Galactic Winds and Bubbles from Nuclear Starburst Rings

Dustin D. Nguyen1,2,4 and Todd A. Thompson1,2,3

1 Center for Cosmology and Astro-Particle Physics (CCAPP) The Ohio State University, Columbus, OH 43210, USA; dnguyen.phys@gmail.com
2 Department of Physics, The Ohio State University, Columbus, OH 43210, USA
3 Department of Astronomy, The Ohio State University, Columbus, OH 43210, USA

Received 2022 May 25; revised 2022 August 2; accepted 2022 August 3; published 2022 August 17

Abstract

Galactic outflows from local starburst galaxies typically exhibit a layered geometry, with cool $10^4$ K flow sheathing a hotter $10^7$ K, cylindrically collimated, X-ray-emitting plasma. Here we argue that winds driven by energy injection in a ring-like geometry can produce this distinctive large-scale multiphase morphology. The ring configuration is motivated by the observation that massive young star clusters are often distributed in a ring at the host galaxy’s inner Lindblad resonance, where larger-scale spiral arm structure terminates. We present parameterized three-dimensional radiative hydrodynamical simulations that follow the emergence and dynamics of energy-driven hot winds from starburst rings. In this letter, we show that the flow shocks on itself within the inner ring hole, maintaining high $10^7$ K temperatures, while flows that emerge from the wind-driving ring unobstructed can undergo rapid bulk cooling down to $10^4$ K, producing a fast hot biconical outflow enclosed by a sheath of cooler nearly comoving material without ram pressure acceleration. The hot flow is collimated along the ring axis, even in the absence of pressure confinement from a galactic disk or magnetic fields. In the early stages of expansion, the emerging wind forms a bubble-like shape reminiscent of the Milky Way’s eROSITA and Fermi bubbles and can reach velocities usually associated with active-galactic-nucleus-driven winds. We discuss the physics of the ring configuration, the conditions for radiative bulk cooling, and the implications for future X-ray observations.

Unified Astronomy Thesaurus concepts: Starburst galaxies (1570); Active galaxies (17); Hydrodynamical simulations (767); Astronomical simulations (1857); Active galactic nuclei (16); Galactic winds (572); Galaxy evolution (594); Stellar feedback (1602)

1. Introduction

Galactic winds are important to galaxy evolution. They drive gas into the circumgalactic medium, help truncate star formation, and set the mass–metallicity relation (see reviews by Veilleux et al. 2005; Zhang et al. 2018). Energy-driven galactic winds, powered by massive-star supernovae (SNe) and stellar winds, may generate the hot ($T \approx 10^6$–$10^7$ K) gas seen in diffuse X-ray emission from local starbursts (Strickland et al. 2004; Strickland & Heckman 2007). While the hot gas kinematics have not yet been directly measured, current models predict velocities of $\sim 500$–$2000$ km s$^{-1}$, depending on the mass loading of the hot phase (Chevalier & Clegg 1985; Strickland & Heckman 2009; Nguyen & Thompson 2021). In the M82 superwind, other local starbursts, and high-redshift rapidly star-forming galaxies, the cooler neutral and ionized gas is observed to be moving at velocities of order $\sim 500$–$1000$ km s$^{-1}$ (Shopbell & Bland-Hawthorn 1998; Shapiro et al. 2009). A motivating fact for this paper is that in local systems where the different thermal components can be spatially resolved, the hot and cool outflows exhibit a layered geometry, with the more cylindrical hot gas surrounded by a cooler gas “sheath” of confining medium (e.g., as seen in M82, NGC 253, NGC 3079, and others; Westmoquette et al. 2009; Leroy et al. 2015; Hodges-Kluck et al. 2020).

A critical open issue in galactic wind physics is the acceleration mechanism for the cool component. One well-known picture is that the cool phase is composed of clouds outside of the star-forming core that are ram pressure accelerated by the emergent hot supersonic wind. Simulations of this interaction often lead to the destruction of clouds by hydrodynamical instabilities (Cooper et al. 2009; Scannapieco & Brüggen 2015; Schneider et al. 2018). In some regimes of cloud parameters, the wind–cloud interaction leads to cloud growth and acceleration (Gronke & Oh 2018), although this process has not yet been shown to operate in global galactic wind simulations (Cooper et al. 2007; Tanner et al. 2016; Schneider et al. 2020). Another possible solution is that the cool phase condenses directly from the hot phase via radiative instability (Wang 1995; Tenorio-Tagle et al. 2003; Silich et al. 2004; Thompson et al. 2016). The condition for rapid cooling is set primarily by the physical size of the wind-driving region and the hot wind mass-loading rate.

