Tagle et al. (2006) have investigated clouds driven by an outflow from a central star cluster and found similar ablated cloud morphologies to those presented in this chapter. In their case the clouds only achieve a maximum velocity of $\sim 50$ km s$^{-1}$ but the theoretical accelerations are similar. This again points to the requirement of high resolution simulations and the dependence on initial conditions in order to fully understand the physics of wind-cloud interactions.

5.4.3 Effect of the ISM

As illustrated in Figure 5.8, the morphology of the Hα emitting filaments is affected by the inhomogeneity of the disk to a greater extent than the hotter wind that surrounds them. Whilst more apparent early in the formation of the wind, asymmetries are seen on both small and large scales, with the distribution and number of filaments differing between the upper and lower winds in all models.

At 1 Myr (top row) the Hα emission starts to become filamentary. These
filaments are asymmetric with the morphology varying from model to model. The filaments in M02 are less extended to those in M01. In the case of M03, the filaments to the north are tilted with respect to the minor axis, and are overall less numerous. At 2 Myr (bottom row) the filaments form a biconical shape, consisting of strings of Hα emitting clouds. These filaments are distributed throughout the wind and rotate in the same direction as the disk. In M02 the filaments have a similar distribution to those in M01, but are slightly more collimated. In contrast, the filaments in M03 are more chaotic than those in M01, with less Hα emitting gas. Filaments are formed from fragments of clouds in the starburst region that have been accelerated into the wind, and the morphology of the filament system somewhat depends on the original location of the clouds in the starburst region.

The mass of Hα emitting gas on the computational grid in M01 and M03 at 2 Myr is $M_{\text{H}\alpha} = 1.5 \times 10^6 \ M_\odot$ and $M_{\text{H}\alpha} = 1.3 \times 10^6 \ M_\odot$ respectively. M02, with its thicker disk, has a Hα mass of $M_{\text{H}\alpha} = 3.9 \times 10^6 \ M_\odot$ contained in the outflow. These numbers compare favorably with known Hα estimates in starburst winds ($\sim 10^5 - 10^7 \ M_\odot$: Veilleux et al., 2005).

The amount of Hα-emitting gas found in the outflow is affected by the amount of disk gas inside and also surrounding the starburst region. For example, the outflow in M02 must interact with considerably more disk gas before it is able to escape the disk. Consequently, more Hα emitting gas is found in the wind. However, M03 which initially contains more gas inside its starburst region than M01 (see table 5.2), has a smaller amount of filamentary gas in the wind, as a result of the more sparse distribution of clouds surrounding the starburst region.

5.4.4 Morphology and Structure

There have been many theories for the origin of the optical line filaments observed in starburst winds. A popular idea is that the filaments are formed from disk gas that is swept up by the wind (Veilleux et al., 2005). These simulations indeed confirm this idea, with the Hα emitting gas forming from disk gas that has been broken up and accelerated into the wind. However, while the filaments do form a biconical outflow (Fig. 5.8), they are immersed inside the hot wind and do not trace the true radial and vertical extent of the outflow as defined by the hot gas (Figs. 5.4 and 5.7). This paints a different picture to the commonly held view of the optical line-emission filaments framing the edges of a biconical outflow. It is possible that current observations of starburst winds at optical and X-ray wavelengths may not indicate the absolute size of the out-
flow. This has implications for observational estimates of the energy contained in these winds, as a significant fraction of the energy contained within the wind may be found in the hottest ($T \gtrsim 10^7$ K) gas that is not traced by H$\alpha$ and X-ray emission (Veilleux et al., 2005).

Our inference of a more extensive wind than implied by the filaments is supported by some observational evidence suggesting that the true extent of M82’s superwind is larger than originally thought. Lehnert et al. (1999) find evidence for H$\alpha$ and X-ray emission at a distance of approximately 11 kpc from the disk. They propose an interaction of the wind with an HI cloud in the halo of M82. This feature is now known to be connected to the main superwind emission by X-ray emission (Stevens et al., 2003), but is possibly of a different origin than the X-ray emission at lower radii (Strickland et al., 2002). Recent Spitzer observations reveal a large mid-infrared filamentary system along the minor axis, which is radially and vertically more extended than the H$\alpha$ emission (Engelbracht et al., 2006). While the nature of this emission is uncertain, there does appear to be a spatial correlation with the H$\alpha$ emitting gas in the region where H$\alpha$ emission is detected. Strickland et al. (2004a) also possibly detect diffuse, low-surface brightness, X-ray emission in in M82’s halo, which has a larger spatial extent and uniformity than the filamentary X-ray emission. On the other hand, they note that this may be caused by low photon statistics. It
is clear that multi-wavelength observations are needed in order to understand the true extent of starburst winds.

The tendency of the filaments to fill the interior of the biconical structure arising from our simulations is also of interest. This is in agreement with observations of the wind in the Circinus galaxy (Veilleux & Bland-Hawthorn, 1997). Other winds, such as M82 (Shopbell & Bland-Hawthorn, 1998) and NGC 3079 (Veilleux et al., 1994), are limb-brightened, with the filaments thought to lie on the surface of a mostly hollow structure. The mechanism responsible for producing an evacuated cavity is uncertain, but in view of the way in which filaments have been formed in our simulations, this feature may reflect the distribution of the interstellar medium in the starburst region itself. Starbursts where much of the molecular gas is situated in a ring (e.g. Telesco et al., 1993), rather than throughout a disk, would most likely produce winds that are hollow, as the clouds in the ring are broken up and entrained into the wind. Another possibility is that the wind has significantly evolved to point where it has evacuated the center of the starburst region of molecular gas, with the filamentary system being fed from gas stripped from the edge of the starburst region, an effect that in fact does occur in our simulations (e.g. Fig. 5.7; lower left panel). The center of the biconical region could also have been swept clear by a previous wind, powered by an earlier burst of star formation (e.g. Bland-Hawthorn & Cohen, 2003; Förster Schreiber et al., 2003).

The source of the ionization of the filaments in a starburst wind is still uncertain. Since photoionization is not included in our simulations, all of the Hα emission arises from shocks. Indeed there are examples of winds where the
emission is shock ionized (e.g. NGC 1482; Veilleux & Rupke, 2002). In other winds, such as M82 and NGC 253, there are signs that some of the filaments may be photoionized. In particular, M82 is known to have a strong ionization cone, where emission in the lower filaments is thought to arise from photoionization, with ionization from shocks dominating at larger radii (Shopbell & Bland-Hawthorn, 1998). While we are unable to study photoionization with our current model, it is likely that it plays a role in the ionization of the filaments in many winds (see, for example, Melioli et al., 2005; Tenorio-Tagle et al., 2006), and warrants further investigation.

5.5 X-Ray Emission

X-ray luminosities implied by the simulations were determined at 0.2 Myr intervals in both the soft (0.5 - 2.0 keV) and hard (2.0 - 10.0 keV) energy bands, utilizing broadband cooling fractions obtained from MAPPINGS IIIr (see Sutherland & Dopita, 1993). Figure 5.10 gives the X-ray luminosity of the wind as a function of time in both energy bands for all models. The peak of the curves in Figure 5.10 is the result of the limited 1 kpc$^3$ spatial range of the simulations. Once the swept-up shell has reached the edge of the computational grid (at ~ 0.8 Myr) it begins to flow off the grid, and its contribution to the X-ray luminosity can no longer be determined. As this happens, the curves in Figure 5.10 begin to decline, flattening when the swept-up shell has completely left the computational grid. The calculated X-ray luminosities of the wind are then comprised solely of emission from the free-wind region, which has grown in
The hard (2.0 - 10.0 keV) X-ray luminosity of the wind for all models in given in the right hand panel of Figure 5.10. The luminosity does not vary significantly between models, being of the order of $10^{38}$ erg s$^{-1}$. The hard X-ray emissivity, through the central y-plane, of M01 at 1.0 Myr (left) and 2.0 Myr (right) epochs is shown in Figure 5.11. At 1 Myr the wind has started to flow of the computational grid, but the internal structure of the wind, as shown in Figure 5.6, can still be seen. The main contributor to the hard X-ray emission is the starburst region itself, with a lesser contribution from the swept-up shell. While the shell is not a strong X-ray emitter at hard energies, having a temperature of the order of $10^6$ K, the volume of the computational grid occupied by the swept-up shell is large, making its contribution to the hard X-ray emission non-negligible, as evident by the drop in luminosity as the shell leaves the grid. Differences in the shape and volume of this shell in each model leads to the variation in the peaks in Figure 5.10, with the thinner shell in M02 resulting in smaller luminosities.

By 2 Myr (Fig. 5.11, right panel), the swept-up shell has completely left the computational grid, and the calculated X-ray luminosity is now comprised solely from emission processes interior to the shell. The starburst region is still the major contributor to the emission, with a lesser contribution from emission processes.
from the more diffuse wind. This is in agreement with the conclusions of both Suchkov et al. (1994) and Strickland & Stevens (2000). Furthermore, Silich et al. (2005) developed an analytic model for the X-ray emission from star cluster winds, which showed that the hard X-ray emission is associated with the hot thermal plasma within the starburst region. As expected, we find no significant difference between the hard X-ray luminosity in each model at the 2 Myr epoch, as the size and power of the starburst is identical in all models. At this time, the luminosity is approximately constant with $L_X \sim 1.2 \times 10^{38}$ erg s$^{-1}$, but as the contribution from the swept-up shell at this time cannot be determined, it is likely that the actual hard X-ray luminosity of each model is higher, increasing as the volume occupied by the wind increases.

5.5.2 Soft X-Ray Emission

Origin of the Soft X-Rays

Chandra observations of starburst galaxies have provided clues to the nature of the soft X-ray emission seen in galactic winds, such as a close spatial correlation between the soft X-ray and Hα emission in the wind (e.g. Strickland et al., 2004a), which is suggestive of a physical relationship between filaments and the production of soft X-rays. However, the actual mechanism for the emission of the soft X-rays is uncertain. Our simulations indicate possi-
ble mechanisms for the production of soft X-rays. Two of these mechanisms involve the mixing of high temperature gas from the hot wind and warm gas from the filaments to produce intermediate temperature gas which emits soft X-rays. Whilst the resolution of these simulations is adequate for the global features of the simulation, it is insufficient to resolve the fine scale interactions between the hot and warm gas. Therefore the production of soft X-rays by mixing can only be regarded as a possible mechanism at this stage.

Notwithstanding the above qualification we discuss the regions of soft X-ray emission that are produced in these simulations, bearing in mind that two of the relevant processes described below will be confirmed by detailed simulations of interactions between winds and filaments in Chapter 6. Figure 5.12 shows the volume emissivity of the soft X-rays at 1 Myr (left) and 2 Myr (right) epochs. As with the hard X-ray emission in Figure 5.11, there is little difference between the models M01, M02, and M03, with X-rays arising from the same processes in each model.

At 1 Myr it can be clearly seen that the swept-up shell is a strong emitter of soft X-rays. This shell consists of halo gas that has been swept into the wind and shock heated to $T \sim 7 \times 10^6$ K. This source of soft X-ray emission is straightforward and is not subject to the qualifications described above.

At 2 Myr, X-ray emission from the free wind starts to be apparent. There are 4 main processes interior to the swept-up shell that give rise to soft X-rays and examples of these are shown in Figure 5.13:

(a) The mass-loaded wind. Turbulent gas in the vicinity of the starburst region is mass-loaded through mixing with clouds in the disk, creating a region of hot ($T \gtrsim 10^6$ K), dense ($n \sim 0.3$ cm$^{-3}$) rapidly cooling gas. This component is a strong X-ray emitter and is the largest contributor to the soft X-ray emission interior to the swept-up shell in all our models. As we have indicated above, numerical diffusion as a result of inadequate resolution may lead to poor estimates of the amount of mixing involved and consequently in the soft X-ray emissivity of the mixed gas. Therefore, higher resolution simulations dedicated to a study of the mixing between the hot wind and the cooler filaments are required in order to correctly determine the amount of mixing involved (see Chapter 6).

(b) Emission from the intermediate temperature ($T \sim 10^6$ K) interface between the hot wind and the cooler filaments. This component is related to the mass-loaded wind, with mixing between the hot and cold gas creating a region of intermediate densities and temperatures. Again inadequate
Fig. 5.13: Highlighted soft X-ray emissivity from the wind in M01. Soft X-rays arise from: (a) The cooling mass-loaded wind, (b) The intermediate temperature interface between hot and cold gas, (c) Bow shocks, and (d) The interaction between bow shocks. The size and location of each panel are indicated in Figure 5.12.

