Outflows from the Magellanic Clouds: MHD Simulations and Multi-Wavelength Synthetic Observations

Proposed Research Summary

Feedback from galaxies – i.e. the process by which galaxies regulate their star formation by consuming or expelling gas – is of fundamental importance in galaxy formation and evolution. This is nowhere more apparent than in dwarf galaxies, which generally exhibit suppressed star formation relative to larger, Milky Way sized galaxies. A combination of environmental processes, such as ram pressure stripping due to the galaxy's motion through its ambient medium, and large-scale, supernova-driven outflows are generally to blame for the expulsion of gas into the intergalactic medium – away from sites of star formation. For this research allocation, we propose to use the Stampede2 supercomputer to run global galaxy simulations of thermally and cosmic ray driven outflows from dwarf galaxies. Using the FLASH magnetohydrodynamics (MHD) code coupled with a novel implementation of cosmic ray transport, we will explore the plausibility of supernova-driven outflow launching from the Large and Small Magellanic Clouds (the LMC and SMC), two dwarf satellite galaxies of the Milky Way exhibiting observational evidence for such outflows. This builds off previous simulations run on the Stampede2 supercomputer through an XSEDE startup allocation (TG-AST170033; PI: Chad Bustard, Co-PI: Ellen Zweibel), in which we modeled the interaction of ram pressure stripping and outflows from the LMC ([1], hereafter B2018). Having now implemented additional physical processes into our simulations, we will undertake a study of outflows from the LMC and SMC, with and without ram pressure, varying key parameters such as method of cosmic ray transport, initial magnetic field strength, and level of supernova clustering. We will then create synthetic observations using extensively tested visualization toolkits, allowing us to directly compare our simulations to both a dwarf galaxy's outflows and its well-studied, resolved structures that drive such flows.

The main scientific objectives and goals of this study include:

- Examining the impact of cosmic ray transport on outflow launching and probing observational signatures, such as the over or under-abundance of certain ions relative to simulations with different cosmic ray transport mechanisms or without cosmic rays at all. We expect that the inclusion of cosmic rays and cosmic ray transport will alter abundances compared to purely thermally driven outflows, specifically making the outflows colder and smoother, which is seen in cosmic ray driven outflow simulations of various scales. Our work will test these results against observations of the well-studied Clouds, providing further insights on the observational signatures of cosmic ray vs thermally driven winds.

- Studying the magnetization of the intergalactic medium due to magnetic fields flux-frozen to stripped and outflowing gas. In B2018, we explored the effects of local upliftings of gas from the LMC due to supernovae, and we found that even fairly weak outflows can be swept away from the LMC by ram pressure. Magnetization of this material will change the dynamics of this process and may stretch, twist, and amplify the magnetic field in filaments trailing behind the galaxy. This may be at play in a number of systems from dwarf galaxies falling into a host galaxy or larger, so-called jellyfish galaxies wading through their ambient intracluster medium and producing extravagant tails similar to jellyfish tentacles.

- Furthering our understanding of the Magellanic System. In addition to other compelling features, this System consists of the Magellanic Clouds and the Trailing Stream, a massive tail of gas extending possibly 100 kiloparsecs behind the Clouds and formed by a combination of tidal stripping, ram pressure stripping, and outflows. Our results will shed light on the plausibility of outflows from the Clouds, their composition, and their mass budget in the Trailing Stream. This work will help other simulators define what processes are most important in the evolution of the Clouds and will add to our current knowledge of the System's various features. In turn, this will enable the community to more accurately use the Magellanic System to comment on galaxy formation in a broader context.

This project is closely connected to the PI's NSF Grant AST 161-6037, "The Basis and Behavior of Cosmic Ray Feedback". Under the auspices of this grant, the PI and collaborators have studied the plasma physics of cosmic ray propagation and confinement, developed general prescriptions for describing these processes through fluid equations, and using the fluid model to develop an integrated picture for how cosmic rays impact the structure and evolution of galaxies. The simulations of the LMC and SMC described in this project offer an ideal opportunity to test the theory in well observed objects. The Co-PI, Professor Elena D'Onghia, has expertise in galaxy dynamics and the Magellanic Stream, and her insights will ensure this project has its greatest possible impact on the community.