Here we argue that the characteristic layered outflow geometry seen in nearby starbursts may be produced by galactic winds driven from a ring-like geometry. Rings of massive star clusters form as a result of gas inflow to the inner Lindblad resonance (Athanassoula 1992; Binney & Tremaine 2008). These rings often dominate the total star formation rate within their host galaxies (Mazzuca et al. 2008). For example, the circumnuclear ring of the archetypal nearby starburst galaxy M82 is well studied. Nakai et al. (1987) discovered a double-lobed distribution of CO, which is interpreted as a molecular torus. Hughes et al. (1994) studied thermal reradiated emission from dust in submillimeter wavelengths and found that the intensity profile can be
Figure 1. Schematic of the nuclear starburst ring model. In this model, SNe inject energy and mass into a ring geometry, leading to a steady-state flow that has an initial temperature within the ring of ~10^7 K, which accelerates to high velocity as it leaves the ring volume. For high mass loading, the wind emanating from the outer ring can become radiative and quickly cool to 10^4 K at the cooling radius, r_{cool} (see Section 3). Within the ring hole, along the minor axis, the flow shocks on itself, thermalizing its kinetic energy and maintaining high temperature. As the hot flow emerges from the inner ring region, it is collimated by the surrounding cooler flow.

modeled as an edge-on nuclear starburst torus. Weiß et al. (2001) provided a multi-transition analysis of the molecular gas and showed that the regions of most violent star formation are confined to the molecular lobes and are arranged in a toroidal topology around the nucleus. Star-forming rings are also observed in the nearby starburst NGC 253 (Arnaud et al. 1995; Leroy et al. 2018; Levy et al. 2022), other local galaxies (see Buta & Crocker 1993; Böker et al. 2008; Comerón et al. 2010; Leroy et al. 2021), and the Milky Way (see Henshaw et al. 2022). 3D ring simulations have focused on the dynamical processes associated with stellar populations and bars and are typically carried out with parameters characteristic of the Galaxy’s Central Molecular Zone (CMZ; Armillotta et al. 2019; Tress et al. 2020). Moon et al. (2021) found that individual SN shocks can merge together to create large hot outflows resembling galactic winds (see also Tenorio-Tagle et al. 2003). These works motivate a focused study of the general properties, dynamics, and morphology of energy-driven winds from star-forming rings. Here we posit the ring structure and focus on the evolution of large-scale outflows that can be produced from parameterized energy and mass injection within the ring volume. As nuclear rings are observed to substantially vary in size, ranging from diameters of tens of parsecs to several kiloparsecs (Buta & Crocker 1993; Comerón et al. 2010), we consider several different ring sizes and mass-loading rates. In addition, we consider two ring geometries: the first is an ideal azimuthally uniform ring, which is used to explore the basic structures that can be obtained from this configuration; the second is a series of uniform spheres distributed in a ring-like geometry that is meant to mimic individual super star clusters formed at the inner Lindblad resonance (Elmegreen 1994). For both sets of simulations, we find that a ring-like distribution of sources can produce an overall wind morphology akin to that seen in observations, where the hot and cool phases are layered, and where the hot flow is confined to a more cylindrical structure.

2. Model and Methods

In Figure 1 we illustrate the model problem. We assume that SNe deposit energy and mass at total rates E_T and M_T, uniformly throughout a symmetric ring with volume V (see Appendix A). The controlling parameters of the problem are the source terms, the energy and mass-loading rates, the ring width R_A, and the ring radius R_B. These quantities are shown in Table 1 and are chosen for simulations “A” and “A_0,” such that the unobstructed flow emanating from the outer ring undergoes bulk cooling.

We use the GPU-accelerated radiative hydrodynamics code Cholla (Schneider & Robertson 2015) to run a suite of simulations to study the properties of the starburst ring model. The simulations and parameters are summarized in Table 1. The simulation box is 10 \times 10 \times 15 kpc for the x \times y \times z directions, respectively. There are two high-resolution simulations, “A” and “A_0,” with 768 \times 768 \times 1152 cells in each spatial dimension, giving a cell resolution of \Delta x \approx 13 pc. These two serve as the fiducial simulations for the study. The uniform ring in simulation “A” (see Section 3.1) has a ring width of R_A = 25 pc. Simulation “A_0” (see Section 3.2) has injection regions modeled as eight identical spherical star clusters distributed in a ring. Each star cluster has a radius of
Table 1
Summary of the Simulation Parameters