Fig. 5.14: Schematic of the Hα and X-ray emission arising in a starburst wind and their spatial relationship.
resolution and numerical diffusion in this region means that the actual contribution to the soft X-ray luminosity is uncertain.

(c) Bow shocks. Soft X-rays arise when a bow shock \((T \sim 10^7 \text{ K})\) forms upstream of clouds of disk gas \((T \sim 10^4 \text{ K})\) that have been accelerated into the flow by the ram pressure of the hot wind \((T \sim 10^5 \text{ K})\). This is a straightforward process where gas is shock heated to X-ray temperatures.

(d) Colliding bow shocks. As disk gas is accelerated into the wind, the resultant bow shocks begin to cool as the wind expands. When 2 shocks collide, the gas is further shock heated to temperatures of the order \(T \sim 10^7 \text{ K}\).

As a result of the limited spatial extent of these simulations, it is difficult to get a clear picture of the distribution of soft X-ray emission throughout the entire wind. However, it is possible to extrapolate from the structure of the wind at 1 Myr and 2 Myr to get an idea of the soft X-ray emission arising from the wind at later times. Figure 5.14 shows a schematic of the X-ray and H\(\alpha\) emitting gas in a starburst wind, based on the results of our simulations. In Section 5.4.1 we proposed the formation of the H\(\alpha\) emitting filaments from the breakup of disk clouds in the starburst region that are then accelerated into the wind by ram pressure. These clouds are potentially the source of the mass-loaded gas discussed above, with tails of soft X-ray gas streaming from their surfaces (subject to the caveats already noted concerning numerical diffusion). The presence of clouds of disk gas in the outflow also results in the formation of bow shocks as they are accelerated by the wind. X-rays that arise from these processes are naturally spatially correlated to the H\(\alpha\) emission in the wind. While the X-ray emission in our simulations is volume filled, which was also found to be the case with the H\(\alpha\) emission (see Fig. 5.8), many starburst winds are found to be limb-brightened in X-rays. However, there is evidence to suggest that some winds may at least be partially volume filled (e.g. NGC 3079: Cecil et al., 2002). Nevertheless, the observed physical connection between the two wavelengths suggests that the same mechanism responsible for the production of limb-brightened outflows in H\(\alpha\), result in limb-brightened X-ray emission.

**Soft X-Ray Luminosity**

We now return to discuss further features of the soft X-ray luminosity (Fig. 5.10). While the soft X-ray luminosity is similar in all of our models, slight differences reflect the morphology of each wind. The models M01 and M03, whose initial ISMs differed only by the distribution of clouds in the disk, have almost identical soft X-ray luminosities. On the other hand, the wind formed in
the model M02, initially has a lower luminosity than the other models. This is a consequence of the thinner shell that forms around the outflow. At 2 Myr, when the contribution of this shell is no longer taken into account, the luminosity of the wind M02 is comparable to that of the other models.

The highest soft X-ray luminosities reached in our models occur when the swept-up shell still lies on the computational grid. At this time, the luminosity of the wind is of the order of $L_x \sim 10^{30}$ erg s$^{-1}$. When the shell is not included, and soft X-ray emission arises solely from the processes associated with the H$\alpha$ emission discussed above, the luminosity is of the order $L_x \sim 10^{38}$ erg s$^{-1}$. Typical soft X-ray luminosities that are observed in starburst winds fall in the range of $10^{38} - 10^{41}$ erg s$^{-1}$ (e.g. Read et al., 1997; Strickland et al., 2004a; Ott et al., 2005b). Our values fall at the lower end of this range, but clearly the X-ray luminosity is dependent on the volume of the wind and would be higher at later times.

5.6 Resolution Effects

In order to test the effect of the numerical resolution on our model, a fourth simulation (M04) was performed on a smaller computational grid of $256 \times 256 \times 256$ cells, but otherwise identical to M01. The effect of the resolution is most significant with respect to the H$\alpha$ emitting gas found in the outflow. Figure 5.15 gives the logarithm of the temperature at 2 Myr in M04 (left) and M01 (right). M04 differs only by its smaller computational grid. Whilst it exhibits a similar overall shape and structure (i.e. biconical structure), smaller structures, such as bow shocks, are not well resolved. The dense gas that makes up the H$\alpha$ filaments has not been adequately resolved, appearing as strands of gas, rather than as the strings of clouds found in the higher resolution simulations.

We find that the lower resolution of M04 results in soft X-ray luminosities that are comparable to those in M01 (Fig. 5.10). The luminosity in both soft and hard energy bands follows a similar trend to that of the three main models, with the luminosity being slightly higher in the soft band and lower in the hard. As with in the other models, the hard X-ray emission originates from the starburst region. On the other hand, as bow shocks are not well resolved at the lower resolution in M04, the majority of the soft X-ray emission arises from the swept-up shell of halo gas, and from the mass-loaded component of the wind.

As previously noted, numerical diffusion causes difficulties in accurately determining the soft X-ray luminosity of the wind in regions of mixing gas. As some of the X-ray emission is poorly resolved (i.e. only a few cells in size) it
is likely that the calculated luminosities may be poorly estimated in these regions. This is particularly likely at the interfaces between the hot wind and the cool entrained gas, which emits strongly in soft X-rays. This region is at best a few cells in width and any X-ray emission is likely a result of mass diffusion between the hot and cold gas and not physical. Numerical diffusion may also be an issue in the mass-loaded component of the wind, which appears to be the largest contributor to the soft X-ray emission. Mixing of the cool gas stripped of clouds accelerated into the wind with the surrounding hot gas may have resulted in temperatures and densities that emit strongly at X-ray energies. However, we note that this effect may be physical in origin. The fact that the soft X-ray luminosity in both M01 and M04 are similar at 2 Myr, when the majority of the emission is from the mass-loaded component, is encouraging, but higher resolution simulations are needed in order to determine if the luminosities achieved in our simulations are realistic.

5.7 Discussion and Conclusions

We have performed a series of three-dimensional simulations of a starburst-driven galactic wind designed to test the evolution of the wind in different ISM conditions. By conducting three-dimensional simulations we are able, for the first time, to study the morphology and dynamics of the entire outflow. The introduction of an inhomogeneous disk enables us to study the development
of asymmetries and the interaction of the wind with clouds in the disk. The results of these simulations are as follows-

(i) The interstellar medium plays a pivotal role in the evolution of a galactic wind. The interaction of the wind with clouds in the disk results in asymmetries and tilted outflows on the small scale. Nevertheless, it is likely that inhomogeneities in the halo are the cause of the large-scale asymmetries in an outflow.

(ii) The distribution of gas surrounding the starburst region assists in collimating the outflow. The thickness of the disk and the location of the starburst are important factors in determining the degree of collimation, with the degree of collimation increasing with the amount of gas surrounding the starburst region.

(iii) The base of the outflow is well confined within a radius of 200 pc over the 2 Myr time frame of the simulation as a result of the high density of the disk gas.

(iv) The Hα filaments form from the breakup of clouds in the starburst region, the fragments of which are then accelerated by the ram pressure of the wind. Filaments are also formed from gas that has been stripped from the sides of the starburst region. The distribution and mass of the filaments is affected by the distribution of clouds in the vicinity of the starburst region.

(v) The Hα filaments appear as strings of disk gas that form a filled biconical structure inside of a more spherical hot wind. The filaments are distributed throughout this structure, but do not trace the true extent to the wind defined by the hot gas.

(vi) The calculated soft X-ray luminosities up until 2.0 Myr are of the order of $10^{38} - 10^{39}$ erg s$^{-1}$ and the hard X-ray luminosities of $10^{38}$ erg s$^{-1}$. These luminosities are dependent on the volume of the wind and would be larger for a more evolved outflow.

(vii) Interior to the swept-up shell of halo gas, soft X-ray emission originates in the same region as the Hα emitting gas. While higher resolution simulations are needed to confirm X-ray emission from mixing processes, we find 4 mechanisms that give rise to Soft X-rays: (i) The mass-loaded wind, (ii) the intermediate temperature interface between the hot wind and cool filaments, (iii) bow shocks, and (iv) interactions between bow shocks. The shell is also a major contributor to the soft X-ray emission, but has no associated Hα emission.
(viii) The hard X-ray emission originates from gas in the starburst region.

The results of these simulations indicate that the host galaxy itself and the environment in which it is situated is a major determinant in the morphology of the outflow. The emission processes that contribute to the Hα and soft X-ray emission may vary from one galaxy to the next. Whether the Hα emission originates from photoionization or from shock-heating (or both) cannot be determined from these simulations. However, we do find an abundance of filamentary T ~ 10⁴ K gas that has been accelerated into the outflow, forming a biconical shaped region that is commonly observed in starburst winds. The source of the soft X-ray emission is also likely to depend upon the environment of the host galaxy. In the case of M82 it is plausible that the interaction of the wind with the surrounding HI clouds is also a contributor to the soft X-ray emission, in addition to the processes mentioned above.

The observed spatial relationship between the Hα and soft X-ray emitting gas can be explained when considering emission processes interior to the wind, such as bow-shocks and the mass-loaded component of the wind. In addition, the presence of the strong X-ray emitting shell with no associated Hα emission is interesting. While the ultimate fate of the shell is unknown at present, this result argues for the presence of X-ray emission more extended than the filamentary Hα gas. Strickland et al. (2002) suggest that this emission may be detectable in more distant starburst galaxies.

Fig. 5.16: Online: Movie the formation of the Hα filaments in M01 over a 2 Myr time frame (http://www.mso.anu.edu.au/~jcooper/movie/video16.mpg).
6. ON THE THREE-DIMENSIONAL INTERACTION OF A SUPersonic WIND WITH A NON-UNIFORM RADIATIVE CLOUD

6.1 Introduction

The interstellar medium is known to be inhomogeneous, consisting of various gaseous phases, from cool molecular clouds to tenuous million degree gas (Cox, 2005). A study of the interaction of a supersonic wind with a dense cloud is a problem with many astronomical applications, such as galactic winds, supernova remnants, and broad absorption line quasars, and has received much attention. In the past this interaction has been studied both analytically (e.g. McKee & Cowie, 1975; Heathcote & Brand, 1983) and numerically (e.g. Sgro, 1975; Woodward, 1976; Nittmann et al., 1982). Over the last two decades, numerous two- and three-dimensional simulations have been performed. Many early attempts assumed an adiabatic interaction (e.g. Stone & Norman, 1992; Klein et al., 1994; Xu & Stone, 1995), while later attempts have included radiative cooling (e.g. Mellema et al., 2002; Melioli & de Gouveia Dal Pino, 2004; Fragile et al., 2004, 2005; Marcolini et al., 2005; Melioli et al., 2005; Tenorio-Tagle et al., 2006; Orlando et al., 2005, 2006, 2008). Among the plethora of simulations reported in the literature, the effects of thermal conduction (e.g. Marcolini et al., 2005; Orlando et al., 2005, 2006, 2008; Recchi & Hensler, 2007), magnetic fields (e.g. Mac Low et al., 1994; Gregori et al., 1999; Fragile et al., 2005; Orlando et al., 2008; Shin et al., 2008), photoevaporation (e.g Melioli et al., 2005; Raga et al., 2005; Tenorio-Tagle et al., 2006), and the presence of multiple clouds (e.g. Poludnenko et al., 2002; Melioli et al., 2005; Pittard et al., 2005; Tenorio-Tagle et al., 2006) have been considered. In this chapter, we report on our high resolution three-dimensional simulations of the interaction of a supersonic wind with a non-uniform radiative cloud. This work is motivated by the global simulations of a starburst-driven galactic wind presented in Chapter 5. These simulations were three-dimensional, radiative, and incorporated an inhomogeneous disk that allowed us to study the interaction of a galactic scale wind with fractal clouds of disk gas. As the global simulations did not in-
clude thermal conduction, magnetic fields, or photoevaporation, they are also not included in this study.

The interaction of a spherical cloud with a shock wave is often characterised by four evolutionary phases (e.g. Klein et al., 1994, and references therein):

(i) An initial phase where the blast wave interacts with the cloud. A shock passes into the cloud, with another shock reflected into the surrounding medium.

