

THREE-DIMENSIONAL SIMULATIONS OF A STARBURST-DRIVEN GALACTIC WIND

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ABSTRACT

We have performed a series of three-dimensional simulations of a starburst-driven wind in an inhomogeneous interstellar medium. The introduction of an inhomogeneous disk leads to differences in the formation of the 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. While higher resolution simulations are required in order to ascertain the importance of mixing processes, we 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 the clouds driven into the flow by the ram pressure of the wind, and the interaction between these shocks.

Subject headings: galaxies: starburst — hydrodynamics — ISM: jets and outflows — methods: numerical

Online material: color figures, mpeg animation

1. INTRODUCTION

In 1963, Lynds & Sandage (1963) first detected an outflow of gas along the minor axis of M82. Chevalier & Clegg (1985) proposed a model in which a galactic-scale outflow could be powered by the combined kinetic energy from supernovae. Starburst galaxies, with their characteristically high star formation rates, provide the perfect environments for these winds to develop. Indeed, galactic winds are ubiquitous in starburst galaxies, having been observed in many nearby galaxies and inferred in galaxies at high redshifts (see Veilleux et al. 2005 and references therein).

The best studied galactic wind is the outflow in M82, which is clearly visible in the light of $H\alpha$, displaying a vast filamentary system extending several kiloparsecs 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 looplike structures (Ohya 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 and 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 the wind, with its size and structure affect-

ing the degree of collimation (Strickland & Stevens 2000) and expansion of the outflow (Strickland et al. 2004b; 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 $H\alpha$ -emitting gas (e.g., Strickland et al. 2000, 2002, 2004a; Cecil et al. 2002; Martin et al. 2002; Grimes et al. 2005; Ott et al. 2005), 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.

Over the past few decades, numerous simulations have been made of starburst-driven winds (Tomisaka & Ikeuchi 1988; Tomisaka & Bregman 1993; Suchkov et al. 1994, 1996; D’Ercole & Brighenti 1999; Tenorio-Tagle & Muñoz-Tuñón 1998; Strickland & Stevens 2000; Tenorio-Tagle et al. 2003). Suchkov et al. (1994) performed two-dimensional, axisymmetric simulations of a galactic wind in an isothermal ISM, with varying densities and temperatures. They concluded that the $H\alpha$ 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 gas and hot, tenuous gas. While these simulations provide some insight

into the origin of the X-ray and H α 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 on previous models and to gain a better understanding of the origin of the H α 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 ISM in a galactic disk is highly complex in all its phases (see, e.g., 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 can 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 paper we present a different model, which follows an approach similar 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 H α -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.

2. NUMERICAL MODEL

2.1. Description of the Code

The simulations were performed using a PPMLR (piecewise parabolic method with a Lagrangian remap) code, which is based on the method described by Colella & Woodward (1984). The code has been extensively modified (see, e.g., Sutherland et al. 2003a, 2003b) from the original VH-1 code (Blondin 1995). It is a multidimensional hydrodynamics code, optimized for use on multiple processors of the SGI Altix computer operated by the Australian Partnership for Advanced Computing. Thermal cooling has been incorporated, based on 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. 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.

2.1.1. The Gravitational Potential

Following Strickland & Stevens (2000), the gravitational potential used in these simulations consists of a stellar spheroid and

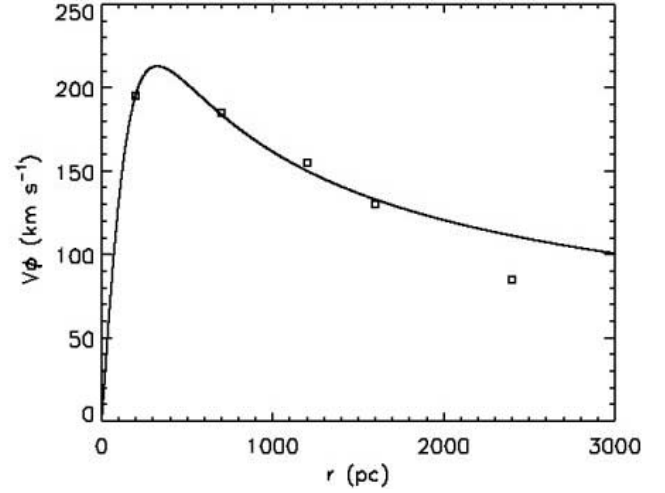


FIG. 1.—Fit to the CO rotation curve of M82 (open squares; Sofue 1998).

a disk. Let $R = (r^2 + z^2)^{1/2}$ be the radius of the stellar spheroid, r_0 the core radius, M_{ss} its mass, M_{disk} the mass of the disk, a its radial scale length, and b its vertical scale length. The potential Φ_{ss} of the stellar spheroid is described by an analytic King model (eq. [1]), and the disk potential Φ_{disk} by a Miyamoto & Nagai (1975) model (eq. [2]). The total gravitational potential is then the sum of the two components ($\Phi_{tot} = \Phi_{ss} + \Phi_{disk}$), where

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

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

While 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. 1); the parameters are summarized in Table 1. 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).

2.1.2. The Interstellar Medium

The ISM 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 (3), where $c_{s,h} = (kT_h/\mu m)^{1/2}$ is the isothermal sound speed of the hot gas and e_h is the ratio of the azimuthal velocity to the Keplerian velocity.

TABLE 1
MODEL PARAMETERS

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

In order to obtain a nonrotating halo, which is supported by pressure alone, we adopt $e_h = 0$:

$$\frac{\rho_{halo}(r, z)}{\rho_{halo}(0, 0)} = \exp \left[-\frac{\Phi_{tot}(r, z) - e_h^2 \Phi_{tot}(r, 0) - (1 - e_h^2) \Phi_{tot}(0, 0)}{c_{s,h}^2} \right]. \quad (3)$$

We follow the same approach as Sutherland & Bicknell (2007) and introduce an ensemble mean density distribution which introduces a turbulence parameter. 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 $c_{s,d} = (kT_d/\mu m)^{1/2}$ be the sound speed of the warm gas, σ_t the turbulent velocity dispersion of the clouds, and e_d the ratio of the

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

$$\frac{\bar{\rho}_{disk}(r, z)}{\bar{\rho}_{disk}(0, 0)} = \exp \left[-\frac{\Phi_{tot}(r, z) - e_d^2 \Phi_{tot}(r, 0) - (1 - e_d^2) \Phi_{tot}(0, 0)}{\sigma_t^2 + c_{s,d}^2} \right]. \quad (4)$$

Figure 2 shows the density contours of various homogeneous ISM distributions, demonstrating the effect of varying the parameters σ_t and T_d . The case of $\sigma_t = 0 \text{ km s}^{-1}$ 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 K) in order to produce reasonable disk scale heights (Figs. 2d–2f). However, this scenario is unrealistic, as gas at this temperature rapidly cools. The turbulence parameter σ_t allows us to increase the disk scale height while 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 cloud velocity dispersions of $\sigma_t = 60$ and 75 km s^{-1} (Figs. 2a and 2b, respectively).