| Simulation Name | Ring Type | α (pc) | β (pc) | R_A (pc) | R_0 (kpc) | Δx (pc) |
|-----------------|-----------|--------|--------|----------|-----------|---------|
| A               | uniform   | 1.0    | 0.6    | 25       | 1.0       | 13.0    |
| A_r             | nonuniform| 1.0    | 0.6    | 25       | 1.0       | 13.0    |
| B_0             | uniform   | 1.0    | 0.6    | 100      | 1.0       | 19.5    |
| B_1             | uniform   | 1.0    | 0.6    | 100      | 0.5       | 19.5    |
| B_2             | uniform   | 1.0    | 0.6    | 100      | 2.0       | 19.5    |
| B_3             | uniform   | 1.0    | 0.6    | 50       | 1.0       | 19.5    |
| B_4             | uniform   | 1.0    | 0.6    | 200      | 1.0       | 19.5    |
| B_5             | uniform   | 1.0    | 1.1    | 100      | 1.0       | 19.5    |
| B_6             | uniform   | 1.0    | 0.2    | 100      | 1.0       | 19.5    |
| C_0             | uniform   | 1.0    | 0.1    | 25       | 1.0       | 19.5    |
| C_1             | uniform   | 1.0    | 0.1    | 25       | 1.0       | 19.5    |
| C_2             | uniform   | 1.0    | 0.1    | 25       | 1.0       | 19.5    |

Note. Simulations “A,” “A_r,” and “B...” serve as the fiducial models of the study. Simulations “A_r,” “A_r,” and “B...” explore the dynamics and morphology of the steady-state wind, when the initialized gas background at t = 0 is already blown out of the simulation domain (see Appendices B and C). Simulations “B...” explore steady-state wind properties for values of the mass-loading parameter β. Simulations “C_0,” “C_1,” and “C_2” explore the early interaction between the flow and the initialized background gas, with varied background densities of \( n_{bgd} = 10^{-3}, 10^{-5}, \) and \( 10^{-7} \) cm\(^{-3}\), respectively (see Appendix D). The dimensionless parameters α and β characterize the total energy and mass injection rates, \( E_T = \alpha \times 3.1 \times 10^{41} \times (M_{SFR}/M_\odot \text{ yr}^{-1}) \) [ergs s\(^{-1}\)] and \( M_F = \beta \times M_{SFR} \), respectively, where \( M_{SFR} = 10 M_\odot \text{ yr}^{-1} \).

\( R_A = 25 \text{ pc} \). The other 10 runs, simulations “B...” and “C...” are run with \( 512 \times 512 \times 768 \) cells, giving a cell resolution of \( \Delta x \approx 19.5 \text{ pc} \). These lower-resolution simulations explore the effects of the flow when the ring geometry, mass-loading rate, or ambient circumgalactic gas density is varied. Within the starburst volume, we inject energy and mass at rates \( E_T = \alpha \times 3.1 \times 10^{41} \times (M_{SFR}/M_\odot \text{ yr}^{-1}) \) [ergs s\(^{-1}\)] and \( M_F = \beta \times M_{SFR} \), where \( \alpha, \beta, \) and \( M_{SFR} \) are the thermalization efficiency, mass-loading rate, and star formation rate, respectively. The cutoff in the mass and energy injection rates (see Equations (A1) and (A2)) at the ring edge yields a characteristic solution similar to Chevalier & Clegg (1985) and Ward (1995), such that a sonic point forms at the edge of the ring volume.

The Cholla simulations (Schneider & Robertson 2015) use a piecewise linear interface reconstruction, an HHLR Riemann solver, an unsplit Van Leer integrator, and a cooling curve that is a piecewise parabolic fit to a CLOUDY curve assuming collisional ionization equilibrium for a solar-metallicity gas (see Schneider & Robertson 2018). We approximately account for background UV heating through the implementation of a cooling floor at \( T_{floor} = 10^4 \text{ K} \). The cooling everywhere is assumed to be optically thin. Because we do not include a disk in these simulations, the wind from the ring escapes unobstructed, even along the azimuthal plane. These flows would be blocked by the gas disk (see Figure 1) in a more realistic simulation setup, which we save for future work. Simulations “A,” “A_r,” and “B...” begin with a constant static background of temperature \( T_{bkgd} = 10^7 \text{ K} \) and density \( n_{bkgd} = 10^{-5} \text{ cm}^{-3} \). Simulations “C...” also start with a static background \( 10^6 \text{ K} \); however, the background density is varied for each simulation (see Table 1). At the start of the simulation, energy and mass are instantaneously deposited into the uniform (“A”) or distributed cluster (“A_r”) ring geometry.