(ii) A phase of shock compression where the flow around the cloud converges on the axis at the rear. During this phase, the cloud begins to flatten, with its transverse size greatly reduced. A shock is also driven into the back of the cloud.

(iii) The re-expansion phase where the shock transmitted into the cloud has reached the back surface and produces a strong rarefaction back into the cloud. This leads to expansion of the shocked cloud downstream.

(iv) A final phase where the cloud fragments and is destroyed by hydrodynamical instabilities (e.g. Kelvin-Helmholtz and Rayleigh-Taylor instabilities).

Klein et al. (1994) performed an extensive series of two-dimensional simulations of an spherical adiabatic cloud interacting with a shock wave. They found that irrespective of the initial parameters, the cloud was destroyed within several cloud crushing times. Xu & Stone (1995) confirm this result in their three-dimensional simulations. However, Mellema et al. (2002) in a short letter, reported their two-dimensional study of the evolution a cloud in a radio galaxy cocoon. Their simulations included the effects of radiative cooling and showed that merging of the front and back shocks leads to the formation of an elongated structure. This structure breaks-up into fragments which are not immediately destroyed. This increased ability for the cloud to survive has been reproduced by all studies that implement radiative cooling in their simulations. In addition, it has been shown that strong cooling in the cloud can cause a thin dense shell that acts to protect the cloud from ablation (Fragile et al., 2004; Melioli et al., 2005).

Thermal conduction can suppress the hydrodynamical instabilities that act to fragment a cloud (Orlando et al., 2005; Marcolini et al., 2005), while the presence of a magnetic field has been shown to both hasten (e.g Gregori et al., 1999) and delay (e.g. Mac Low et al., 1994; Fragile et al., 2005) the cloud's destruction. More recently, Orlando et al. (2008) performed three-dimensional simulations
of the wind/cloud interaction that included the effects of radiative cooling, thermal conduction, and magnetic fields. They showed that in the presence of an ambient magnetic field, the effect of thermal conduction in stabilizing the cloud may be diminished depending on the alignment of the field. Clearly the survival of a cloud interacting with a strong wind is a problem of significantly more complexity than indicated by the purely adiabatic scenario investigated by Klein et al. (1994) and others.

We further investigate the effects of radiative cooling on the survival of the cloud, by performing high \( \sim 0.1 \) pc resolution simulations of both a radiative and an adiabatic cloud, allowing us to perform a direct comparison between the two scenarios. Symmetry is not assumed, with the entire cloud being modeled, in contrast to the strategy employed in many previous three-dimensional models. In order to understand the effects of the cloud's structure on the wind/cloud interaction, we consider two different cloud geometries: a fractal cloud, similar to those that comprised the inhomogeneous disk in Chapter 5, and a spherical cloud. The effect of the cloud's geometry on its evolution has been investigated before. Xu & Stone (1995) considered the interaction of a shock wave with a spherical and two different prolate cloud geometries, each with a different alignment of the cloud's major axis. In addition, Mellema et al. (2002) considered both spherical and elliptical cloud geometries. Both studies show that the initial geometry of the cloud can alter the evolution of the cloud significantly.

One of the most important results from Chapter 5 was our suggestion of a mechanism for the formation of the filaments seen in starburst-driven winds at optical wavelengths (see Veilleux et al., 2005, ; for review). According to Chapter 5 the filaments are formed from clouds of disk gas that have been accelerated into the outflow by the ram-pressure of the wind. An important question that arises is: Can the clouds survive being immersed in a hot supersonic wind long enough to form a filament and remain sufficiently cool to emit at optical temperatures? Or will they be heated and destroyed by hydrodynamical instabilities? Here we set out to answer this question.

Another significant result to arise from Chapter 5 is our proposal of four different mechanisms that would give rise to soft X-ray emission that is spatially correlated with the filamentary optical emission; a major finding of recent Chandra observations (Strickland et al., 2002, 2004a,b; Cecil et al., 2002; Martin et al., 2002). Our global simulations found that soft X-rays can arise from (i) mass-loading from ablated clouds, (ii) the intermediate temperature interface between the hot wind and cool filaments, (iii) bow shocks upstream of clouds accelerated into the outflow, and (iv) interactions between these bow shocks.
The first two mechanisms involve the mixing of hot and cold gas, and are possibly caused by numerical diffusion in the simulations, and thus may not be physical. To investigate this possibility, we have performed a detailed resolution study of the wind/cloud interaction. The study also allows us to test the impact of the numerical resolution on the evolution of the cloud.

6.2 Numerical Method

6.2.1 Description of the Code

The simulations were performed using the PPMLR (Piecewise Parabolic Method with a Lagrangian Remap) code utilised in Chapter 5. PPMLR is a multidimensional hydrodynamics code based on the method described by Colella & Woodward (1984) and has been extensively modified (e.g. Sutherland et al., 2003a,b) from the original VH-1 code (Blondin, 1995). Thermal cooling, based on output from the MAPPINGS III code (Sutherland & Dopita, 1993) has been implemented. This allows for a realistic evolution of a radiatively cooling gas (Sutherland et al., 2003b; Saxton et al., 2005). The simulations discussed in this chapter are three-dimensional and utilise Cartesian \((x,y,z)\) coordinates. They were performed on the SGI Altix computer operated by the the Australian Partnership for Advanced Computing.

6.2.2 Problem Setup

In order to study the wind/cloud interaction in sufficient detail, whilst still retaining the ability to follow the evolution and survival of the cloud over a period of approximately 1 million years, the simulations cover a physical spatial range of \(50 \times 50 \times 150 \text{ pc}\), with the cloud centered on the origin. As our intent is to compare these simulations to the formation and survival of the clouds found in Chapter 5, we choose initial conditions for the wind based upon the results of those simulations (Table 6.1). In order to understand our choice, we briefly recount the formation and evolution of the starburst-driven winds which we simulated in Chapter 5:

(a) A series of small bubbles of hot \((T \gtrsim 10^7 \text{ K})\) gas form in the starburst region. As these bubbles expand, they merge and follow the path of least resistance out of the disk of the galaxy, i.e. the tenuous hot gas surrounding the denser disk clouds.
Table 6.1. Initial Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Temperature (K)</td>
<td>$T_w$</td>
<td>$5 \times 10^6$</td>
</tr>
<tr>
<td>Wind Density (cm$^{-3}$)</td>
<td>$n_w$</td>
<td>0.1</td>
</tr>
<tr>
<td>Wind Velocity (km s$^{-1}$)</td>
<td>$v_w$</td>
<td>1200</td>
</tr>
<tr>
<td>Wind Mach Number</td>
<td>$M_w$</td>
<td>4.6</td>
</tr>
<tr>
<td>Average Cloud Temperature (K)</td>
<td>$T_c$</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>Cloud Velocity (km s$^{-1}$)</td>
<td>$v_c$</td>
<td>0</td>
</tr>
<tr>
<td>Cloud Radius (pc)</td>
<td>$r_c$</td>
<td>5</td>
</tr>
<tr>
<td>Fractal Cloud Volume (pc$^3$)</td>
<td>$V_c_{frc}$</td>
<td>1491</td>
</tr>
<tr>
<td>Spherical Cloud Volume (pc$^3$)</td>
<td>$V_c_{sph}$</td>
<td>523</td>
</tr>
</tbody>
</table>

(b) As the bubble breaks out of the disk, it begins sweeping up the surrounding halo gas entering the “snow-plow” phase of its evolution. The structure of the wind in the phase is characterised by 5 different zones: (i) the injection zone, (ii) a supersonic free wind, (iii) a region of hot, shocked turbulent gas, (iv) a cooler “shell” of swept-up halo gas, and (v) the undisturbed ambient gas.

(c) Clouds of disk gas inside and surrounding the central injection zone are broken-up by the freely expanding wind; fragments of disk gas are accelerated into the outflow by the ram-pressure of the wind.

Since it is the interaction of the clouds with the freely expanding wind that results in their fragmentation, we select the temperature, density and velocity of our supersonic wind to be that of the inner free-wind region, namely $T_w = 5 \times 10^6$ K, $n_w = 0.1$ cm$^{-3}$, and $v_w = 1200$ km s$^{-1}$ respectively.

Our simulations make use of two cloud geometries: a fractal shaped and a spherical shaped cloud. The fractal cloud was chosen in order to allow us to compare the break-up of the clouds in this study to the results of our global model in Chapter 5 and has the same form as the clouds in the inhomogeneous disk used in the global study. The use of the fractal cloud also allows us to investigate the effects of inhomogeneities in the clouds’s density distribution on its evolution. A spherical cloud was also modeled in order to allow us to better understand the importance of the assumed cloud geometry. To create the fractal cloud we first created a $1024 \times 1024 \times 1024$ sized fractal cube using the method described in Sutherland & Bicknell (2007) and Chapter 5. A single cloud was isolated and extracted from this cube using a blob-coloring technique where each cell is examined, and any discontinuous group of non-
The Interaction of a Supersonic Wind with a Radiative Cloud

Fig. 6.1: Volume renderings of the projected density showing the initial distribution of the fractal (left) and spherical (right) clouds.

zero cells given a unique label. An appropriate cloud was then selected and placed at cell number (256,256,256) of a 512 × 512 × 1536 sized grid, i.e. the origin of the simulation. The smaller resolution grids used in our fractal simulations were created by downsizing this larger grid (see Table 6.2). These arrays represent the density of the cloud.

The initial grid was setup by first setting the density \( n^w \) and pressure \( P_w = n_w k T_w / \mu m_p \) to be that of the hot wind. The fractal cloud was then created by adding the density array representing the cloud to the density of the halo gas. To create the spherical cloud, a high density spherical region of radius \( r_c = 5 \text{ pc} \) was centered on the origin of the computational grid. The radial profile of the density of the spherical cloud is described by an exponential with a scaling radius of 3, in order to mimic the tapered density distribution in the fractal cloud’s core. The boundary condition on the inner z axis was set to have a fixed inflow with the same properties as that of the hot wind (e.g. \( T_w = 5 \times 10^6 \text{ K} \), \( n_w = 0.1 \text{ cm}^{-3} \), and \( v_w = 1200 \text{ km s}^{-1} \)). All other boundaries were set to be inflowing/outflowing.

Figure 6.1 shows the initial density distribution of both the fractal and spherical clouds. The average number density of the fractal cloud is set to be \( n_c = 63 \text{ cm}^{-3} \) and has a total mass of \( M_c = 1387 \text{ M}_\odot \), occupying a volume of \( V_{c,\text{frc}} = 1491 \text{ pc}^3 \). The spherical cloud is setup to occupy a similar volume to the dense core of the fractal cloud, having a radius of \( r_c = 5 \text{ pc} \) and occupying a volume of \( V_{c,\text{sph}} = 523 \text{ pc}^3 \). The average density of the spherical cloud is \( n_c = 91 \text{ cm}^{-3} \) and has a total mass of \( M_c = 523 \text{ M}_\odot \). The lower average density of the fractal cloud is due to the large volume of less dense \( (n_c = 30 \text{ cm}^{-3}) \) gas that surrounds the cloud core (Fig. 6.1; left panel). In order to understand the effect of the cloud’s assumed initial density on its evolution, a simulation in which the density of
the fractal cloud was doubled \( n_c = 126 \text{ cm}^{-3} \) was also performed. In all simulations, the temperature and velocity of each cloud was set to be \( T_c = 5 \times 10^3 \text{ K} \) and \( v_c = 0 \text{ km s}^{-1} \) respectively.

While these simulations were designed to be applicable to starburst-driven winds and therefore have densities and temperatures typically found in a such an environment, they are also applicable to other astronomical phenomena that involve the interaction of a supersonic wind with a cloud of gas (e.g. supernova remnants). When cooling is included, the PPMLR code has a one parameter scaling, which is discussed in Sutherland & Bicknell (2007). In general, the density scale of the simulations is inversely proportional to the spatial scale, so that within reason, these simulations can be adapted to problems on both larger and small scales.

6.2.3 The Simulations

The interaction of a supersonic wind with a cloud of dense gas is a problem of some complexity. Whilst there are many factors that could affect a clouds evolution and survival, such as thermal conduction (Marcolini et al., 2005; Orlando et al., 2005), magnetic fields (Fragile et al., 2005) and photoevaporation (Tenorio-Tagle et al., 2006), here we focus on the importance of radiative cooling and the effect on the clouds initial structure. We have also performed a comprehensive resolution study in order to ascertain the degree as to which the assumed resolution effected our global simulations in Chapter 5.