While these values are supersonic, with Mach numbers on 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.

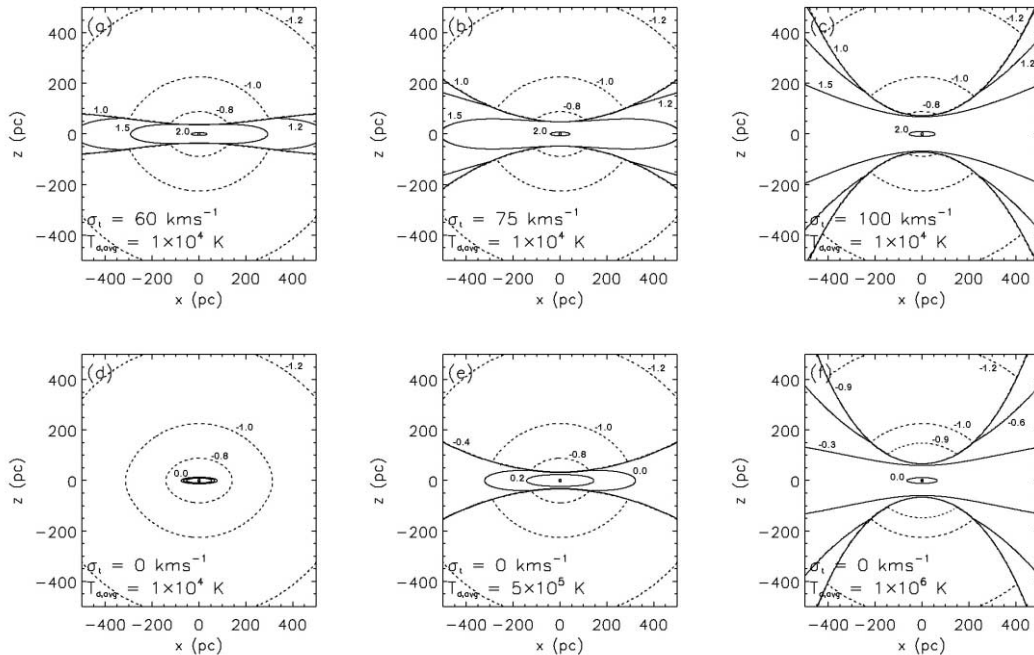


FIG. 2.—Log-density contours of the disk and halo showing the effect of the parameters (a–c) σ_t and (d–f) T_d on the scale height of the disk. The solid contours represent the disk gas, while the dashed contours represents the halo gas.

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 of $\sim 200 \text{ km s}^{-1}$ in M87 and up to 400 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 lognormal ISM such as has been incorporated into our initial data. Further justification for a lognormal ISM and its relation to supersonic/super-Alfvénic 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 utilizing a similar potential (e.g., Tomisaka & Bregman 1993) is still present in our model, most noticeably in Figures 2c and 2f. 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 paper.

A specific inhomogeneous ISM (out of an ensemble of such possible ISMs) is obtained by multiplying equation (4) by a fractal distribution, which has lognormal 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 2007). 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 $T_d = 3.0 \times 10^4 \text{ K}$ 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 we compensated for this by adopting $e_d = 1.0$ (i.e., azimuthal velocity equal to the 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 $P/k = 10^6 \text{ cm}^{-3} \text{ K}$, consistent with the central regions of starburst galaxies (Chevalier & Clegg 1985). The parameters of the hot halo and warm disk are summarized in Table 1.

2.1.3. 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 ρ (eqs. [5] and [6]) so that regions of the ISM

TABLE 2
SIMULATION PARAMETERS

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

^a Mass of the starburst region.

^b Velocity dispersion of the clouds.

^c Scale height of the disk.

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

$$\frac{dM}{dt dV} = \frac{\dot{M}\rho}{\int \rho dV}, \quad (5)$$

and the energy injection rate per unit volume by

$$\frac{dE}{dt dV} = \frac{\dot{E}\rho}{\int \rho dV}, \quad (6)$$

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 summarized in Table 1.

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 2. The resolution is $512 \times 512 \times 512$ cells, covering a spatial extent of 1 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 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 the initial stages of the evolution of the wind.

1. Model M01 is the standard model, using the parameters given in Table 1.

2. Model 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.

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 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. The altered ISM distributions result in

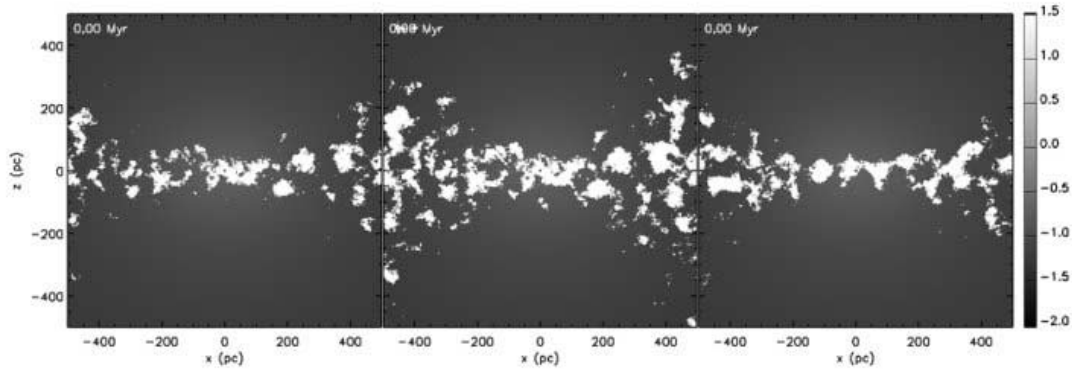


FIG. 3.— Initial density distribution through the central $y = 0$ plane in the three main models: (1) the standard model M01 (*left*), (2) the thicker disk in M02 (*middle*), and (3) the modified cloud distribution in M03 (*right*). [See the electronic edition of the *Journal* for a color version of this figure.]

minor differences in the mass contained within the starburst region (M_{sb}) 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 $\text{H}\alpha$ -emitting material in the simulations to be gas originating from the disk whose temperature evolves to within the range of $T = 5 \times 10^3$ to 3×10^4 K, using a tracer variable to follow the disk gas.