This work will also serve as an educational tool for a graduate student, Chad Bustard, who will perform the majority of simulations. Through his NSF Graduate Research Fellowship, Chad has served as the PI on our recently renewed startup allocation on Stampede2, entitled "Thermal and Cosmic Ray Driven Galactic Winds in Disk Galaxies" (TG-AST170033), and he is experienced with the FLASH code we will use for this work. This project will cement his knowledge of high performance computing and proper resource management, and it will be his major research focus before defending his thesis in summer 2020.

Scientific Motivation

How gas flows in and out of galaxies is an important and open question in galaxy formation and evolution, and the Magellanic System contains the full bag of processes that lead to such flows. While falling into the Milky Way halo, the Clouds orbit around each other, triggering bursts of star formation and also tearing each other apart as their gravitational forces loosen and strip material. Combined with the constant headwind they experience during their infall, their galactic dance flings gas behind the Clouds, contributing to the Trailing Magellanic Stream. This massive gaseous tail extending many tens of kiloparsecs behind the Clouds may someday fall onto the Milky Way disk and enhance our Galactic ecosystem by providing more fuel to form stars. Fortunately, because of our birds-eye view, the Magellanic System gives us an incredible window into how galaxies expel and feed on gas; both the large-scale gas cycles in and between galaxies, as well as the small-scale, internal processes that drive gas flows.

Our simulations focus on two contributors to this gas cycle: ram pressure (RP) stripping, whereby motion through an ambient medium strips material from galaxies, and galactic outflows (or winds). Large-scale supernova-driven winds from galaxies are prevalent throughout the Universe and can greatly impact galaxy evolution by quenching star formation and redistributing metals from the inner galaxy to the circumgalactic medium, for instance. The composition of these outflows and the physical processes that drive them, however, are not well understood, and there are large

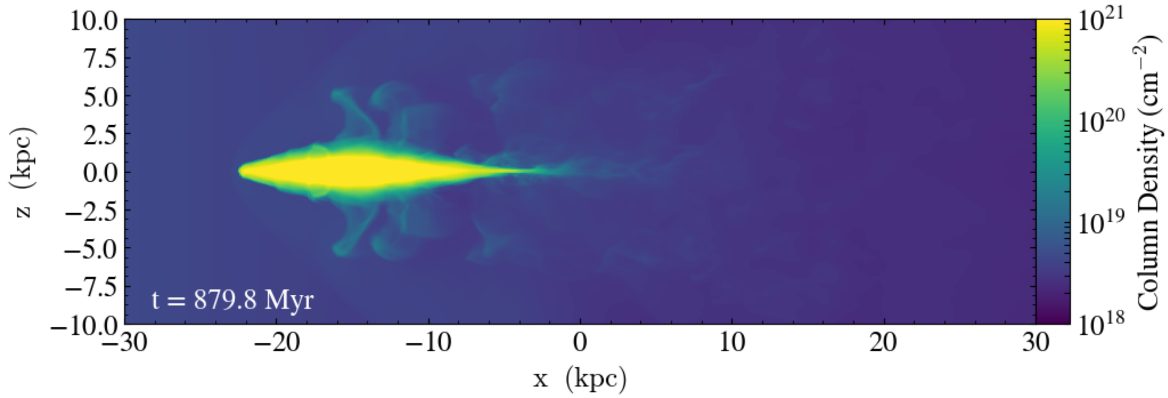

Figure 1: Edge-on view of multiple outflows expelled from the LMC disk and swept downstream by ram pressure. $t = 0$ is the start of the simulation, while $t = 1$ Gyr is present-day.

discrepancies between observations and theory. This work proposes to close that gap by using the well-studied Clouds as a test-bed for feedback.