We adopt the following naming convention for our simulations: An \( r \) or an \( a \) indicates whether the simulation includes radiative cooling or is adiabatic, while an \( f \) or an \( s \) indicates if the geometry of the cloud is fractal or spherical respectively. The numerical value indicates the number of cells in the x-plane of the computational grid. For example, the simulation \( rf384 \) includes radiative cooling, incorporates a fractal cloud and utilises a computational grid of size \( 384 \times 384 \times 1152 \) cells. An exception to the naming convention is \( rfd384 \), which is identical to \( rf384 \), but whose cloud is twice as dense.

In total, eleven simulations were performed, with the purpose of each falling within the four different categories outlined below.

1. **Resolution Study** - Models \( rf064, rf096, rf128, rf192, rf256, rf384, \) and \( rf512 \) form our resolution study. These seven simulations all include radiative cooling and utilise a fractal cloud. The resolution of each simulation is given in Table 6.2 and ranges from 0.79 to 0.10 pc per cell width.
Table 6.2. Simulation Parameters

<table>
<thead>
<tr>
<th>Model</th>
<th>Grid Size</th>
<th>Resolution (pc)</th>
<th>$n_c^a$ (cm$^{-3}$)</th>
<th>$M_c^b$ (M$\odot$)</th>
<th>Cooling?</th>
<th>Shape$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>rf064</td>
<td>64 $\times$ 64 $\times$ 192</td>
<td>0.78</td>
<td>63</td>
<td>1387</td>
<td>yes</td>
<td>F</td>
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<tr>
<td>rf096</td>
<td>96 $\times$ 96 $\times$ 288</td>
<td>0.52</td>
<td>63</td>
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<td>F</td>
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<tr>
<td>rf128</td>
<td>128 $\times$ 128 $\times$ 384</td>
<td>0.39</td>
<td>63</td>
<td>1387</td>
<td>yes</td>
<td>F</td>
</tr>
<tr>
<td>rf192</td>
<td>192 $\times$ 192 $\times$ 576</td>
<td>0.26</td>
<td>63</td>
<td>1387</td>
<td>yes</td>
<td>F</td>
</tr>
<tr>
<td>rf256</td>
<td>256 $\times$ 256 $\times$ 768</td>
<td>0.20</td>
<td>63</td>
<td>1387</td>
<td>yes</td>
<td>F</td>
</tr>
<tr>
<td>rf384</td>
<td>384 $\times$ 384 $\times$ 1152</td>
<td>0.13</td>
<td>63</td>
<td>1387</td>
<td>yes</td>
<td>F</td>
</tr>
<tr>
<td>rf512</td>
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<td>1387</td>
<td>yes</td>
<td>F</td>
</tr>
<tr>
<td>af384</td>
<td>384 $\times$ 384 $\times$ 1152</td>
<td>0.13</td>
<td>63</td>
<td>1387</td>
<td>no</td>
<td>F</td>
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<tr>
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<td>384 $\times$ 384 $\times$ 1152</td>
<td>0.13</td>
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<td>703</td>
<td>yes</td>
<td>S</td>
</tr>
<tr>
<td>as384</td>
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<td>91</td>
<td>703</td>
<td>no</td>
<td>S</td>
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<tr>
<td>rfd384</td>
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<td>0.13</td>
<td>126</td>
<td>2770</td>
<td>yes</td>
<td>F</td>
</tr>
</tbody>
</table>

$^a$Average cloud density

$^b$Cloud mass

$^c$Cloud Shape: F = fractal, S = spherical
2. **Cloud Structure** - Model rs384 has a resolution of 0.13 pc per cell width, includes radiative cooling and utilises a spherical cloud. By comparison to rf384, this model is designed to investigate the effect of the shape of the cloud on its break-up and survival.

3. **Radiative Cooling** - Models af384 and as384 have the same properties as rf384 and rs384 respectively, but are adiabatic in nature. Both models are designed to help understand the importance of radiative cooling on the evolution and survival of a cloud.

4. **Cloud Density** - Model rfd384 is identical to rf384, but has a larger cloud density and mass of \( n_c = 126 \text{ cm}^{-3} \) and \( M_c = 2770 \, M_\odot \) respectively. This model is designed to investigate the effect of the clouds initial density on its evolution.

A summary of the parameters used in each simulation is given in Table 6.2.

For each simulation we record the density, temperature, pressure, velocity, emissivity, and a cloud gas tracer in each cell at intervals of 0.01 Myr. With the exception of rf512, each simulation is followed until the time at which the cloud flows off computational grid. In the case of rf512, a computational error occurred while the simulation was in progress. Unfortunately this simulation is too computationally expensive to re-run, and we are therefore only able to follow the evolution of rf512 to a time \( t = 0.7 \) Myr. As such, our resolution study only considers the first 0.7 Myr of the evolution.

### 6.3 Evolution

#### 6.3.1 Description of the Wind/Cloud Interaction

**Spherical Cloud**

We start with the simple case of the interaction of a spherical radiative cloud (rs384) with a supersonic wind, before describing the evolution of the fractal cloud. In order to illustrate the hydrodynamics of the wind/cloud interaction, throughout this section we will use slices of the density, temperature, pressure and velocity through the central \( y=0 \) plane. Figure 6.2 shows the evolution of the spherical cloud a 6 different epochs from 0.1 to 1.1 Myr at 0.2 million year intervals. Each panel represents the logarithm of the number density \( (\text{cm}^{-3}) \). The top panels of Figure 6.3 show the logarithm of the temperature (K), the middle panels show the logarithm of the pressure \( (\text{cm s}^{-2}) \), and the bottom
Fig. 6.2: Logarithm of the density through the y=0 plane in model rs384 showing the evolution of a radiative spherical cloud.

Fig. 6.3: Log-temperature (top), log-pressure (middle), and velocity (bottom) at 0.35 (right) and 0.75 (left) epochs through the y=0 plane in model rs384.
panels show the magnitude of the velocity (km s$^{-1}$). The evolution at two different epochs is given: 0.35 Myr (left panels) and 0.75 Myr (right panels).

The spherical cloud is initially at rest and is immersed in a hot ($T = 10^6$ K), supersonic ($V = 1200$ km s$^{-1}$) wind. A bow shock is immediately formed upstream of the cloud. At 0.10 Myr (Fig. 6.2; upper left panel), the "front" of the cloud has been exposed to the high pressure of the shock, while gas is ablated from the "back" of the cloud a result of the Kelvin-Helmholtz instability and the strong rarefaction that is formed. A high density shock ($n = 1000$ cm$^{-3}$) begins to propagate through the cloud, reflecting of the back wall at approximately 0.30 Myr (Fig. 6.2; middle left panel). The Kelvin-Helmholtz instability continues to work, stripping material from the edge of the cloud. This material is funneled to approximately 5 pc behind the cloud where it combines and condenses forming a tail of dense ($n \sim 10$ cm$^{-3}$), cool ($T \sim 10^4$ K) cloudlets, which are entrained into the hot turbulent flow downstream from the main cloud (Fig. 6.3; upper left panel).

As the cloud evolves (Figs. 6.2 and 6.3; right panels), the tail of cool gas continues to grow, becoming thicker as the cloud elongates. The cloud material appears as a filament of cool, low velocity ($v < 400$ km s$^{-1}$) gas, immersed inside a region of hot ($T > 10^7$ K), turbulent gas with velocity $v \sim 400 - 1000$ km s$^{-1}$. Small cloudlets continue to be broken off the main cloud as the Kelvin-Helmholtz instability acts to shed its outer later. However, at 0.75 Myr only 12% of the mass of material that remains on the computational grid is found mixed into the hot wind. The bulk of the mass is still found in the cloud’s elongated core and tail, and despite the driving of radiative shocks into the cloud(s) there is little increase in the temperature of the cloud material as it radiates heat, remaining cool and cohesive as it leaves the computational grid.

**Fractal Cloud**

Figure 6.4 shows the evolution of the radiative fractal cloud in model rf384 from 0.1 to 1.1 Myr through density slices at intervals of 0.2 Myr. Figure 6.5 is identical to Figure 6.4, but shows the evolution of a cloud (rfd384) with twice the density and mass than rf384. As with the radiative spherical cloud, a bow shock immediately forms upstream of the cloud. However, a significant effect of the inhomogeneous structure of the cloud is the formation of a shock off each ridge on the cloud’s surface that is exposed to the wind. This has the effect of creating a "web" of interacting shocks.

By 0.3 Myr (Fig. 6.4; middle left panel), the density at the front front of the
Fig. 6.4: Logarithm of the density through the $y=0$ plane in model rf384 showing evolution of a radiative fractal cloud.

Fig. 6.5: Logarithm of the density through the $y=0$ plane in model rfd384 showing the effect of the clouds initial density on the evolution of a radiative fractal cloud.
cloud has jumped to $n \sim 1000 \text{ cm}^{-3}$, but fallen to approximately $n = 10 \text{ cm}^{-3}$ at the rear of the cloud. Despite the high pressure exerted on the cloud, very little heating occurs, with the cloud maintaining temperatures of $T \sim 10^3 - 10^4 \text{ K}$ (Fig. 6.6; left upper two panels). As the cloud evolves, small cloudlets are broken off the main cloud by the Kelvin-Helmholtz instability. These cloudlets form a filamentary structure downstream of the main cloud and have velocities in the range of $0 - 400 \text{ km s}^{-1}$, somewhat slower than the velocity of the surrounding stream ($v > 800 \text{ km s}^{-1}$) (Fig. 6.6; bottom panels).

The cloud is exposed to the high temperature and velocity of the wind at all points along the front surface of the cloud. The cloud breaks up fastest in regions where the density is lowest and the radius of the cloud is at its smallest. The cloud is continually eroded by the Kelvin-Helmholtz instability, the fragments of which are immersed in a low pressure, turbulent gas. At 0.75 Myr, the percentage of the mass of cloud material remaining on the computational grid that has mixed into the hot wind is $\sim 25\%$. The bulk of the original cloud mass is found in the remaining core remnant and the stream of small, dense $\sim 1 \text{ pc}$ cloudlets. If these cloudlets are exposed to the wind they produce their own high pressure bow shock upstream of their position. However, the majority of the cloudlets are sheltered from the wind by other fragments broken off from the main cloud. These cloudlets survive to leave the computational grid.

The higher density of the cloud in model rfd384 results in the cloud retaining structural integrity far longer than the lower density cloud in rf384. While
As observed by Xu & Stone (1995), the initial shape of the cloud has an effect on its subsequent evolution, with our fractal cloud fragmenting faster than the spherical cloud. While this is due in part to the lower average density of the fractal cloud, even the high density fractal cloud, whose average density and total mass is greater than that of the spherical cloud (see Table 6.2), has a greater degree of fragmentation and is less cohesive when it leaves the computational grid. This is a result of the inhomogeneous nature of the fractal cloud’s initial density distribution and the larger cross-section it presents to the incident wind (Fig. 6.1; left panel). The cloud first fragments along regions where the wind finds paths of least resistance, i.e. regions of low density. As a result the fractal cloud breaks-up into multiple core fragments. As the wind finds no regions of least resistance in the spherical cloud, it is able to retain a single cohesive structure for a longer period of time. Thus, not only is the initial geometry of the cloud important in determining its evolution, the distribution of the cloud’s
6.3 Evolution

Fig. 6.8: Log-temperature (top), log-pressure (middle), and velocity (bottom) at 0.35 (right) and 0.75 (left) epochs through the y=0 plane in model af384.

density determines how quickly the cloud begins to fragment. More homogeneous density distributions would result in less initial fragmentation.

6.3.2 Effect of Radiative Cooling

Adiabatic Case

In order to understand the degree as to which the inclusion of radiative cooling affects the survival of a cloud, we performed 2 simulations in which cooling was neglected: as384 and af384 for the spherical and fractal case respectively. Figure 6.7 shows the density of the adiabatic clouds in as384 (left) and af384 (right) at 0.3, 0.6, 0.9 Myr epochs. It can be immediately seen that in the absence of radiative cooling there is a far greater degree of mixing of cloud material with the surrounding stream, with 40% and 59% of the fractal and spherical clouds' masses respectively on the computational grid found mixed into the hot wind at 0.75 Myr.