3. FORMATION OF A WIND

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 six different epochs (0.5, 0.75, 1.0, 1.25, 1.5, and 2.0 Myr) is depicted in Figure 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 the 1 and 2 Myr epochs in the models M01, M02, and M03 is shown in Figure 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, 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,

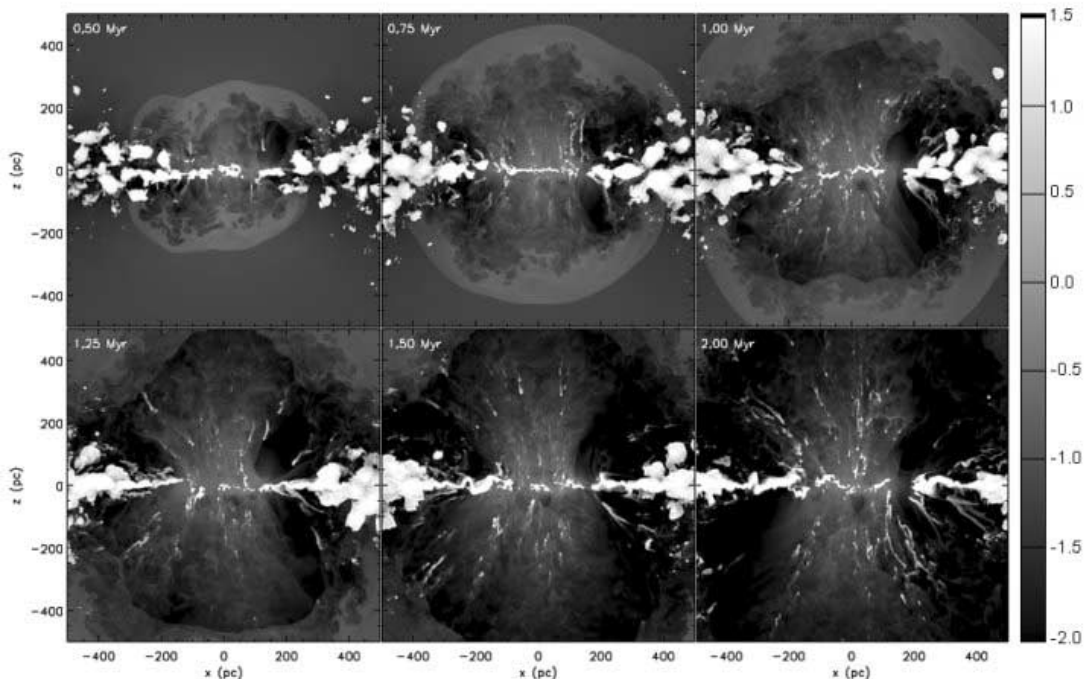


FIG. 4.— Logarithm of the density (cm^{-3}) through the central y -plane of the wind in M01 at the 0.5, 0.75, 1.0, 1.25, 1.5, and 2.0 Myr epochs. [See the electronic edition of the *Journal* for a color version of this figure.]

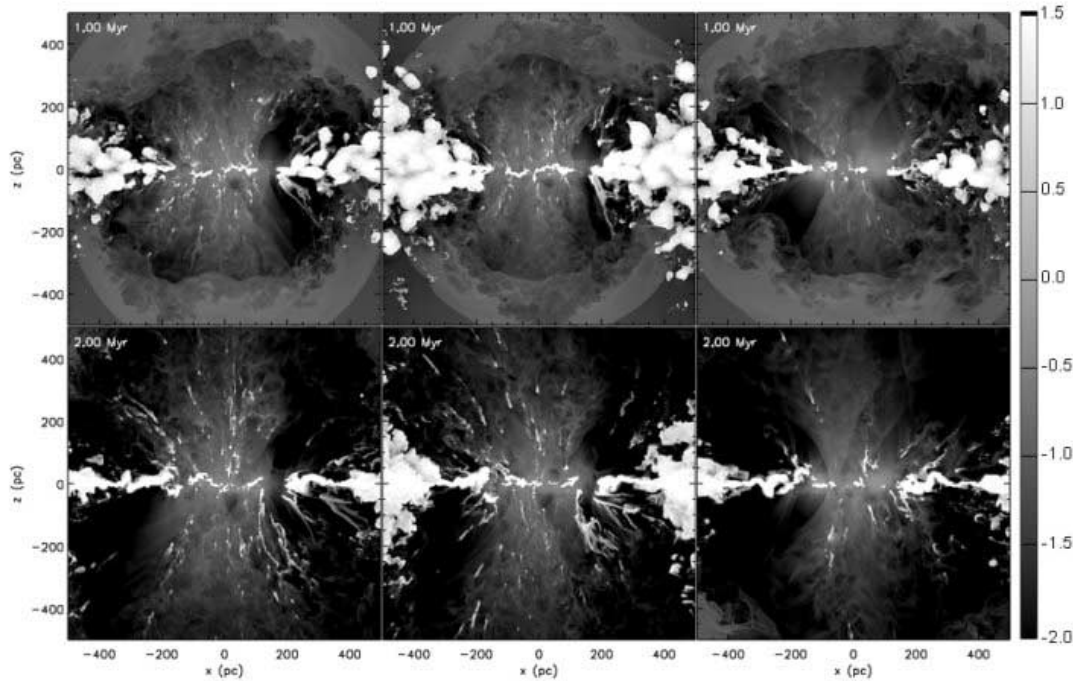


FIG. 5.—Log-density through the central y -plane illustrating the morphology of the winds in M01 (left panels), M02 (middle panels), and M03 (right panels) at 1.0 Myr (top panels) and 2.0 Myr (bottom panels). [See the electronic edition of the *Journal* for a color version of this figure.]

e.g., 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 a 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 the 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. 4, top left) 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 ($v \gtrsim 1000 \text{ km s}^{-1}$), hot ($T \gtrsim 10^7 \text{ K}$), turbulent gas, surrounded by a slower ($v \sim 300\text{--}400 \text{ km s}^{-1}$), 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, top panels) the outflow resembles the basic structure of a superbubble in the “snowplow” phase of its evolution (Tomisaka & Ikeuchi 1988), wherein the bubble is sweeping a substantial amount of the am-

bient hot ISM. This phase is characterized by five zones, which are illustrated in Figure 6:

1. The central injection zone ($T > 5 \times 10^7 \text{ K}$).
2. A supersonic free wind ($T \gtrsim 10^6 \text{ K}$, $v \sim 1000\text{--}2000 \text{ km s}^{-1}$).
3. A region of hot, shocked, turbulent gas ($T \gtrsim 10^7 \text{ K}$, $v \sim 500\text{--}1200 \text{ km s}^{-1}$).
4. A cooler, dense outer shell ($T \sim 7 \times 10^6 \text{ K}$, $v \sim 300\text{--}400 \text{ km s}^{-1}$).
5. The undisturbed ambient gas ($T = 5 \times 10^6 \text{ K}$).

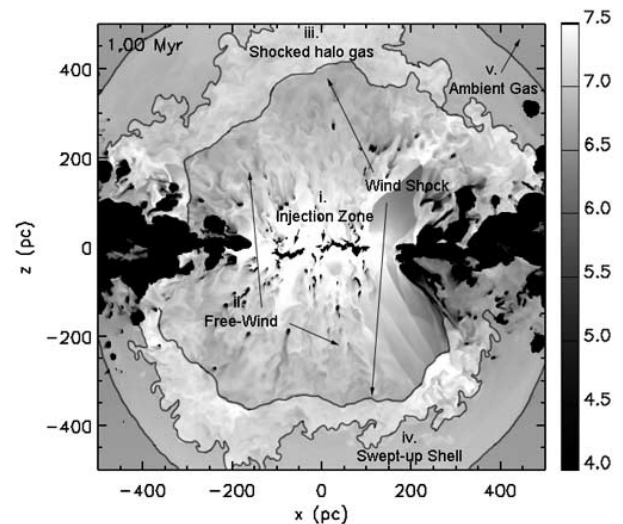


FIG. 6.—Log-temperature through the central y -plane of M01 at 1 Myr, indicating the five characteristic zones of a superwind in the “snowplow” phase of its evolution. [See the electronic edition of the *Journal* for a color version of this figure.]