Simulations “A,” “A_r,” produce radiative flows. As we discuss in Section 3, the condition for bulk cooling is set primarily by the mass-loading term β and the physical width of the wind-driving region \( R_A \), as in the analogous spherical models (Thompson et al. 2016). Models with lower mass loading and/or thicker ring widths (see Appendices C and D) do not produce radiative flows, and a hot wind emerges in all directions.

3. Results

3.1. Uniform Ring

We first discuss the results for the uniform ring model from simulation “A” (see Table 1). In Figure 2, we plot three different 2D slices of the gas number density, temperature, velocity, and entropy at 20 Myr of simulation “A.” Each row displays a different 2D slice through the volume. The bottom row is a slice through the origin in the \( x-z \) plane, which is a slice through the ring plane. The middle row is a slice through the \( x-z \) plane, showing the biconical hot outflow. The top row is another 2D slice through the \( x-z \) plane, but at a height of \( z = 1.875 \text{ kpc} \). As seen in the middle row of Figure 2, the hot unimpeded flow emerging away from the ring undergoes bulk cooling, while the inner wind material shocks, producing a hot biconical flow with a flared cylinder geometry. These effects are evident in 1D skewers of the unimpeded and shocked flows, shown below. After an initial transient (discussed more and shown in Figure 5), the system quickly reaches a steady state within the first few Myr. Because the resolution is comparable to the ring width, there are grid effects.

Figure 3 shows number density, temperature, velocity, entropy, Mach number, and pressure profiles for 1D \( \xi \) (red) and \( \hat{\xi} \) (blue) skewers. The \( \hat{\xi} \) and \( \xi \) skewers pass through the origin at \( x = y = 0 \) and \( y = z = 0 \), respectively. The \( \hat{\xi} \) skewer goes along the minor axis, where the flow is collimated. For this \( \hat{\xi} \) skewer (blue line) the peaks, most notably in the top left and middle panels, correspond to the region where energy and mass are injected into the ring. Looking at the blue line in the top middle panel and starting at one of the peaks, we see that the flow begins to undergo cooling as it moves toward the origin and is then abruptly shock heated back to \( 10^7 \text{ K} \). This compresses the flow, increasing the density and pressure, while thermalizing its kinetic energy, pushing the flow back into the subsonic \( M < 1 \) regime (see bottom middle panel, \( \hat{\xi} \) skewer, blue line). The effects of radiative cooling are most apparent in the entropy profile (bottom left panel). The hot collimated flow along the minor axis (\( \xi \) skewer, red line) maintains a constant entropy. Conversely, the unobstructed flow (\( \hat{\xi} \) skewer, blue line) undergoes strong cooling with a rapid decrease in entropy as a function of distance. The distance at which the flow becomes marginally radiative is most apparent in the entropy profile (bottom left panel of Figure 3), where the entropy gradually decreases at around \( \pm 2.5 \text{ kpc} \); or about 1.75 kpc away from the ring. Near the base of the outflow, the hot collimated flow along the minor axis (red line) has shallower temperature, density, and velocity gradients than a spherical flow with the same parameters, as expected from Nguyen & Thompson (2021). The asymptotic velocities of both the collimated hot flow and the unimpeded cool flow are \( v_{kin} = \sqrt{2 E_T / M_F} \approx 992 (\alpha/\beta)^{1/2} \text{ km s}^{-1} \approx 1280 \text{ km s}^{-1} \). The temperature of the shocked gas reaches...
equivalent temperatures of the uniform wind-driving ring (see the central peaks, blue line in Figure 3). We find the central temperature of the ring hole to be identical to that derived by Chevalier & Clegg (1985) for a spherical wind-driving region (hereafter CC85). In CC85, $E_T$ and $M_T$ fill a sphere, whereas here it is the supersonic wind, which has already left the wind-driving ring, feeding into the shocked volume that supplies the energy and mass. In the center of the ring hole, the kinetic energy is thermalized, such that (see Strickland & Heckman 2009) $T_0 = T_{ring} = 0.4 E_T / M_T \mu m_p / k_B = 1.43 \times 10^7 (\alpha / \beta) K = 2.38 \times 10^7 K$, where $\mu m_p$ and $k_B$ are the average particle mass and Boltzmann constant, respectively.