The destruction of the adiabatic fractal cloud occurs faster and is more complete than the adiabatic spherical cloud. At 0.9 Myr the cloud has been almost completely destroyed (Fig. 6.7; bottom right panel), with the cloud material mixed into the hot gas. The initial interaction with the wind is the same as in the radiative case, with a bow shock forming upstream of the cloud. However, the cloud gas quickly begins to heat to temperatures of the order of $T \sim 10^6$ K
Fig. 6.9: Log-temperature (top), log-pressure (middle), and velocity (bottom) at 0.35 (right) and 0.75 (left) epochs through the y=0 plane in model as384.

(Fig. 6.8; upper left panel) and the cloud expands. Again the cloud breaks up first in regions where the density is low and the cloud radius is at its smallest. The high pressure exerted on the cloud (Fig. 6.8; middle left panel) and the Kelvin-Helmholtz instability act to strip material from the cloud. While this material is able to survive in the radiative model, here the cloudlets broken off the main cloud are quickly heated and destroyed. The bulk velocity of the gas downstream of the main cloud is lower than that found in the radiative case (Fig. 6.8; lower panels).

In the case of the adiabatic spherical cloud, the shedding of the cloud’s outer layer by the Kelvin-Helmholtz instability, also seen in the radiative model, is greatly enhanced. By 0.9 Myr (Fig. 6.7; bottom left panel), only the cloud core remains and is subsequently destroyed by the Kelvin-Helmholtz instability as the simulation progresses. As with the fractal cloud, the bulk velocity of the gas downstream of the main cloud is lower than that of the radiative spherical cloud at the same time (Fig. 6.9; lower right panel). The evolution of a spherical adiabatic cloud is discussed in more detail below.

Cloud Survival

One of the significant effects of the inclusion of radiative cooling is the longer life time of the impacted cloud. While this effect has been observed in the past by other authors (e.g. Mellema et al., 2002; Melioli et al., 2005), our
Fig. 6.10: Logarithm of the density through the y=0 plane in models as384 (left) and rs384 (right) showing the initial evolution of a spherical cloud over the first 0.35 million years.

study is of higher resolution and does not assume any symmetry, making it is a useful exercise to directly compare the simple case of the evolution of the spherical cloud in both our adiabatic (as384) and radiative (rs384) models in order to determine the mechanism behind the radiative clouds survival. The initial interaction of the wind and cloud is shown via density slices in Figure 6.10 at 0.05, 0.20 and 0.35 Myr epochs in both adiabatic (left) and radiative (right) models. It can be clearly seen that while the evolution begins almost identically with a bow shock forming upstream of the cloud, in the adiabatic case cloud material immediately starts being ablated from the back of the cloud.

As in the radiative model, a shock propagates through the adiabatic cloud. However, the initial density increase observed in the cloud is not as extreme (e.g. $n < 1000 \text{ cm}^{-3}$). The cloud material is heated to temperatures of the order of $T > 10^5 \text{ K}$ and the cloud expands. The shock travels though the cloud, reflecting off the back surface at approximately 0.27 Myr, somewhat faster than in the radiative cloud. The adiabatic cloud expands transversely as it is accelerated downstream. However, this transverse expansion is suppressed in the radiative cloud as a result of the lower degree of heating of the cloud gas (Fig. 6.3; upper panels). In both cases, the Kelvin-Helmholtz instability acts to strip material from the edges of the cloud forming a tail of material downstream of the cloud position (Fig. 6.10; middle and lower panels). In the adiabatic model, this tail is geometrically thick with density and temperature $n \sim 1 \text{ cm}^{-3}$ and $T \sim 10^6 \text{ K}$ respectively. In contrast, the tail formed in the radiative model is
The Interaction of a Supersonic Wind with a Radiative Cloud

Fig. 6.11: Left: mass flux through a surface at z=0.75pc for a resolution on 0.78 pc/cell (navy), 0.52 pc/cell (blue), 0.39 pc/cell (cyan), 0.26 pc/cell (green), 0.20 pc/cell (gold), 0.13 pc/cell (orange), and 0.10 pc/cell (red). Right: Total mass flux integrated over the first 0.7 Myr as a function of the numerical resolution.

geometrically thin with density $n \sim 10$ cm$^{-3}$ and temperature $T \sim 10^4$ K.

In the adiabatic model, the internal cloud shock reflects again off the front the cloud at approximately 0.35 Myr. At this time, the transverse expansion of the cloud persists and the Kelvin-Helmholtz instability continues to strip material from the clouds exterior into the downstream tail of gas. (Fig. 6.10; lower left panel). The transverse expansion (Fig. 6.9; middle panels) results in a higher rate of acceleration in the adiabatic model. As a consequence, the cloud has a lower relative Mach number relative to the stream (Fig. 6.9; lower left panel) than the radiative cloud (Fig. 6.3; lower left panel). The growth rate of the Kelvin-Helmholtz instability is lower for higher Mach numbers and its effect is strongly diminished for the radiative cloud. The adiabatic cloud is more easily disrupted and destroyed. This can be dramatically seen in the middle left panel of Figure 6.7 where the Kelvin-Helmholtz instability has stripped the entire outer layer of the adiabatic spherical cloud.

Since a radiative cloud is broken-up via the Kelvin-Helmholtz instability into a filamentary structure of small $\sim 1$ pc sized clouds, the survival of these small clouds is of interest. We now compare the cloud crushing time ($t_{\text{crush}}$) and the Kelvin-Helmholtz timescale ($t_{\text{KH}}$) to the cooling time ($t_{\text{cool}}$) of a cloud with radius $R_c = 1$ pc, density $\rho_c = 10$ cm$^{-3}$, temperature $T_c = 10^4$ K, and velocity $v_c = 200$ km s$^{-1}$. The cloud crushing time of such a cloud is $t_{\text{crush}} \approx R_c/v_{\text{sh}} \approx (\rho_c/\rho_w) R_c/v_w = 3 \times 10^{12}$ s, where the density and velocity of the wind is $\rho_w = 0.1$ cm$^{-3}$ and $v_w = 1000$ km s$^{-1}$ respectively. The Kelvin-Helmholtz timescale is $t_{\text{KH}} = R_c(\rho_c + \rho_w)/(v_c - v_w)(\rho_c\rho_w) = 3 \times 10^{11}$ s. The cooling time for a 1 pc cloud in our simulations is of the order of $10^{10}$ seconds, somewhat shorter
than the cloud crushing time and the Kelvin-Helmholtz timescale, suggesting that the cloudlets may remain sufficiently stable to ablation and survive to later times. In addition, we note that the self-gravity of the clouds may cause them to collapse, becoming more difficult to disrupt (Mellema et al., 2002).

6.4 Resolution Study

6.4.1 Mass Flux

In order to test the dependence of our results on the numerical resolution of the code, we have performed seven simulations of the radiative fractal cloud interacting with a supersonic wind at increasing resolutions from 0.78 - 0.10 pc per cell width (see Table 6.2). We calculated the flux of mass through a surface at \( z = 75 \) pc over the first 0.7 million years of each simulation in our resolution study. Figure 6.11 shows this mass flux for each simulation as a function of time (left panel), as well as the total mass flux integrated over the first 0.7 Myr of the simulation as a function of resolution (right panel). The mass flux over the first 0.4 Myr of the evolution is similar at all resolutions. This is a result of the well resolved hot stream of gas passing through the flux surface. After this point, the cloud material begins to pass though the surface and the mass flux starts to vary with resolution.

The initial drop in the mass flux seen in the left hand panel of Figure 6.11 is due to the rarefaction that passes though the flux surface (see Fig. 6.2; top left panel). From approximately 0.2 to 0.4 Myr, the density of the stream increases as mass is ablated from the rear of the cloud resulting in a similar flux at all resolutions. During this time, the mass flux gradually increases as the \( n = 0.1 \text{ cm}^{-3} \) mass loaded stream of gas passes through the flux surface. At approximately 0.4 Myr, the mass flux begins to vary rapidly, dramatically increasing in each simulation. The large variation in the mass flux is due to the turbulent nature of the gas passing though the flux surface and the dense cloudlets immersed within this gas. The cloudlets pass through the surface at different times resulting in fluctuations in the mass flux.

There is a general trend of increasing mass flux with the resolution of the simulation. This trend can be explained by the increase in fragmentation of the cloud with increasing numerical resolution. Figure 6.12 shows volume renderings of the projected density at 0.7 Myr in models rf064, rf128, rf256 and rf512, which have resolutions of 0.78, 0.39, 0.20, and 0.10 pc per cell width respectively. The increase in the fragmentation of the cloud with resolution can
clearly be seen, and will be discussed in more detail in Section 6.4.2. At the highest resolution attempted in this study (0.1 pc), the filaments resemble a “foam” of cloudlets, while at low resolution the cloud has been broken-up into only a few large fragments. As a consequence, the cross-section of dense material that passes through the flux surface at any given time after 0.4 Myr is larger in the higher resolution simulations.

The total integrated mass flux passing through the surface at $z = 0.75$ pc over the first 0.7 Myr also increases with numerical resolution (Fig. 6.11; right panel). Again this is caused by the larger degree of fragmentation at high resolution, resulting in more ablation of cloud material from the back of the cloud. Between our highest and lowest resolution simulations the difference in mass flux is approximately 10%. This discrepancy is likely to increase at higher resolutions, although it is possible that convergence may occur at extremely high resolution simulations ($> 0.1$ pc) that utilise an adaptive mesh. For the 2 pc per cell width resolution of our global simulations in Chapter 5, this error is
increased to approximately 20%. We will discuss the impact of the numerical resolution on the results of Chapter 5 in Section 6.5.

6.4.2 Cloud Fragmentation

The most significant effect of increasing the numerical resolution of the simulation is the increase in fragmentation of the cloud. The increase in cloud fragmentation can clearly be seen in Figure 6.12, with the cloud broken into only a few large fragments in the lowest resolution simulations, but hundreds of fragments at higher resolution. Nevertheless, filamentary structure, where the concentration of cloudlets is higher, can still be made out at high resolution. These "filaments" are located in similar positions to the filaments in the low resolution simulations.

We are able to calculate the properties of each cloudlet by using an algorithm which allows us to pick out and select fragments. Note that we impose a minimum mass of $M_c = 10^{-3} \, M_\odot$ for a fragment to be selected. Figure 6.13 shows the number of cloudlets produced as a function of numerical resolution. The number of cloudlets increases exponentially with increasing resolution. Even with larger computational resources and an adaptive mesh, this
The trend is likely to continue ad infinitum. The dependence of the degree of fragmentation on the numerical resolution has been observed by other authors in both two-dimensional (Klein et al., 1994) and three-dimensional (Stone & Norman, 1992) simulations of a spherical cloud. This effect can be explained by the growth rate of Kelvin-Helmholtz instability, which is faster at smaller wavelengths. As the resolution is increased, this instability is increasingly resolved and more fragmentation of the cloud is observed. This is illustrated in Figure 6.14, where the Kelvin-Helmholtz instability can clearly be seen to increasingly fragment the cloud at higher numerical resolution.

Figure 6.15 gives mass (left) and velocity (right) histograms of the cloudlets at 0.7 Myr for the 4 resolutions shown in Figure 6.12. The massive fragments \( M \gtrsim 10^2 - 10^3 \, M_\odot \) present at all resolutions are the remnants of the cloud core. Since the number of cloudlets increases with resolution, the highest resolution simulations are comprised of numerous low mass cloudlets. In general, there is a trend towards increasing smaller mass fragments at all resolutions. On the other hand, the velocity of the cloudlets does not vary significantly with resolution. Despite the large number of lower mass fragments present in the high resolution simulations, they still fall within the velocity range of \( v_c = 150 - 400 \, \text{km s}^{-1} \). The bulk of the cloudlets at all resolutions have a velocity in the range of \( v_c = 180 - 220 \, \text{km s}^{-1} \). This is likely to increase as the evolution progresses and the cloudlets are further accelerated by the wind.
Unfortunately, we are unable to fully resolve the interaction of a radiative cloud with a supersonic wind at this time. A significant increase in numerical resolution and/or the use of an adaptive mesh would be required in order for convergence to possibly occur. Nevertheless, there is a clear trend in the wind/cloud interaction at all resolutions considered in this study, allowing us to draw some physical conclusions. For example, the soft X-ray luminosity is sufficiently resolved and is almost constant with numerical resolution (see Section 6.5.2). The effect of radiation in keeping the cloud cool, suppressing the transverse expansion and minimizing the effect of the Kelvin-Helmholtz instability, is also not effected by the resolution of the simulation. In all cases, the cloud is not immediately destroyed and mixed into the hot wind as seen in adiabatic models, but is instead broken-up into numerous small cloudlets. The major effect of increasing the resolution is the increased fragmentation of the cloud. However, we still see the same qualitative structure at high resolution, with the cloud breaking-up to form a filamentary structure that becomes finer and finer as more detail is resolved.