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 from that of M01, with the outer swept-up shell and wind shock being wider and flatter.

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 hourglass-like appearance. The wind shock appears more asymmetric in the case of M03, while M02 displays structure similar to but less evolved than that of 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 (Fig. 5, *bottom 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 $v \sim 100\text{--}800 \text{ km s}^{-1}$ (Fig. 10).

In view of the above descriptions at various epochs, it is apparent that inhomogeneities in the disk result in asymmetries on relatively small ($\sim 100 \text{ pc}$) 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).

3.2. Base Confinement

A difficulty with previous two-dimensional simulations of starburst winds has been 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 & 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 $\sim 400 \text{ pc}$ (Shopbell & Bland-Hawthorn 1998). While the base diameter of $\sim 600\text{--}800 \text{ pc}$ 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 & Muñoz-Tuñón (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 being 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 $\sim 200 \text{ pc}$ over the 2 Myr time frame (see Fig. 4). While it is possible that the size of the base may increase if the simulations are followed to later times, the density of the disk gas ($\sim 100 \text{ cm}^{-3}$) is large enough to impede the expansion of the outflow along the major axis of the disk.

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 $\text{H}\alpha$ filaments,

$\theta_{\text{H}\alpha}$, and the opening angle of the cone defined by the hot wind, θ_{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 ($\theta_{\text{H}\alpha} \approx 30^\circ$; 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 $\theta_{\text{HW}} \sim 100^\circ$, whereas in models M01 and M03, $\theta_{\text{HW}} \sim 160^\circ$.

While the hot wind is poorly collimated when compared to the degree of collimation in M82 defined by the $\text{H}\alpha$ filaments, the morphology of the $\text{H}\alpha$ -emitting material in our simulations compares somewhat more favorably. In M02 the filaments are collimated to the greatest extent, with $\theta_{\text{H}\alpha} \sim 60^\circ\text{--}70^\circ$. 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 ($\theta_{\text{H}\alpha} \sim 80^\circ\text{--}90^\circ$) than those in M01 ($\theta_{\text{H}\alpha} \sim 70^\circ\text{--}80^\circ$). 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 § 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.

4. FILAMENTARY $\text{H}\alpha$ EMISSION

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 7 shows log-temperature slices through the central $y = 0$ plane of M01 over the period of 0.75–1.75 Myr. The filaments appear as dense clouds of disk gas that has been drawn into the flow. Since energy is injected into the starburst region in proportion to the local density, a significant fraction of the energy is injected into the dense clouds which appear in the lognormal, fractal distribution. The binding energy of the clouds is quickly overcome, and the $\text{H}\alpha$ filaments then form from the breakup 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 7, where at 0.75 Myr (*top left*) the starburst region is filled with clumped disk gas. Over the next 1 million yr the breakup of the central clouds can be seen, with material being drawn out into strings of dense clouds (*bottom 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 onward.)

The filamentary structure can be seen best in Figure 8, which shows the three-dimensional structure of the $\text{H}\alpha$ -emitting gas at 1 Myr (*top panels*) and 2 Myr (*bottom 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 moment in the formation of the filaments in M01 is shown in Figure 9. The entire formation process is available in an mpeg animation in the electronic edition of the *Journal*. At 2 Myr the velocity of the $\text{H}\alpha$ -emitting gas in all

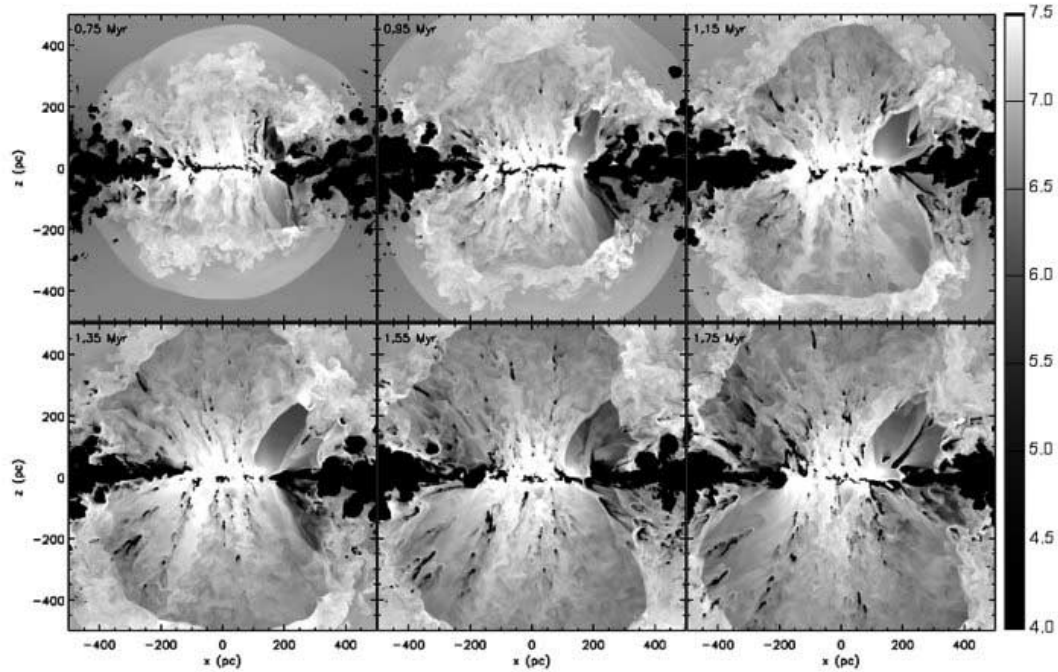


FIG. 7.—Logarithm of the temperature (K) through the central y-plane of M01 at 0.2 Myr intervals between 0.75 and 1.75 Myr, illustrating the formation of the filaments. [See the electronic edition of the *Journal* for a color version of this figure.]

models falls within the range $v \sim 100\text{--}800 \text{ km s}^{-1}$ (see Fig. 10) and increases with height z above the disk. This is comparable to the velocities observed in M82, at a height of 500 pc, of $v = 500\text{--}800 \text{ km s}^{-1}$ (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).

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, 2006; Melioli et al. 2005; Marcolini et al. 2005; Pittard et al.