The hot wind is nonspherical. We calculated transverse (with respect to the minor axis) areas for each height $z$ for simulation “A” and a functional fit to these values. We model the flow as a flared cylinder (Breitschwerdt et al. 1991; Nguyen & Thompson 2021) with $A(z) = A_0 [1 + (z/z_b)^{\Delta}]$. The flared cylinder function maintains an approximately constant area $A_0$ up until height $z_b$ when it transitions to a constant solid-angle power-law expansion ($\Delta = 2$ for spherical flow). The best fit of the flared cylinder has $A_0 = 0.54$ kpc$^2$, $z_b = 0.58$ kpc, and $\Delta = 2.14$. The term $d \ln A / dz$ describes the areal divergence rate of the flow (e.g., $A = \Omega r^2$ and $d \ln A / dr = 2 / r$ for constant $\Omega$). The flared cylinder has a slower areal divergence rate than a spherical flow for $z \lesssim 1.5$ kpc, corresponding to the flow through the cylinder of $A(z)$. However, it eventually matches closely with the spherical expansion model, implying that the flared cylinder fit approaches a constant solid angle.
expansion rate. Slower-than-spherical areal flows lead to shallower temperature and density gradients (Nguyen & Thompson 2021). The combination of the kinetic energy thermalization and cylindrical flow geometry means that the emerging flow does not become radiative along the minor axis. This is in contrast to the unobstructed flow, which becomes radiative (see entropy profiles, Figures 2 and 3). This occurs because the cooling rate is dependent on the gas temperature, and at the sustained temperatures of \( T \gtrsim 10^6 \) K, it is at least an order of magnitude less than that of the unimpeded flow when it is at \( 10^5 \) K. The inferred hot cylindrical flow geometries, described by the \( A(z) \) fit, are different for both varied mass-loading rates \( \beta \) (see Appendix C) and varied ring geometries (see Appendix B).

3.2. Nonuniform Ring

For comparison with the uniform ring in simulation “\( A_s \),” we contrast with simulation “\( A_m \),” where energy and mass are injected into eight spherical star clusters distributed in a ring-like geometry (see Table 1). Each cluster generates a wind that is identical to that predicted by the CC85 wind model, but with strong bulk radiative cooling outside of the individual cluster volume (Wang 1995; Silich et al. 2004; Thompson et al. 2016). To make a direct comparison with the uniform ring model presented in Section 3.1, we use the same total energy and mass injection rates \( E_T \) and \( M_T \), appropriate for a mass-loaded SN-driven flow and a constant star formation rate. We thus neglect the time-dependent nature of cluster evolution where massive-star wind precedes SNe, with different relative energy and mass injection rates (Silich et al. 2004; Lochhaas et al. 2018). In Figure 4, we plot three different 2D slices of the gas number density, temperature, velocity magnitude, and entropy as in Figure 2. As in simulation “\( A_m \),” after an initial transient the system reaches a quasi-steady state. The flow interaction between pairs of clusters is reminiscent of colliding winds from massive-star binary-star systems (Girard & Willson 1987; Kenny & Taylor 2005).

The nonuniform ring develops multiphase outflow with a stronger temperature contrast than the layered wind generated by the uniform ring (in contrast with Figure 2). This is due to the relative mass loading within each star cluster. The distance at which a flow becomes radiative is critically dependent on this volumetric mass-loading rate (Wang 1995; Silich et al. 2004; Thompson et al. 2016). With fixed \( E_T \) and \( M_T \), for a ring of \( N \)-star clusters, the cooling radius, centered on an individual star cluster, is \( R_{\text{cool}} = 81.5 \) pc \( (\alpha^{2.13}/\beta^{0.92}) (N/8)^{0.79} (\mu/0.6)^{2.13} (R_s/25 \) pc\( )^{1.70} \). For this simulation, we find \( R_{\text{cool}} \approx 0.36 \) kpc. As shown in Figure 4, this appears to be the case. The inner ring flow briefly undergoes rapid cooling to \( 10^4 \) K before it is shock heated back up to \( 10^7 \) K at the ring’s center. Material from the cool outflow is continuously incorporated and mixed with the hot phase at the “edges” of the cone. Intermediate warm \( (T \approx 10^5) \) temperature “spokes” are formed by the cluster spacing. The hot flow near the top and bottom of the simulation begins to approach a cool—warm temperature, as the cooling rate becomes more dominant over the advection rate. Surprisingly, the cool phase has a higher velocity than the hot phase. Because the resolution is comparable to the radius of an individual cluster, there are grid effects. Our resolution tests suggest that the qualitative features shown here are robust to changes in resolution. Details of mixing between the hot and cooler phases may be affected by spatial resolution.