With recent observational evidence of galactic winds from the Clouds, we can, for the first time, connect the wealth of data we have on the Clouds to their outflows. In the LMC, Barger et al. 2016 [2] estimate a current mass-loss rate of $0.4M_{\odot}/yr$ from outflows with velocities ≈ 100 km/s. Through observations, we have a sense of the magnetic field strength and orientation in the LMC [3], diffuse gamma ray emission that estimates the cosmic ray population injected from supernovae, neutral and ionized hydrogen maps of the Clouds and Trailing Stream [4], as well as positions of current-day star clusters, HI holes, and X-ray emitting shells [5, 6, 7].

Likewise, new high-resolution observations of the SMC provide us a crucial, second mode of comparison for our simulations. While our inputs may result in outflows matching certain aspects quite well for the LMC, they may not reproduce the SMC outflows. McClure-Griffiths et al. 2018 [8] estimate that the total mass flux in neutral hydrogen emanating from the SMC is $\approx 0.2 - 1.0M_{\odot}/yr$, and more may be visible primarily in more ionized gas as it lifts further above the disk. Morphological similarities between this gas and supergiant shells in the SMC, combined with an association between the gas location and hotter, breaking shells visible as ionized hydrogen, strongly suggest that this material is outflowing instead of infalling, resulting from a recent burst of star formation within the last 25 - 60 Myrs. Combined with the RP the SMC is experiencing, much of this gas will likely end up in the Trailing Stream. With our models, we can test the hypotheses outlined in [8] for a recent burst, extend that using the star formation history for the past Gyr, and compare to our LMC outcomes.

While we acknowledge that star formation and feedback in galaxies is an extremely multi-scale problem, and matching all of these observables of the Clouds is currently impossible, this data gives us a sense of what our inputs should be. Combined with information about the outflows that manifest from these inputs, we can test what works and does not work to drive the observed flows.

Past Results

In B2018, we used published simulations of supernova-driven outflows from the Clouds and compared them to observations of the Trailing Stream. We set up a wind-tunnel like simulation to follow the LMCs motion as it falls into the Milky Way halo, and we found that, in this environment, even small fountain outflows that would otherwise fall back on the LMC disk will be expelled by RP (see Fig. 1). This gas then trails behind the LMC, forming a filament that matches qualitatively well with an observed filament of gas that is offset in abundance and velocity from the rest of the Magellanic Stream (which is primarily formed by tidal stripping between the Clouds [9, 10]). This corroborates past suggestions that this filament could be formed by a series of outflows [11], and, as we expect for our proposed simulations too, it provides useful commentary on galaxy formation more broadly. Interestingly, the LMCs significantly star-forming regions near the leading edge of the galaxy may be partially generated by compression due to RP [12] or condensation of halo gas due to RP, as seen in some cosmological simulations [13]. Our results, then, suggest that RP may have a dual ability to both trigger star formation and also sweep away supernova-launched gas resulting initially from that star formation. This interplay between RP and outflows may be important in a number of systems, including dwarf galaxies orbiting in the halos of larger host galaxies and so-called jellyfish galaxies [14] being RP stripped by their surrounding intracluster medium.

New Simulation Components

To achieve our scientific goals listed in the Proposed Research Summary section, we have extended our model to include additional components of the interstellar medium, i.e. magnetic fields and cosmic rays, which were previously neglected in our B2018 model. We have also made a concerted effort to bring our implementations of the gas equation of state and radiative cooling closer to reality. This greatly improves our ability to compare simulation output to observations, and our request for additional computer resources is driven by these improvements. The main additions since B2018, in more detail, are:

Cosmic ray wind driving. Cosmic rays, the most energetic, non-thermal particles in the universe, have been shown in previous simulations to be extremely effective in driving winds [15, 16, 17]. The detailed microphysics of cosmic rays are hard to capture in large-scale simulations, however, because they are extremely sub-grid. With reasonable assumptions and the quasilinear theory oft-invoked in plasma physics, though, one can derive a fluid approximation to a kinetic-scale instability, referred to as the cosmic ray streaming instability, that dominates the motion (or transport) of the bulk cosmic ray population [18, 19]. The resulting streaming picture differs from a standard diffusion process [20] more easily implemented in hydrodynamic solvers, and it requires one of a few novel methods to properly capture streaming in a fluid simulation (see the Scaling and Performance document for more information). The FLASH cosmic ray module we employ has been used in numerous galaxy-scale simulations [21, 22] as well as in recent localized simulations of a stratified ISM made unstable by cosmic ray streaming (Heintz, Bustard, and Zweibel, in prep). Using this module to probe the viability and observational signatures of outflows from the Clouds and other dwarf galaxies will greatly improve our understanding of such objects.