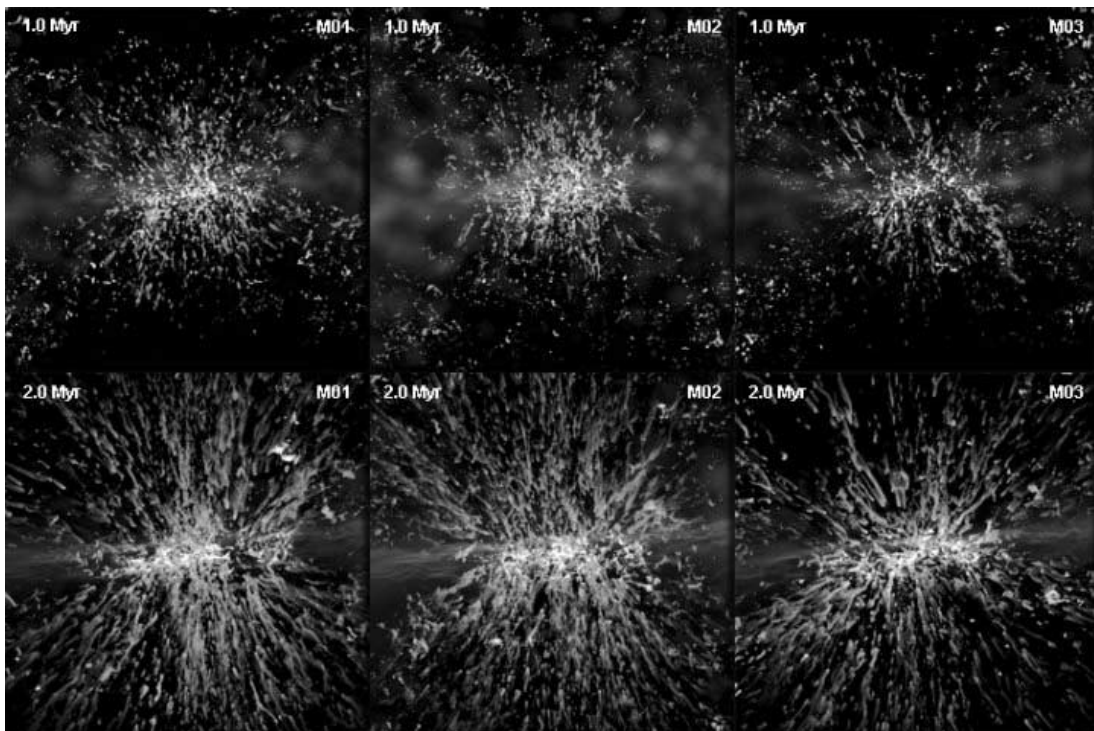


FIG. 8.—Volume renderings, utilizing a depth cue average, of the $\text{H}\alpha$ -emitting gas in the three models at 1 Myr (top panels) and 2 Myr (bottom panels). [See the electronic edition of the *Journal* for a color version of this figure.]

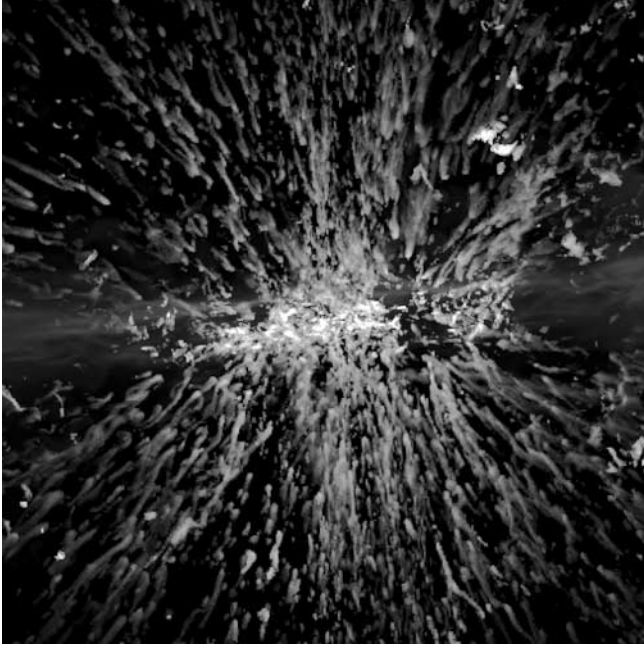


FIG. 9.—Selected moment in the formation of the H α filaments in M01 over a 2 Myr time frame. [This figure is available as an mpeg animation in the electronic edition of the Journal.]

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 in 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 Kelvin-Helmholtz timescale $t_{\text{KH}} = R_c(\rho_c + \rho_w)/(v_c - v_w)(\rho_c\rho_w)^{1/2}$, 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 order 10^{10} s. This is far shorter than the crushing time of the same cloud, $t_{\text{crush}} \sim 10^{14}$ s, and the growth rate of the Kelvin-Helmholtz instability, $t_{\text{KH}} \sim 10^{12}$ s, 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 against 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 ρ_c and radius R_c being driven by a wind of density ρ_w and velocity v_w . Let the drag coefficient be $C_D = 1$. Then the theoretical acceleration of the cloud is

$$f_{\text{th}} = \frac{3}{8} C_D \left(\frac{\rho_w}{\rho_c} \right) \frac{v_w^2}{R_c}. \quad (7)$$

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 $f_{\text{th}} = 5 \times 10^{-12}$ km s $^{-2}$. The observed acceleration of a gas cloud in our simulations is $f_{\text{ob}} \approx 1.3 \times 10^{-11}$ 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

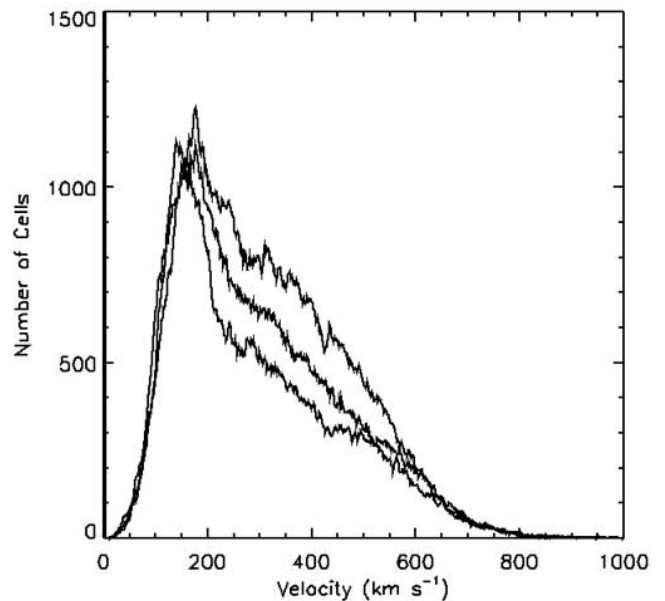
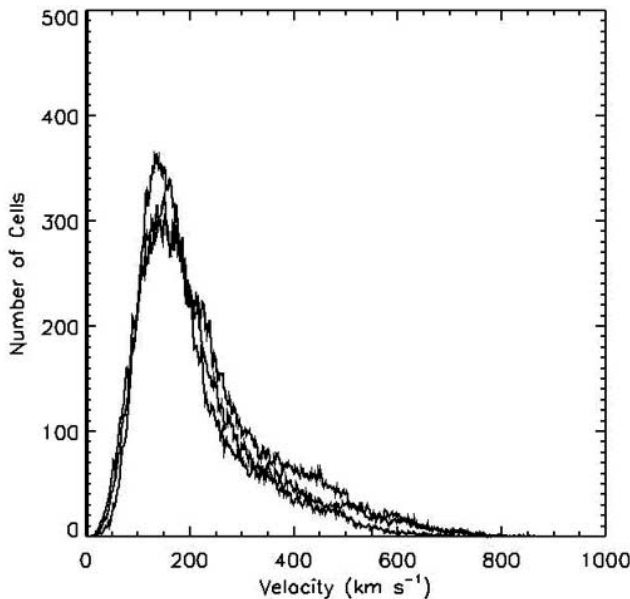


FIG. 10.—Histogram of the velocity at 1 Myr (left) and 2 Myr (right) of the H α -emitting gas in M01, M02, and M03. [See the electronic edition of the Journal for a color version of this figure.]

are necessary in order to investigate this problem in sufficient detail. These simulations are currently in progress.