In Figure 5, we plot temperature and velocity slices for five different early times, \( t = 0.5, 1.0, 1.5, 2.5, \) and 4.5 Myr, for simulation “\( A_m \).” The simulation domain at \( t = 0 \) is filled with an initial background of a warm, low-density gas \( (n = 10^{-5} \) cm\(^{-3}\) and \( T = 10^6 \) K) that gets blown out of the simulation domain within 10 Myr. During the initial blowout, the maximum speed of the material on the computational grid is \( \sim 4000 \) km s\(^{-1}\) at the leading edge of the collimated shock (see \( t = 1.0 \) Myr in Figure 5), which is approximately three times the asymptotic velocity of the flow driven from the

Figure 3. 1D \( \hat{z} \) skewer (red lines), 1D \( \hat{x} \) skewer (blue lines), and the analytic solutions to the shocked gas temperature and asymptotic velocity in orange. The \( \hat{z} \) and \( \hat{x} \) skewers pass through the origin at \( x = y = 0 \) and \( y = z = 0 \), respectively. The \( \hat{z} \) skewer goes along the minor axis, in the direction of the hot collimated wind.
individual clusters ($v \approx 1300 \text{ km s}^{-1}$) or two times the noncollimated shock front ($\sim 2000 \text{ km s}^{-1}$). These speeds occur only during the initial transient, which takes a bubble-like shape. This is not to be confused with the wind behind the bubble transient and shock front, which also appears bubble-like in the rightmost panel of Figure 5. This structure reaches its final steady-state shape within an additional Myr and will then appear like the outflows shown in Figures 2 and 4. The high-velocity bubble transient appears to be driven from the initial compression of the gas within the ring hole, before a steady-state rarefied volume develops. The subsequent dynamics is consistent with the expectations for a bubble driven with constant energy injection in a uniform-density medium (see Appendix D). Shown in the middle panels of Figure 5, the deceleration of the bubble is well described by Equation (D2), where at 1 Myr it is predicted that $v \sim 4300 \text{ km s}^{-1}$, which slows down to $v \sim 3000 \text{ km s}^{-1}$ at 2.5 Myr. The high-velocity bubble leaves the simulation domain ($z = 7.5 \text{ kpc}$) within $t \sim 5 \text{ Myr}$.

In Figure 6, we calculate the instantaneous X-ray surface brightness of the steady-state winds of simulations “A0” and “A0v” as $S_{X}^{\text{wind}}(x, y, z) = \int_{0}^{L_{\nu}} dv \int_{0}^{L_{z}} dy \ n(x, y, z)^{2} \Lambda(T(x, y, z), v)$, where $L_{\nu}$ is the length of the simulation domain. This calculation assumes no obscuration, collisional equilibrium ionization of the plasma, solar metallicity, and optically thin cooling. The energy band of the calculation is carried out in $E_{\nu} = 0.3-2 \text{ keV}$. In both models, the edge-on projected surface brightness peaks at the wind-driving rings and is bright along the collimated hot outflows.
4. Summary

In this work we study the outflows from a starburst ring. We explore parameterized models with both uniform rings and star clusters distributed as a ring (Section 3). We consider a range of different ring geometries (Appendix B), different mass-loading rates (Appendix C), and different background densities (Appendix D). In analogy with previous calculations of spherical outflows, unobstructed flows that are sufficiently mass loaded (see Figure 8 in Appendix C) and/or have a sufficiently thin ring radius $R_A$ (see Figure 7 in Appendix B) undergo rapid bulk cooling (Wang 1995; Silich et al. 2004; Thompson et al. 2016). Critically, the ring model proposed here creates a layered, multitemperature outflow (see Figures 2 and 4) in which the hot ($T \geq 10^6$ K) phase is collimated and surrounded by the cool ($T = 10^4$ K) phase. This layered morphology is qualitatively similar to that observed in nearby starbursts such as M82 (Leroy et al. 2015), NGC 253 (Bolatto et al. 2013), and NGC 3079 (Hodges-Kluck et al. 2020). This model also produces a fast ($v \geq 1000$ km s$^{-1}$) cool phase.