An improved implementation of supernova energy deposition, which is the main driver of outflows in galaxies. Our newly implemented method, based on the results of small patch simulations of supernovae in inhomogeneous media [23], includes both the thermal energy injection near the supernova and kinetic energy injection that still persists at large radii after the expanding supernova remnant shell has radiated away most of its thermal energy. This method is resolution-dependent and tunes the amount of thermal or kinetic energy injection into affected cells to give consistent results regardless of resolution. To carry out this energy injection, we use active particles in FLASH to represent clusters of stars that evolve and explode over a given time period, depositing energy and momentum to the surrounding cells according to the fitting functions of [23] and the star cluster implementation of [24].

Implementation of photoionization equilibrium cooling instead of collisional ionization equilibrium cooling. Photoionization from the extragalactic UV background can significantly alter radiative cooling, especially for low density gas, and there is growing evidence that the cold phase of many observed outflows are altered by photoionization. For example, [25] use O I, Si II, Si III, and Si IV ultraviolet absorption lines to probe different ionization states of outflowing gas, and they find that photoionization models give the best fits to the line equivalent widths.

With these new additions at-hand, we will first run simulations of the LMC as a follow-up to B2018, but we will also broaden our scope to include the SMC. We are specifically excited to create mock observations of these simulations using the yt, Trident, and astropy packages. Combined with our implementation of photoionization, we can use these packages to self-consistently create theoretical absorption lines and ion column density maps.

Preliminary Results

In Figure 2, we show preliminary, low-resolution results after 250 Myrs of the LMC with cosmic ray streaming included. These mock observations were made using the yt and Trident software packages and demonstrate our ability to directly compare simulations to observations. On the left is neutral hydrogen (H I) and the right is ionized hydrogen (H II). The H I image shows some of the holes and shells similar to what we see in real observations of the LMC, while the H II image also shows a finer haze predominantly due to outflows. These outflows were launched from observationally determined star formation sites, for which we know the star formation rates at over 1300 coordinates at ten time snapshots over the past billion years [26, 27]. Similar data is available for the SMC, as well. In between these coarse time snapshots, we randomly draw cluster masses from a probability distribution function, which we can vary, and populate each coordinate with star clusters such that the total mass formed as stars matches the total mass given by [26, 27] during that time interval. We leave the number of star forming events as a free parameter; fewer events necessitate either larger mass particles or more particles per event (supernovae that are more clustered), while more frequent events necessitate lower mass particles. This allows us to probe the effects of supernova clustering on outflow generation.

Computational Methods

Our computational tool of choice is the FLASH v4.2 MHD code [28]. Within this framework, we use the directionally unsplit staggered mesh solver [29], which is based on a finite-volume, high-order Godunov scheme and which employs a constrained transport (CT) scheme to enforce the divergence free magnetic field condition. We use an additional cosmic ray module [21, 22] that evolves cosmic rays as a second, relativistic fluid in addition to the usual thermal gas. In the absence of cosmic ray diffusion or streaming, the presence of cosmic rays adds another pressure term and affects the sound speed of the now hybrid cosmic ray - gas fluid. This effective sound speed is used when solving the Riemann problem as well as for determining the hydrodynamic timestep. This implementation is presented in [21] and tested extensively.

In addition, cosmic ray streaming at the Alfven speed is included according to the regularization method of [30]. This streaming results in an advection term for the cosmic ray flux and an associated heating term for the thermal gas (see Scaling and Performance document for more information).