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 ablated cloud morphologies similar to those presented in this paper. In their case the clouds only achieve a maximum velocity of $\sim 50 \text{ km s}^{-1}$, 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.

4.3. Effect of the ISM

As illustrated in Figure 8, the morphology of the $\text{H}\alpha$ -emitting filaments is affected by the inhomogeneity of the disk to a greater extent than the hotter wind that surrounds them. While 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 (Fig. 8, *top panels*) the $\text{H}\alpha$ emission starts to become filamentary. These filaments are asymmetric, with the morphology varying from model to model. The filaments in M02 are less extended than 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 (Fig. 8, *bottom panels*) the filaments form a biconical shape, consisting of strings of $\text{H}\alpha$ -emitting clouds. These filaments are distributed throughout the wind and rotate in the same direction as the disk. In M02 the filaments have a distribution similar to those in M01 but are slightly more collimated. In contrast, the filaments in M03 are more chaotic than those in M01, with less $\text{H}\alpha$ -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 $\text{H}\alpha$ -emitting gas on the computational grid in M01 and M03 at 2 Myr is $M_{\text{H}\alpha} = 1.5 \times 10^6$ and $1.3 \times 10^6 M_{\odot}$, respectively. M02, with its thicker disk, has an $\text{H}\alpha$ mass of $M_{\text{H}\alpha} = 3.9 \times 10^6 M_{\odot}$ contained in the outflow. These numbers compare favorably with known $\text{H}\alpha$ estimates in starburst winds ($\sim 10^5$ – $10^7 M_{\odot}$; Veilleux et al. 2005).

The amount of $\text{H}\alpha$ -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 $\text{H}\alpha$ -emitting gas is found in the wind. However, M03, which initially contains more gas inside its starburst region than M01 (see Table 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.

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 $\text{H}\alpha$ -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. 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. 4 and 7). This paints a different picture from 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 sizes of the outflows. This has implications for observational estimates of the energy contained in these winds, as a significant fraction of the energy contained within a wind may be found in the hottest ($T \gtrsim 10^7 \text{ K}$) gas that is not traced by $\text{H}\alpha$ 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 $\text{H}\alpha$ and X-ray emission at a distance of approximately 11 kpc from the disk. They propose an interaction of the wind with an H I 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 it 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 $\text{H}\alpha$ emission (Engelbracht et al. 2006). While the nature of this emission is uncertain, there does appear to be a spatial correlation with the $\text{H}\alpha$ -emitting gas in the region where $\text{H}\alpha$ emission is detected. Strickland et al. (2004a) also possibly detect diffuse, low surface brightness X-ray emission 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 multiwavelength 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 (Shoppell & 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 ISM 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 will significantly evolve to the 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. 7, *bottom left*). 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 $\text{H}\alpha$ 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 those in 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 (Shoppell & 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

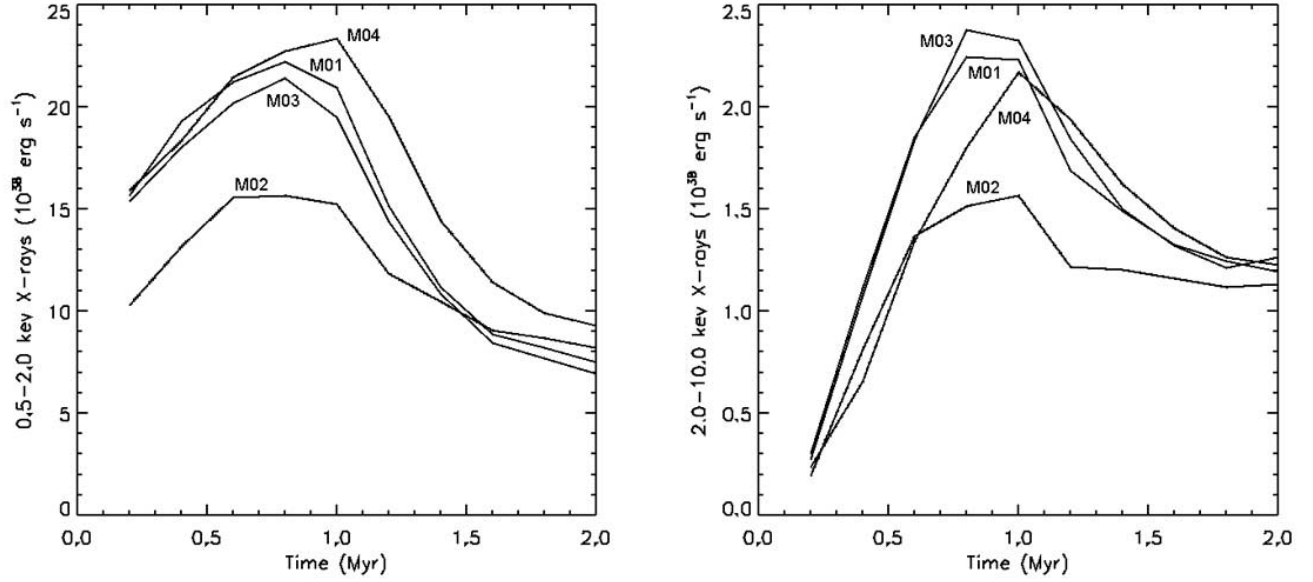


FIG. 11.—X-ray luminosities in both the soft (*left*) and hard (*right*) energy bands for all models. [See the electronic edition of the *Journal* for a color version of this figure.]

filaments in many winds (see, e.g., Melioli et al. 2005; Tenorio-Tagle et al. 2006), and warrants further investigation.

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 11 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 11 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 $\sim 0.8 \text{ Myr}$), 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 11 begin to de-

cline, 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 size to fill the computational grid.