The Milky Way is observed to have $\gamma$-ray (Su et al. 2010) and X-ray (Predehl et al. 2020) emitting bubbles extending several kiloparsecs above and below the disk. While the origin of the bubbles is under debate, a popular model is active galactic nucleus (AGN) feedback. Yang et al. (2022) showed that a single event of jet activity from the central supermassive black hole can explain the bubbles. In Figure 5, we show that the steady-state ring-driven wind is preceded by a transient structure that exhibits a bubble-like morphology. Here we emphasize that star-forming rings may be able to reproduce the bubble morphology; however, we do not carry out a study with CMZ-like parameters and conditions for a detailed comparison. The kinematics and structure of the bubbles depend on the density of the ambient medium (see Appendix D). For background densities of $n_{\text{bgd}} = 10^{-3}$ and $10^{-5}$ cm$^{-3}$ (see Appendix D), we find that the bubbles reach velocities of $v = 3000$–10,000 km s$^{-1}$. These velocities are within the regime of AGN-driven outflows (e.g., King & Pounds 2015) and the fast outflows seen from compact post-starburst galaxies (Diamond-Stanic et al. 2012). The dynamics of the bubbles...
appears to be consistent with expectations for a bubble driven by constant energy injection (see Appendix D and Equation (D2)).

The two models highlighted in Figures 2 and 4 employ a rather large ring width of \( R_\text{A} = 25 \text{ pc} \). The radius of a typical super star cluster in M82 is much smaller, at around 5 pc (Smith et al. 2006). A limitation of our work is the spatial resolution (\( \Delta x = 13.0 \text{ pc} \)). As a result, we cannot accurately model individual realistic clusters with much smaller radii. This limitation is apparent in simulations “A” and “A,” where grid effects are present (see Figures 2 and 4). Silich et al. (2004) found that radiative outflows should be generic for super star clusters with mass and energy injection by stellar winds. We note that we do not model the time-dependent evolution of clusters, where a wind phase precedes SN energy and mass injection. To make the comparison between models “A” and “A,” clearest, we treat the properties of the energy and mass injection as constant over the short time required to establish a steady-state structure. A future study will include different evolutionary phases of each star cluster (as in Schneider et al. 2020).

Our simulations are simple parameterized models that neglect some pieces of physics in an effort to sketch the main components of winds driven by star-forming rings and to contrast with the spherical CC85 model. Probably the most important for the qualitative character of the outflow is that we neglect the gas disk that would surround any star-forming ring. The gas densities of a typical disk are several orders of magnitude larger than that of the initialized background in our simulations (see Section D) and may seed the hot and cool outflows with clumpy structures provided by the wind–ISM interaction (Cooper et al. 2007; Tanner et al. 2016; Tanner & Weaver 2022). A future work will explore simulations including both a disk and more realistic ISM and kiloparsec-scale CGM structures. Because of the large velocities obtained in these simulations, we have also neglected gravity. For models with lower thermalization efficiency and higher mass loading, the outflows will have lower velocities for which gravity may become important. We have further used a simple approximation radiative cooling and have neglected nonequilibrium ionization and irradiation effects, which is important to the ionization state of the outflow (Gray et al. 2019; Sarkar et al. 2022).

D.D.N. and T.A.T. thank the OSU Galaxy/ISM Meeting for useful discussions. D.D.N. thanks Evan Schneider for guidance with running Cholla simulations. We thank Ryan Tanner and Rebecca Levy for insightful conversations. We thank the anonymous referee for comments that have improved the manuscript. D.D.N. thanks Ohio Supercomputing Center engineer Zhi-Qiang Yuo for technical assistance. D.D.N. and T.A.T. are supported by National Science Foundation grant No. 1516967, NASA ATP 80NSSC18K0526, and NASA 21-ASTRO21-0174.

**Software:** numpy (Harris et al. 2020), scipy (Virtanen et al. 2020), Cholla (Schneider & Robertson 2015), pyatomdb (Foster & Heuer 2020), yt (Turk et al. 2011).
The physical system is specified by energy and mass injection within a ring. We choose to specify the starburst volume in a method similar to that in CC85. In the spherical CC85 model, the problem can be viewed in one dimension, namely, the region of energy and mass injection is satisfied by the bounds \( r \leq R \), where \( R \) is the radius of the wind-driving sphere (Chevalier & Clegg 1985). The ring requires additional variables. The controlling parameters of the ring system are the distance from the origin to the center of the ring, \( R_B \), and the radius of the ring, \( R_A \). For a given \( R_A \) and \( R_B \), we determine the minimum and maximum radii, \( R_{\min}(\Gamma) \) and \( R_{\max}(\Gamma) \), which bisect outer and inner ring surfaces, respectively. For specific line-of-sight angle, \( \Gamma \), the line-of-sight chord endpoints, which skewer the ring surface twice, are derived to be:

\[
R_{\min} = R_B \cos(\Gamma) - (R_A^2 - R_B^2/2 + R_B^2 \cos(2\Gamma)/2)^{1/2}
\]

and

\[
R_{\max} = R_B \cos(\Gamma) + (R_A^2 - R_B^2/2 + R_B^2 \cos(2\Gamma)/2)^{1/2}.
\]