6.5 Emission in Starburst-Driven Winds

6.5.1 Filamentary Hα Emission

At optical wavelengths (such as Hα), starburst-driven winds appear as spectacular filamentary systems extending several kpc along the minor axis of the host galaxy, e.g. M82 (Shopbell & Bland-Hawthorn, 1998), NGC 3079 (Veilleux et al., 1994), NGC 1569 (Westmoquette et al., 2008). While it has long been pro-
posed that this filamentary material was expelled from the central region of the galaxy (Lynds & Sandage, 1963; Bland & Tully, 1988), until now the mechanism behind the formation of the filaments has not been completely understood. In Chapter 5, we proposed that the filaments were formed via clouds of disk gas that are broken-up and accelerated into the outflow by the ram-pressure of the wind. In order for this mechanism to be viable, the cloud fragments need to survive and remain sufficiently cool to emit at H\(\alpha\) temperatures. The simulations presented in this chapter allow us to address this important issue.

As in Chapter 5, we define the H\(\alpha\) emitting gas to be cloud material with temperatures in the range of \(T = 5 \times 10^3 - 3 \times 10^4\) K. We note that as photoionization is not included in our model, the H\(\alpha\) emission discussed in this chapter arises solely from shock ionization. However, photoionization is known to play a role in the ionization of the filaments in many winds. For example, the filaments in M82's wind are known to be photoionized at low distances above and below the galactic plane, with shock ionization becoming dominant at large distances. An investigation into the effects of photoionization on the cloudlets is warranted, but is beyond the scope of this study. Figure 6.16 shows a three-dimensional volume rendering of the density of the H\(\alpha\) emitting gas at 0.5 Myr in model rf384 (Online: Movie of evolution of the H\(\alpha\) emitting gas in rf384 over the first 1.37 Myr). It can be immediately seen in Figure 6.16 that the H\(\alpha\) emitting material corresponds to the dense cloud material. Thus, the survival mechanism for a cloud proposed in Section 6.3.2 can be invoked to explain the filaments observed in starburst-driven winds.

As discussed in Section 6.3, the cloud is broken-up via the Kelvin-Helmholtz instability, with the fragments subsequently entrained into the outflow forming a filamentary structure. Figure 6.17 (left panel) gives the emission weighted histogram of the z-velocity along the filament at 0.7 Myr in model rf384. The majority of the H\(\alpha\) emission has velocities in the range of \(v \sim 0 - 30\) km s\(^{-1}\),
with the velocity increasing with distance along the $z$-axis. This is consistent with the Hα gas reaching higher velocities at larger distances above the galaxy plane, which was observed in the global simulations in Chapter 5. Note that this result represents only the velocity dispersion at the base of a single filament early in its evolution, with the velocity likely to increase as the cloudlets, which form the filament, are further accelerated in the direction of the flow.

As in our global simulations, we again find that it is the ram-pressure of the wind that accelerates the clouds. The main difference between the filaments formed in Chapter 5 and the filaments found here is the number of cloudlets that comprise the filament; a direct result of the higher numerical resolution of the simulations in this work. If we were able to increase the resolution of the global simulations, we would find similar fine structure in the filaments that are formed. Figure 6.18 (left) shows the mass flux of the Hα emitting gas through a surface at $z = 75$ pc at each resolution considered in our study. As expected, there is no Hα emitting gas passing through the surface until approximately 0.3 Myr, as the dense cloud material has yet to encounter the flux surface. As in Figure 6.11, the difference in the mass flux at each resolution is a result of the increasing fragmentation of the Hα emitting clouds at high resolution. The right hand panel of Figure 6.18 shows the total integrated mass flux, over the first 0.7 Myr, of the Hα emitting gas as a function of resolution. We see an increase in the total mass passing through the flux surface, again caused by the increase in fragmentation as the Kelvin-Helmholtz instability is further resolved. Even at the high resolution of these simulations the Hα mass flux is yet to converge.

In Section 6.3.2 we discussed how a cloud could survive the interaction with a hot supersonic wind. The ability of a cloud to radiate heat is crucial for the clouds survival, allowing it to remain stable to ablation and emit at Hα temper-
The Interaction of a Supersonic Wind with a Radiative Cloud

Fig. 6.18: Left: mass flux of the H$\alpha$ emitting gas through a surface at $z=0.75$ pc for a resolution on 0.78 pc/cell (navy), 0.52 pc/cell (blue), 0.39 pc/cell (cyan), 0.26 pc/cell (green), 0.20 pc/cell (gold), 0.13 pc/cell (orange), and 0.10 pc/cell (red). Right: total integrated mass flux for the H$\alpha$ emitting gas over 0.7 Myr as a function of the numerical resolution.

atures. Without this ability, the cloud quickly heats above $T = 10^6$ K, expands and becomes susceptible to the Kelvin-Helmholtz instability. While a radiative cloud is still disrupted, the small sized fragments that are broken off the main cloud have cooling times faster than the cloud crushing time and the Kelvin-Helmholtz growth rate, and thus, may possibly survive. In the adiabatic case, the fragments get heated and destroyed, with the cloud material quickly becoming mixed into the hot wind. If the fragments survive, they are drawn-out into strands and form a filament downstream of the original cloud position, reminiscent of the filaments seen in starburst-driven winds.

6.5.2 Soft X-Ray Emission

In Chapter 5 we proposed four mechanisms that could give rise to the soft X-ray emission that is observed to be spatially correlated to the H$\alpha$ emitting filaments. This correlation has been observed by Chandra in many starburst-driven winds (e.g Cecil et al., 2002; Strickland et al., 2004a,b). Here we summarise the proposed mechanisms:

(a) The mass-loaded wind. This is the largest contributor to the soft X-ray emission in the global simulations. As mass is ablated from the clouds it is mixed into the surrounding turbulent gas, creating a region of hot ($T \gtrsim 10^6$ K) rapidly cooling gas that emits strongly at soft X-ray energies.

(b) The intermediate temperature interface between the hot wind and cool fil-
Emission in Starburst-Driven Winds

Fig. 6.19: Soft X-ray emissivity \((10^{-25} \text{ erg s}^{-1} \text{ cm}^{-3})\) in the \(y=0\) plane of models rf128 (left) and rf512 (right) at 0.3 (top), 0.5 (middle), and 0.7 (bottom) Myr epochs.

...ments. Gas at the boundary between the hot and cool gas mixes to produce a thin region of intermediate density and temperature. Like the mass-loaded wind, this mixed gas is a strong emitter of soft X-rays.

(c) Bow shocks. Gas is heated to X-ray temperatures as a bow shock is formed upstream of dense clouds accelerated into the flow.

(d) Colliding bow shocks. When two bow shocks interact, the gas is further shock heated to X-ray temperatures.

The first two processes involve the mixing of hot and cold gas and could be the result of numerical diffusion in the simulations and therefore not physical. Our resolution study allows has to examine the effect of increasing resolution on the soft X-ray emission and determine the realism of the above possible emission processes.

As in Chapter 5, we infer the X-ray luminosity in the soft (0.5 - 2.0 keV) energy band using broadband cooling fractions obtained from the MAPPINGS IIIr code (Sutherland & Dopita, 1993). Figure 6.19 shows the soft X-ray emissivity in models rf128 (left) and rf512 (right) at 0.3, 0.5, and 0.7 Myr epochs. The strongest X-ray emitter in both models is the bow shock that immediately forms upstream of the cloud as it interacts with the wind. Regions where bow shocks are interacting result in the highest X-ray emissivities. Apart from a few marginally bright tails coming off some of the cloudlets, particularly in model rf128 (see Fig. 6.19; bottom left panels), we see no evidence that mass-loading
of the wind by ablation from the cloud is a significant contributor to the soft X-ray luminosity. We also see very little evidence that the intermediate temperature interface plays a significant role. There are a few bright regions upstream of cloudlets that have been exposed to the wind. However, it is likely that this enhanced emission is related to the X-ray emitting bow shocks that have formed around each cloudlet.

The main difference between the simulations shown in Figure 6.19 at high (right panel) and low (left panel) resolution is in the structure of the main bow shock and the emission from the cloudlets. While we observe some structure in the low resolution simulations, as the resolution is increased we see clear regions where colliding bow shocks lead to a significant increase in the X-ray emissivity. This is more evident at later times when the main cloud has fragmented and there are many X-ray emitting bow shocks upstream of the resulting cloudlets (Fig. 6.19; bottom right panels). It may be expected that the increase in fragmentation at higher resolutions would lead to an increase in the X-ray luminosity as more bow shocks are formed. However, the majority of the cloudlets formed are sheltered from the impacting wind by the main cloud and do not form a bow shock. Thus, they are not seen at soft X-ray energies and do not contribute to the X-ray luminosity (Fig. 6.19; right panels).
6.5.3 OVI Emission

The importance of radiative cooling in the formation and survival of the filaments was discussed in Section 6.3.2. For our proposal of the formation of a...
The Interaction of a Supersonic Wind with a Radiative Cloud filament, via the break-up and acceleration of cool disk gas into the wind, to be a viable mechanism, cooling must be present in the outflow. Observations of the OVI emission line could be used to detect this cooling in the filaments. Heckman et al. (2001) report the detection of OVI emission in the dwarf starburst galaxy NGC 1705, which they associate with cooling in the outflow from gas at temperatures of $T \gtrsim 3 \times 10^5$ K. They propose turbulent mixing layers (e.g. Slavin et al., 1993) as a possible origin for this emission.

In order to determine were the OVI emission may arise in our simulations, we have produced a “map” of the predicted OVI emission in models rf384, rs384, af384, and as384 at 0.7 Myr (Fig. 6.21). We assume that the OVI emission in our simulations falls within the temperature range of $T = 1 \times 10^5 - 4 \times 10^5$ K. When cooling is neglected (bottom two panels), OVI emission is only observed around the surviving cloud core. This emission is the result of the high degree of mixing of the hot and cold gas seen in the adiabatic simulations. In the radiative models (top two panels), OVI emission is observed throughout the flow and is closely aligned to the filamentary gas. This emission is caused by the mixing of hot and cold gas in the vicinity of each cool cloudlet that comprises the filament.

The distribution of the OVI emission is most significant in the radiative fractal model (rf384; top panel), where the structure of the filament can still be clearly seen. The emission weighted histogram of the z-velocity for this model at 0.7 Myr is shown in the right hand panel of Figure 6.17. The velocity dispersion of the OVI gas is similar to that of the Hα emitting filaments, falling in the range of $v \sim 0 - 40$ km s$^{-1}$. While our investigation of the OVI emission is only preliminary, further detection of OVI kinematics similar to those proposed in this work would lend support the premise of cooling in the filaments of starburst winds.

6.6 Summary

We have performed a series of three-dimensional simulations of the interaction of a supersonic wind with a radiative cloud. We consider two different cloud geometries (i.e. fractal and spherical), which enable us to investigate the impact of the initial shape and structure of the cloud on its subsequent evolution. This work was motivated by the simulations of the formation of a starburst-driven galactic wind in a inhomogeneous interstellar medium, reported in Chapter 5. The aim of this work is to investigate the possible survival mechanism of a cloud accelerated by a hot freely expanding wind. We also set
out to determine the effect of the numerical resolution of the evolution of the cloud and the implied soft X-ray emission associated with the interaction. The results of this study are as follows:

(i) Both the initial geometry and the density distribution of the cloud significantly affect its evolution. A cloud which has a more inhomogeneous distribution of density fragments more than a cloud with a more uniform structure (e.g. a sphere). The wind more rapidly breaks the cloud apart in regions where it encounters the least density.

(ii) A radiative cloud survives longer than an identical adiabatic cloud. This is a result of the lower degree of heating in the radiative cloud, which suppresses the transverse expansion seen in the adiabatic case. The radiative cloud experiences a lower degree of acceleration and has a higher relative mach number to the flow, diminishing the destructive effect of the Kelvin-Helmholtz instability.