5.1. Hard X-Ray Emission

The hard (2.0–10.0 keV) X-ray luminosity of the wind for all models is given in Figure 11 (*right*). The luminosity does not vary significantly between models, being of the order of $10^{38} \text{ erg s}^{-1}$. The hard X-ray emissivity of M01, through the central y -plane, is shown in Figure 12 at the 1.0 Myr (*left*) and 2.0 Myr (*right*) epochs. At 1 Myr the wind has started to flow off the computational grid, but the internal structure of the wind, as shown in Figure 6, can still be seen. The main contributor to the hard X-ray emission is the starburst region itself, with a lesser contribution

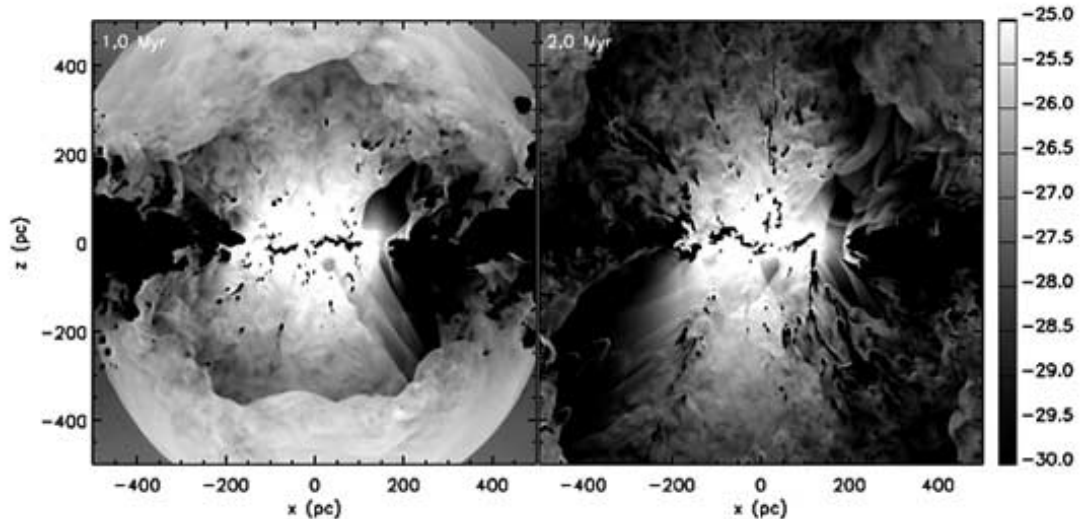


FIG. 12.—Logarithm of the hard X-ray emissivity ($\text{erg s}^{-1} \text{ cm}^{-3}$) through the central y -plane of M01 at 1 Myr (*left*) and 2 Myr (*right*). [See the electronic edition of the *Journal* for a color version of this figure.]

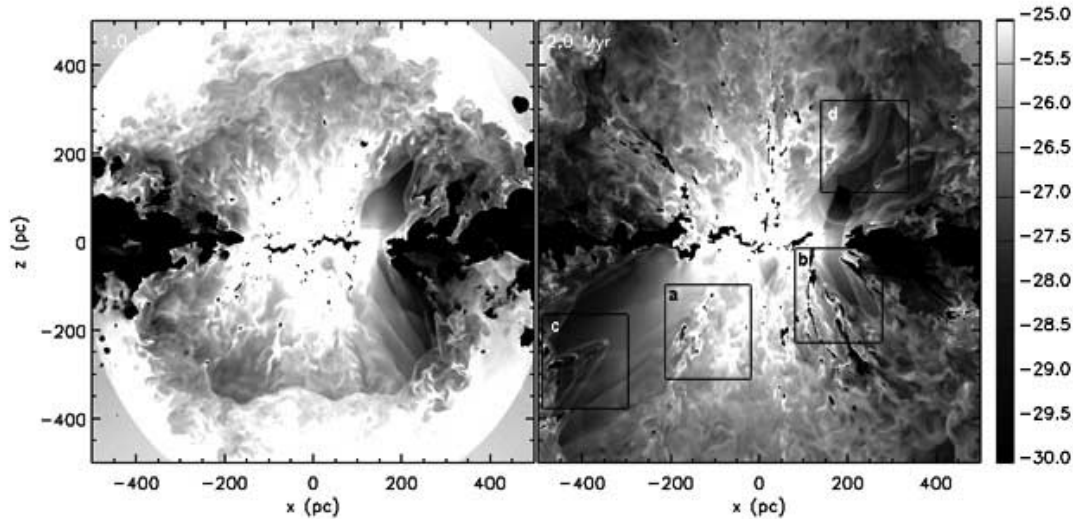


FIG. 13.—Logarithm of the soft X-ray emissivity ($\text{erg s}^{-1} \text{cm}^{-3}$) through the central y -plane of M01 at 1 Myr (*left*) and 2 Myr (*right*). The squares indicate the location of regions of X-ray emission that are highlighted in Fig. 14. [See the electronic edition of the *Journal* for a color version of this figure.]

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 evidenced by the drop in luminosity as the shell leaves the grid. Differences in the shape and volume of this shell in each model lead to the variation in the peaks in Figure 11, with the thinner shell in M02 resulting in smaller luminosities.

By 2 Myr (Fig. 12, *right*) the swept-up shell has completely left the computational grid, and the calculated X-ray luminosity is comprised solely of emission processes interior to the shell. The starburst region is still the major contributor to the emission, with a lesser contribution from emission 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 luminosities in each model at the 2 Myr epoch, as the size and power of the starburst are identical in all models. At this time, the luminosity is approximately constant, with $L_X \sim 1.2 \times 10^{38} \text{ erg s}^{-1}$, 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.

5.2. Soft X-Ray Emission

5.2.1. 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 $\text{H}\alpha$ 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 possible 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. While 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 need to be confirmed by planned detailed simulations of interactions between winds and filaments. Figure 13 shows the volume emissivity of the soft X-rays at the 1 Myr (*left*) and 2 Myr (*right*) epochs. As with the hard X-ray emission in Figure 12, 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 four main processes interior to the swept-up shell that give rise to soft X-rays, and examples of these are shown in Figure 14:

1. 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 ($n \sim 0.3 \text{ cm}^{-3}$), 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.

2. 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 resolution and numerical

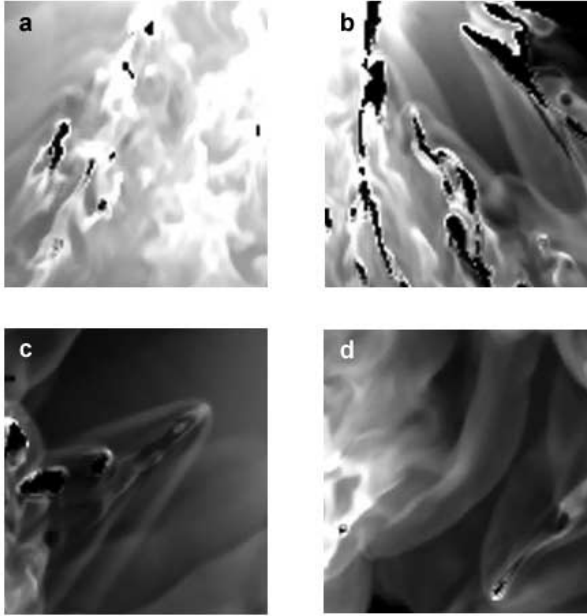


FIG. 14.— Highlighted soft X-ray emissivity from the wind in M01. Soft X-rays arise from (a) the cooling mass-loaded wind, (b) the intermediate-temperature interface between hot and cold gas, (c) bow shocks, and (d) the interaction between bow shocks. The size and location of each panel are indicated in Fig. 13. [See the electronic edition of the *Journal* for a color version of this figure.]

diffusion in this region mean that the actual contribution to the soft X-ray luminosity is uncertain.