The bounds, in spherical coordinates, corresponding to the ring volume are derived to be:

\[
R_{\min} = R_B \cos(\Gamma) - (R_A^2 - R_B^2/2 + R_B^2 \cos(2\Gamma)/2)^{1/2},
\]

\[
R_{\max} = R_B \cos(\Gamma) + (R_A^2 - R_B^2/2 + R_B^2 \cos(2\Gamma)/2)^{1/2}.
\]

The uniform volumetric energy and mass injection rates are then:

\[
q(r, \theta) = \begin{cases} \frac{M_{\text{hot}}}{V}, & R_{\min} \leq r \leq R_{\max} \\ 0, & R_{\max} < r \text{ or } r < R_{\min} \end{cases}
\]

(A1)

\[
Q(r, \theta) = \begin{cases} \frac{E_{\text{hot}}}{V}, & R_{\min} \leq r \leq R_{\max} \\ 0, & R_{\max} < r \text{ or } r < R_{\min} \end{cases},
\]

(A2)

where the normalizations for \( E_T \) and \( M_T \) are described in Section 2, and \( V \) is the volume of the starburst ring:

\[
V = 2\pi^2 R_A^2 R_B.
\]

### Appendix B

**Varied Ring Geometries**

**B.1. Varied Uniform Ring Geometries**

In Figure 7, we show 2D temperature slices for simulations “B0,” “B2,” “B3,” and “B4” (see Table 1). As we would expect, changing the ring hole radius \( R_B \) affects the width of the cylindrical hot outflow. Smaller \( R_A \) values lead to a smaller cooling radius, and thus a more prominent temperature contrast between the unobstructed wind and the hot thermalized wind along the minor axis. Simulation “B1” (not plotted) similarly produces an expected morphology. The most radiative model, simulation “B3,” produces an hourglass-like morphology.

**Figure 7.** 2D temperature slices of simulations “B0,” “B2,” “B3,” and “B4.” We see that the different ring geometries produce different outflow morphologies despite equivalent energy and mass injection rates \( \alpha \) and \( \beta \).
Appendix C

Varied Mass-loading Rates

In Figure 8, we show 2D density, temperature, velocity, and Mach number slices of simulations “B5,” “B0,” and “B6.” As detailed in Table 1, these simulations have varied the SN mass-loading rates described by \( \beta = 1.1, 0.6, \) and 0.2, respectively. The ring geometry produces the layered wind morphology with a temperature contrast dependent on the mass loading. Higher mass loading leads to a stronger contrast. The nonradiative ring wind models quickly approach a steady state. The highly mass-loaded wind model approaches a quasi-steady state, with small thermal instability filaments forming within the bicone. As shown in Figure 8, different mass loading leads to different

**Figure 8.** 2D slices of density, temperature, velocity, and Mach number at 40 Myr for varied energy thermalization efficiencies within the starburst ring: \( \beta = 1.1, 0.6, \) and 0.2 (simulations “B5,” “B0,” and “B6” respectively, see Table 1). All models have the same ring geometry of \( R_A = 0.025 \) kpc and \( R_C = 1.0 \) kpc.
outflow morphologies. We fit the flared cylinder function $A(z) = A_0 [1 + (z/z_0)^2]^{3/2}$ to the simulations. For $\beta = 1.1$, we find $A_0 = 0.56 \text{kpc}^2$, $z_0 = 0.51 \text{kpc}$, and $\Delta = 1.8$. For both $\beta = 0.2$ and $\beta = 0.6$, we find $A_0 = 0.85 \text{kpc}^2$, $z_0 = 0.75 \text{kpc}$, and $\Delta = 2.3$. We find that the highest mass-loaded model $\beta = 1.1$ produces the narrowest cylindrical hot outflow along the ring axis. Both $\beta = 0.2$ and $\beta = 0.6$ produce equivalently sized hot cylindrical outflows. Highly radiative models appear to produce narrower collimated hot outflows than nonradiative models.

**Appendix D**

**Varied Initialized Ambient Backgrounds**

Here we vary the initialized background gas density to probe the initial interaction between the flow and ambient background during the transient phase, before the steady-state wind is established, to understand how fast velocities at the leading edge of the initial interaction between the narrowest cylindrical hot outflows than nonradiative models.

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Dustin D. Nguyen © https://orcid.org/0000-0002-1875-6522

Todd A. Thompson © https://orcid.org/0000-0003-2377-9574