(iii) The number of fragments formed by the break-up of the cloud increases with increasing numerical resolution. This is a direct result of further resolving the Kelvin-Helmholtz instability, which grows more quickly at shorter wavelengths. The number of fragments formed increases down to the resolution of the simulation and will not converge.

(iv) The calculated mass flux increases with numerical resolution. This is due to the turbulent nature of the stream and the increasing fragmentation of the cloud. High (< 0.1 pc/cell) resolution and an adaptive mesh would be required for convergence to possibly occur.

(v) A radiative cloud fragments into numerous cool, small dense cloudlets. These cloudlets are entrained into the turbulent flow, forming an overall filamentary structure, with regions where the concentration of cloudlets is higher. The velocity of the cloudlets at 0.7 Myr falls in the range of $v_c = 150 - 400\, \text{km s}^{-1}$ irrespective of resolution.

(vi) The filamentary structure that is formed and the range of velocities found are in good agreement with optical observations of starburst-driven winds. Thus, we confirm our conclusion from Chapter 5, that H$\alpha$ emitting filaments can be formed from clouds accelerated into a supersonic wind by the ram-pressure of the wind.

(vii) There is little variation in the estimated soft X-ray luminosity of the radiative fractal cloud at all numerical resolutions considered, indicating that the X-ray emission is well resolved.
(viii) Soft X-ray emission arises primarily from the main bow shock, produced in the initial interaction, and from bow shocks produced upstream of fragments that are directly exposed to the wind. Regions where these bow shock interact are strong X-ray emitters. We see little evidence that the mixing of hot and cold gas (e.g. mass-loading and the boundary between the cool cloud material and the hot wind), contribute significantly to the X-ray emission.

(ix) The OVI emission arises is the same vicinity as the Hα emission and has comparable emission weighted velocities, suggesting that the detection of OVI in an outflow may be indicative of cooling in the filaments.

The ability for a cloud to radiate heat is crucial for it to survive immersed inside a hot, turbulent, supersonic wind. While effects such as thermal conduction and magnetic fields will have an effect on the clouds survival, without radiative cooling the cloud is quickly destroyed by the Kelvin-Helmholtz instability, with the cloud's material completely mixed into the surrounding stream. Thus, for a model of the wind/cloud interaction to be realistic, radiative cooling certainly cannot be neglected.
7. CONCLUSIONS AND FUTURE DIRECTIONS

Starburst-driven winds are spectacular objects that extend for kiloparsecs along the minor axis of their host galaxy. At optical wavelengths they appear as striking filamentary systems that display various morphologies, such as the classic bipolar structure in the wind in M82 and the more bubble-like outflow in NGC 3079. At X-ray wavelengths, the emission is known to be spatially correlated with the optical emission, and is thought to have a physical relationship to the filamentary gas. In order to understand the nature of these objects and the physics that govern them, I have performed a series of high (2 pc/cell) resolution three-dimensional hydrodynamical simulations of a starburst-driven galactic wind. These simulations build upon the earlier work of Strickland & Stevens (2000), the key advancements being the extension to three-dimensions and inclusion of an inhomogeneous disk, allowing the study of the interaction of the supersonic wind with clouds of gas (Chapter 5). These global simulations were complimented by more detailed simulations, at extremely high (~0.1 pc/cell) resolution, of the interaction of a freely expanding supersonic wind with a single cloud (Chapter 6). Through detailed simulations of the wind/cloud interaction, I was able to test the dependence of the results on the assumed numerical resolution. I was also able to investigate the mechanism via which the disk gas in the global simulations is able to remain stable to ablation long enough to form a filament and remain sufficiently cool to emit at optical temperatures. The conclusions of this work are summarised in Sections 5.7 and 6.6, and are further discussed below.

7.1 Effect of the Inhomogeneous Interstellar Medium

The overall evolution of the starburst-driven winds presented in the global simulations in Chapter 5, is similar to that found in the earlier two-dimensional work, with the main difference to the earlier simulations caused by the interaction of the wind with the inhomogeneous disk. In this thesis, the wind begins as a series of small hot bubbles inside the starburst region. These bubbles merge to form a single large bubble that follows the path of least resistance out of the
disk, i.e. the hot tenuous gas between the dense clouds. A consequence of this is the absence of "blow-out", which is a notable characteristic of models with an homogeneous ISM. In a model where the wind must travel through a disk of cool dense homogeneous gas, it sweeps up this gas to form a dense shell surrounding the outflow. The wind will then blow-out of this shell and begin to expand freely after it has grown to a few scale heights in size. On the other hand, in an inhomogeneous model, by following the path of least resistance out of the disk, the bubble flows around the cool clouds and instead sweeps up the halo gas to form a "shell" of more tenuous hot gas. The overall shape of this outflow is dependent upon the initial distribution of the ISM in the host galaxy into which it flows.

Older models of starburst-driven winds suffer from two significant problems: (a) the inability to confine the base of the outflow and (b) lack of collimation of the outflow to the degree observed in many winds. The base of the outflow in the global simulations presented in Chapter 5 does not expand beyond a radius of 200 pc, but is likely to increase slowly as the wind evolves over a larger period of time. However, this result compares more favorably with the ~ 400 pc radius observed by Shopbell & Bland-Hawthorn (1998) in M82, than the kpc sized bases observed in older models. This feature is the result is the higher density of the disk material that was utilised in the global simulations in this thesis, where the average density and temperature of the disk was chosen to be in pressure equilibrium with the hot halo, with pressure $P/k = 10^{6} \text{ cm}^{-3} \text{ K}$. Unfortunately, the collimation of the outflow in these simulations is still far too large having an opening angle of ~ 160° for the hot gas and ~ 90° for the filamentary gas. This result is poor when compared to the collimation observed in M82 of ~ 30°. Clearly there must be some mechanism in place to produce this high degree of collimation, with the properties of the interstellar medium above the disk into which the outflow expands likely to play a role.

The outflow spends a significant fraction of its life time in the well studied snow-plow phase, where it sweeps up the surrounding halo gas as it expands in the ambient medium. The hydrodynamical processes seen in the outflow during this phase match up well to those first seen by Tomisaka & Ikeuchi (1988) in their early two-dimensional work on galactic winds, and by many authors in subsequent models. In this phase, the outflow is characterised by five zones: (i) a central injection region, (ii) a freely expanding wind, (iii) a region of hot, turbulent shocked gas, (iv) a swept-up shell of halo gas, and (v) the ambient halo gas. Zones (iii) and (iv) are separated by a reverse wind shock, whose shape is dependent on the initial distribution of the ISM. The main difference to the classic picture revealed by the inhomogeneous model is the presence of dense
clouds in the free wind region. These clouds are accelerated into the outflow by the ram-pressure of the wind. Hydrodynamical instabilities act to fragment the clouds, resulting in the formation of filaments of cool dense material. These filaments form a bipolar structure emanating from the starburst region, which is reminiscent of the outflow in M82. The morphology of the filaments is dependent on the initial distribution and position of the clouds from which they are formed. They also do not trace the true radial and vertical extent of the outflow. The hot wind gas extends to larger distances in both radial and vertical directions.

An optical emitting filament can form via the break-up of a single cloud of disk gas. My simulations of the single cloud interacting with a free-wind show that the Kelvin-Helmholtz instability acts to fragment the cloud, resulting in the formation of a string of small cloudlets that form a filamentary structure downstream of the surviving cloud core. The speed and degree of fragmentation is dependent on the internal structure of the cloud. Again, the inclusion of inhomogeneities in the cloud's structure affects the evolution of the wind/cloud interaction. A cloud that has a more inhomogeneous structure breaks up at a
significantly faster rate than a cloud which is more uniform, e.g. a spherical cloud. The fragmentation occurs more quickly in regions where the density and radius of the cloud are smallest, resulting in the break-up of the cloud into multiple core fragments that subsequently evolve in a similar manner to a spherical cloud interacting with the supersonic wind.

While previous simulations of starburst winds that develop inside a dense homogeneous disk have provided important insights into the overall evolution of the wind, they were unable to reproduce many of the observed morphological and observational features, e.g. the optical line-emitting filaments. While some features of a wind, such as the collimation of the outflow, are still unexplained, the inclusion of inhomogeneities within the ISM has provided a natural mechanism for the formation of the filaments and the spatially correlated X-ray emission. The interaction of the wind with dense disk clouds also results in asymmetries in the outflow, with inhomogeneities in the ISM of the halo of the galaxy (e.g. HI gas surrounding M82; see Fig. 7.1) the likely cause of large scale asymmetries observed in the filaments of starburst winds. In this thesis, I have shown that any future model of a starburst wind must take into account the multiphase nature of the interstellar medium in its host galaxy in order to gain an accurate picture of the evolution of the outflow.

7.2 Filamentary Hα Emission

The optical line-emitting filaments observed in starburst-driven winds are a spectacular feature of these objects. However, their origin has remained obscure. A significant result presented in this thesis is the formation of an extensive filamentary structure in the global simulations of a starburst-driven wind presented in Chapter 5. By considering the $T = 5 \times 10^3 - 3 \times 10^4$ K gas in the simulations, I was able to estimate where the Hα emission may arise in these simulations. The Hα emitting filaments form via the break-up of clouds inside and surrounding the starburst region, the fragments of which are then accelerated into the outflow by the ram-pressure of the wind. At the high resolution considered in the simulations of the wind/cloud interaction presented in Chapter 6, an Hα emitting filament is still formed in the same manner. The Kelvin-Helmholtz instability acts to break-up each cloud, with the fragments being drawn out by the wind to form a single string of dense cloudlets that together form the filament. While the number of fragments that are produced is dependent on the numerical resolution of the simulation, there is a clear pattern to the evolution of the interaction at all resolutions. A filament is still clearly discerned amongst the foam of cloudlets even at the highest resolution.
The filaments evolve to form a bipolar structure along the minor axis of the galaxy. The velocity of the filaments that form in the global simulations fall within the range of \( v = 100 - 800 \text{ km s}^{-1} \), which is in good agreement with estimates from observations of starburst winds. While many winds are known to be limb-brightened in the optical (e.g. M82, NGC 3079), the H\(\alpha\) emission found in the winds formed in this work are volume filled, with filaments distributed throughout the entire volume of the outflow. Volume filled winds are known to exist (e.g. the wind in the Circinus galaxy); a possible explanation for this being the original position of the clouds from which each individual filament is formed. As noted, the distribution of the filaments is dependent on the structure of the ISM in the host galaxy, so if the majority of the material in the starburst region was to reside in a torus, it is likely that the outflow would take on a limb-brightened appearance. The periodic nature of starbursts may also play a role, with an earlier burst of star formation and the resulting outflow having evacuated the gas from the central regions of the starburst.

When considering the H\(\alpha\) emitting filaments it is also important to consider the ionizing mechanism responsible for the emission. The simulations presented in this thesis do not take into account the ionizing radiation from the starburst, with the H\(\alpha\) emission arising entirely from shock ionization. However, from observations we know that photoionization is important in many winds, especially at low distances above the galactic plane. The formation of the H\(\alpha\) emitting filaments in this thesis that bear a striking resemblance to those seen in starburst winds is an important step forward in the modeling of these outflows. However, the inclusion of photoionization and a more sophisticated treatment of the H\(\alpha\) emission would provide more clues to the nature of these fascinating filaments.

7.3 Importance of Radiative Cooling

For clouds of disk gas inside and surrounding the starburst region to be a viable origin for the formation of the filaments, they must be able to survive being accelerated by the wind to large distances above the galactic plane and still remain sufficiently cool to emit at optical temperatures. Many early simulations of the wind/cloud interaction have suggested that a cloud would be destroyed by hydrodynamical instabilities within a few cloud crushing times. Therefore, the survival of the filamentary systems presented in Chapter 5 becomes an important question. As noted by previous authors (e.g. Mellema et al., 2002), the
Conclusions and Future Directions

Inclusion of radiative cooling in a numerical simulation of the interaction results in a marked increase in the stability of cloud. In Section 6.3.2, I discussed the role of radiative cooling in preventing the destruction of a cloud. This process is briefly summarised below:

(i) In an adiabatic simulation, a cloud expands as it is heated above $T > 10^5$ K. As it is accelerated downstream by the wind, the cloud continues to expand transversely, with the Kelvin-Helmholtz instability stripping material from the cloud which then forms a thick tail downstream of the surviving cloud core.