3. Bow shocks. Soft X-rays arise when a bow shock ($T \sim 10^7$ K) forms upstream of clouds of disk gas ($T \sim 10^4$ K) that have been accelerated into the flow by the ram pressure of the hot wind ($T \sim 10^6$ K). This is a straightforward process where gas is shock-heated to X-ray temperatures.

4. Colliding bow shocks. As disk gas is accelerated into the wind, the resultant bow shocks begin to cool as the wind expands. When two shocks collide, the gas is further shock-heated to temperatures of order $T \sim 10^7$ 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 and 2 Myr to get an idea of the soft X-ray emission arising from the wind at later times. Figure 15 shows a schematic of the X-ray- and $H\alpha$ -emitting gas in a starburst wind based on the results of our simulations. In § 4.1 we proposed the formation of $H\alpha$ -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. 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

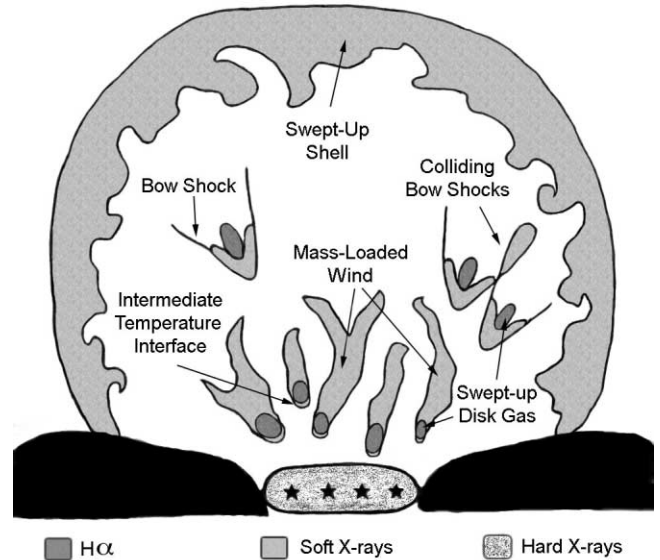


FIG. 15.— Schematic of the $H\alpha$ and X-ray emission arising in a starburst wind and their spatial relationship.

mechanism responsible for the production of limb-brightened outflows in $H\alpha$ results in limb-brightened X-ray emission.

5.2.2. Soft X-Ray Luminosity

We now discuss further the features of the soft X-ray luminosity (Fig. 11). 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 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 in 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 $L_X \sim 10^{39}$ 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 of $L_X \sim 10^{38}$ erg s $^{-1}$. Typical soft X-ray luminosities 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. 2005). 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.

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 16 gives the logarithm of the temperature at 2 Myr in M04 (left) and M01 (right). M04 differs only by its smaller computational grid. While it exhibits a similar overall shape and structure (i.e., bi-conical structure), smaller structures, such as bow shocks, are not

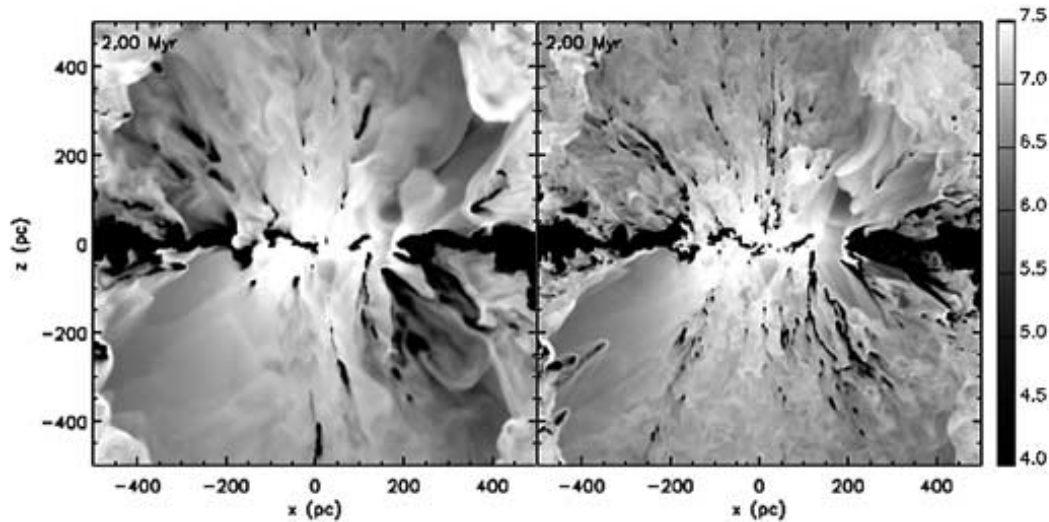


FIG. 16.—Logarithm of the temperature (K) in the central y -plane at 2 Myr in M04 (left) and M01 (right). [See the electronic edition of the *Journal* for a color version of this figure.]

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. 11). 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 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 from 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 luminosities 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 whether the luminosities achieved in our simulations are realistic.

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:

1. The ISM 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.
2. 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.
3. 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.
4. The $H\alpha$ 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 are affected by the distribution of clouds in the vicinity of the starburst region.
5. The $H\alpha$ filaments appear as strings of disk gas that form a filled biconical structure inside a more spherical hot wind. The filaments are distributed throughout this structure but do not trace the true extent of the wind defined by the hot gas.
6. 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, 10^{38} erg s $^{-1}$. These luminosities are dependent on the volume of the wind and would be larger for a more evolved outflow.
7. Interior to the swept-up shell of halo gas, soft X-ray emission originates in the same region as the $H\alpha$ -emitting gas. While higher resolution simulations are needed to confirm X-ray emission from mixing processes, we find four mechanisms that give rise to soft X-rays: (a) the mass-loaded wind, (b) the intermediate-temperature interface between the hot wind and cool filaments, (c) bow shocks, and (d) interactions between bow shocks. The shell is also a major contributor to the soft X-ray emission but has no associated $H\alpha$ emission.

8. 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 are a major determinant in the morphology of the outflow. The emission processes that contribute to the H α and soft X-ray emission may vary from one galaxy to the next. Whether the H α emission originates from photoionization or from shock heating (or both) cannot be determined from these simulations. However, we do find an abundance of filamentary $T \sim 10^4$ 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 on the environment of the host galaxy. In the case of M82 it is plausible that the interaction of the wind with the surrounding H I clouds is also a contributor to the soft X-ray emission, in addition to the processes mentioned above.

The observed spatial relationship between the H α - 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 H α 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 H α gas. Strickland et al. (2002) suggest that this emission may be detectable in more distant starburst galaxies.

In future work we shall investigate the evolution of a wind over a larger time frame and spatial extent than our current study, and look at the total energy budget of the outflow. It is also important to further test the effect of resolution on the filaments, and in particular the associated soft X-ray emission that arises through mixing of the hot wind and the cooler disk gas, which will be the subject of a subsequent paper.

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