(ii) In a radiative simulation, cooling of the cloud material suppresses the transverse expansion. Material is still stripped from the cloud via the Kelvin-Helmholtz instability, but the resulting tail is thin and made up of small, dense cloudlets.

(iii) The transverse expansion of the cloud in an adiabatic simulation results in a higher rate of ram-pressure driven acceleration, and the adiabatic cloud consequently has a lower relative Mach number to the stream than a radiative cloud.

(iv) Since the growth rate of the Kelvin-Helmholtz instability is smaller for higher Mach numbers, its effect is diminished for a radiative cloud. An adiabatic cloud is more easily disrupted and destroyed.

As discussed, the filaments that form in this work are not a single long strand of dense material, but are made up of a string of numerous (perhaps hundreds) of small cloudlets. While my simulations of the wind/cloud interaction were unfortunately unable to follow the evolution of these small cloudlets to late times, due to the limited spatial range covered by the computational grid, a comparison of the cooling time of such a small cloud to the cloud-crushing time and the Kelvin-Helmholtz timescale indicates that these cloudlets may indeed remain sufficiently stable to ablation and survive to late times.

The ability of the dense optical emitting filamentary material to radiate heat is crucial for its survival. Without this ability, the clouds from which the filaments are formed would be heated to temperatures above $T = 10^5$ K, making them highly susceptible to the Kelvin-Helmholtz instability and readily destroyed. A possible indicator of the presence of radiative cooling in starburst-driven winds is OVI emission, which is thought to arise from gas that is cooling from temperatures above $T \sim 3 \times 10^5$ K. A map of the predicted OVI emission in my radiative model of a fractal cloud interacting with a supersonic wind is given in the top panel of Figure 6.21. In this case, the OVI emission is clearly
distributed throughout the stream and is strongly correlated to the position of
the filamentary \( \text{H} \alpha \) emission and has similar velocities. This suggests that Ovi
emission may in indeed be a good indicator of cooling in the filamentary gas.
Heckman et al. (2001) may have already observed this cooling, reporting the
detection of Ovi emission in the outflow in the dwarf starburst galaxy NGC
1705.

7.4 X-ray Emission

The extended X-ray emission observed in starburst-driven winds has been
the motivation behind many previous models, with its origin a subject of some
debate. With detailed observations by the \textit{Chandra} X-ray observatory, it is
now suspected that this emission is physically related to the filamentary op-
tical emission. The three-dimensional nature of the simulations presented in
this thesis, and the formation of an extensive filamentary system, renders this
work a good testing ground to determine the origin of the X-ray emission. To-
wards this goal, using broadband cooling fractions obtained by Ralph Suther-
land from the \textit{MAPPINGS} IIIr code, I have estimated the predicted X-ray emis-
sion in both soft (0.5 - 2.0 keV) and hard (2.0 - 10.0 keV) energy bands. This was
done for the global simulations presented in Section 5.5 and followed up in
Section 6.5.2 by a detailed examination of the effect of the assumed numerical
resolution on the soft X-ray emission.

The hard X-ray emission in the global simulations arises from the hottest
gas in the starburst region, which emits strongly at hard X-ray temperatures.
There is a smaller contribution from the swept-up shell of halo gas and from
the free-wind. This result agrees with the conclusions of both Suchkov et al.
(1994) and Strickland & Stevens (2000), who also found the starburst region to
be the most significant contributor to the hard X-ray emission. The hard X-
ray luminosity does not depend on the initial distribution of the ISM, having a
value of \( L_x \sim 10^{38} \text{ erg s}^{-1} \) in all models considered in Chapter 5.

The origin of the soft X-ray emission is less certain, and as noted, is thought
to be physically related to the filamentary optical emission. Previous simul-
ations have provided contradictory results with some suggesting shocked gas
to be the primary emission mechanism. Others find the contribution from the
shocked gas to be negligible and suggest that the intermediate temperature in-
terface between the hot and cold gas, or the wind material itself, to be the main
source. In addition, mass-loading from ablated clouds immersed within the
outflow has also been suggested as a mechanism for the production of soft X-
rays. In the global model presented in Chapter 5, the swept-up shell of halo gas that surrounds the outflow is a strong soft X-ray emitter, as this gas is shock heated to X-ray temperatures. However, this shell has no associated optical emission and has not been seen in X-ray observations of starburst winds. While the fate of this shell cannot be determined in this study due to the limited spatial range covered by the global simulations, clearly either the shell must somehow be prevented from emitting at X-ray temperatures, or it is present but has yet to be detected.

In Chapter 5, four mechanisms for the production of soft X-ray emission that are physically related to the predicted Hα emission were proposed. Interior to the swept-up shell of halo gas, the possible major contributors to the soft X-ray emission are:

(a) **The Mass-Loaded Wind** - Turbulent gas in the vicinity of the starburst region is mass-loaded through mixing with clouds in the disk, creating a region of hot rapidly cooling gas.

(b) **The Intermediate Temperature Interface** - Mixing between the hot wind and the cold gas in the filaments creates a region of intermediate densities and temperatures.

(c) **Bow Shocks** - Soft X-rays arise when a bow shock forms upstream of clouds of disk gas that have been accelerated into the flow by the ram pressure of the hot wind. This is a straightforward process where gas is shock heated to X-ray temperatures.

(d) **Colliding Bow Shocks** - As disk gas is accelerated into the wind, the resultant bow shocks begin to cool as the wind expands. When 2 shocks collide, the gas is further shock heated to soft X-ray temperatures.

As mechanisms (a) and (b) involve the mixing of hot and cold gas to X-ray temperatures, the soft X-ray emission may be the result of numerical diffusion caused by insufficient resolution, and possibly unphysical. The production of soft X-rays in the high resolution simulations of a single cloud interacting with a freely expanding wind indicate that these processes do not contribute appreciably to the soft X-ray emission (Section 6.5.2). I conclude that bow shocks produced upstream of gas clouds accelerated into the outflow, and the interaction of these shocks, are the primary source of the soft X-ray emission observed in starburst-driven winds.
7.5 Numerical Resolution Considerations

In Chapter 5, I assumed a numerical resolution of 2 pc per computational cell in my global simulations of a starburst wind. However, as this assumption can have an impact on the results, a detailed resolution study of the interaction of a supersonic wind with a single cloud was also performed (Section 6.4). In their study, Strickland & Stevens (2000) noted that it was the coolest gas that was affected the most by the numerical resolution of the simulation. This result was confirmed in Section 5.6, where the cool filamentary H$\alpha$ gas in the global model is less well defined in the lower resolution test simulations.

Unfortunately even at the high resolution of the single cloud simulations in Chapter 6, the dense H$\alpha$ emitting gas is still not fully resolved, with the flux of mass passing through a fixed surface increasing with resolution. This is a result of the increased fragmentation of the cloud. The number of fragments produced by the break-up of the cloud increases exponentially with increasing resolution, and is likely to continue down to smaller scales as the Kelvin-Helmholtz instability is further resolved. This process is dramatically illustrated in Figures 6.12 and 6.14, where the number of fragments can clearly be seen to significantly increase in the higher resolution simulations. In light of this result, future models will need to sufficiently resolve the coolest gas in the simulations in order to gain an accurate understanding of its dynamics. Nevertheless, there is still a clear trend in the interaction that allows us to draw physical conclusions. A filament is still clearly visible amongst the foam of cloudlets at all resolutions. In addition, the soft X-ray luminosity is sufficiently resolved and it almost constant with numerical resolution.

7.6 Future Directions

The simulations presented in Chapters 5 and 6 of this thesis present a significant advance in the modeling of starburst-driven winds. By fully considering all three dimensions of the outflow and including an inhomogeneous fractal disk, which has been shown here to have a significant effect on the winds evolution, I have been able to produce filamentary H$\alpha$ structures that strongly resemble the filaments seen in starburst winds. I was also able to produce complementary soft X-ray emission, which explains the observed spatial correlation between the soft X-ray emitting gas and these filaments. However, this work represents only the beginning of a new generation of three-dimensional simulations which will provide further insights into these objects.
Improvements in the physics that are included in the model are a necessary next step. Magnetic fields and thermal conduction have been shown in some cases to provide further stability to a dense cloud overrun by a supersonic wind, and thus may play a role in the formation of the filamentary gas. As discussed, photoionization is known to contribute to the ionization of the filaments, so that its inclusion in a model will lead to a better understanding on the morphology of the Hα emitting gas. Improved modeling of the starburst that powers that outflow is also a desirable feature. The distribution of gas in the starburst region, the number and location of the super star clusters that power the outflow, as well as the star formation history of each cluster, will likely have an impact on the morphology and evolution of the wind.

Another important consideration is the spatial range covered by the model. In order to retain a reasonable numerical resolution, I restricted the global simulations to cover only the inner 1 kpc region of the galaxy, allowing the evolution of the entire outflow to only be followed for a short period of time (~ 1 Myr). However, starburst winds can be several kiloparsecs in size and have ages of around 10 million years. Thus, a model which covers a considerably larger spatial range, yet retains a numerical resolution that is at least comparable to that considered here, would be desirable. Such a model would be computationally expensive, necessitating the use of an adaptive mesh in order to adequately resolve the cool disk gas. With an increase in spatial range, a more sophisticated treatment of the host galaxy’s halo becomes possible. As with the ISM in the disk of the galaxy, the halo is unlikely to be homogeneous, and is possibly responsible for the large scale asymmetries observed in many winds. For example, the cloud of neutral hydrogen that is known to surround the galaxy M82 will impact the morphology of its outflow. Indeed, M82’s wind is known to be entirely engulfed by this HI gas (see Fig. 7.1). The inclusion of such a neutral hydrogen halo into the model would provide a valuable insight into its impact on the evolution of the spectacular wind in M82.

An investigation into the transport of mass and energy via a starburst-driven wind was not attempted in this thesis due to the limited spatial range of the simulations. However, galactic winds are likely to be a significant mechanism for the removal of material from galaxies, as well as a source for the heating and enrichment of the intergalactic medium. This makes a study of the energetics of the outflow, and the transport of the ISM and metals via the wind essential. An important question to answer is what fraction of the energy of the starburst is transferred to the outflow and how much is radiated away? Another question to consider is where this energy is stored? Preliminary calculations of the energy budget, based on the simulations in Chapter 5, indicate that less than
0.1% of the energy from the starburst resides in the cool Hα emitting gas, making the filaments a poor indicator of the energetics of the outflow. The majority of the energy found in the outflow resides in the hot wind that constitutes a significant fraction of its volume. This result could have implications on the estimated energetics of starburst winds, but needs to be further qualified by additional simulations designed to investigate this important question.

The hot wind is also the major source of the metallicity of the outflow, with this gas being enriched by the supernovae in the starburst. As this gas has velocities in excess of $v = 1000 \text{ km s}^{-1}$, it is unlikely to have difficulty escaping from the gravitational potential of the host galaxy. The fraction of metals that are transported into the intergalactic medium could be estimated by implementing a tracer to track the metals injected by the starburst. The ability for the wind to transport the ISM of the host galaxy out of the potential is another important question. This gas has velocities that are considerably lower than that of the hot supernova enriched gas, and may not be able to escape the potential well of the galaxy. It is possible that this gas may instead fall back into the plane of the galaxy, replenishing the ISM and fueling additional star formation. As this gas is cool, it will be significantly affected by the numerical resolution of the simulation. Thus, any accurate model will need to provide sufficient resolution in order to obtain realistic estimates of the escape fraction of the ISM.

The importance of galactic winds in the formation and evolution of galaxies is just beginning to be understood. However, multi-wavelength observations are unable to fully reveal the structure of starburst-driven winds, with the hottest gas, in which the majority of the metals and energy from the starburst are thought to reside, yet to be reliably detected. Thus, hydrodynamical simulations provide a unique platform in which to study feedback processes, such as the transport of the ISM and metals from the host galaxy into the IGM, as discussed above. Starburst-driven winds are also fascinating objects in their own right, displaying spectacular and complex structure at all wavelengths. While this thesis has shed light into the origin of the filamentary optical emitting gas, as well as the related soft X-rays, work still needs to be done in order to fully understand these objects. In particular, as shown in Chapter 6 further detection of OVI emission in the filaments of starburst-driven winds would provide further evidence for the role played by cooling in the development of this gas. This would also provide validation of the mechanism for the formation of the filaments proposed in this thesis.
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