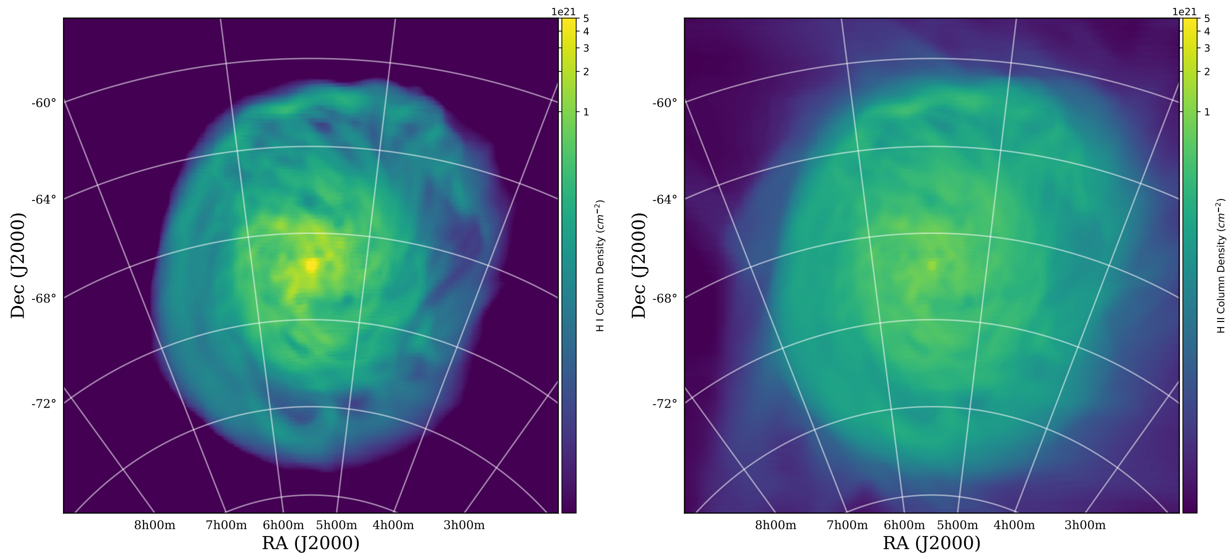

Figure 2: Line-of-sight mock observation of the LMC after 250 Myrs. Left: neutral hydrogen (H I); right: ionized hydrogen (H II). H I holes and shells show similarities to those in the real LMC disk, while the additional haze in the H II image is due to hotter, outflowing gas above the disk.

Putting together the usual ideal MHD equations with the additional influence of cosmic rays, our simulations solve the following equations [19, 22]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u_g}) = 0 \tag{1}$$

$$\frac{\partial \rho \mathbf{u_g}}{\partial t} + \nabla \cdot (\rho \mathbf{u_g} \mathbf{u_g} - \frac{\mathbf{B}\mathbf{B}}{4\pi}) = \rho \mathbf{g} + \dot{p}_{SN} \tag{2}$$

$$\frac{\partial B}{\partial t} - \nabla \times (\mathbf{u_g} \times \mathbf{B}) = 0 \tag{3}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[(e + p_{tot}) \mathbf{u_g} - \frac{\mathbf{B}(\mathbf{B} \cdot \mathbf{u_g})}{4\pi} \right] = \rho \mathbf{u_g} \cdot \mathbf{g} - \nabla \cdot \mathbf{F_c} - C + H_c + H_{SN} \tag{4}$$

$$\frac{\partial e_c}{\partial t} + \nabla \cdot (e_c \mathbf{u_g}) = -p_c \nabla \cdot \mathbf{u_g} - H_c + H_{SN} - \nabla \cdot \mathbf{F_c} \tag{5}$$

where ρ is the gas density, $\mathbf{u_g}$ is the gas velocity, $\mathbf{B}$ is the magnetic field, $p_{tot} = (\gamma_g - 1)e_g + (\gamma_c - 1)e_c + \mathbf{B}^2/8\pi$ is the total pressure, and $e = 0.5\rho \mathbf{u_g}^2 + e_g + e_c + \mathbf{B}^2/8\pi$ is the total energy density: the sum of kinetic energy density, gas energy density (e_g), cosmic ray energy density (e_c), and magnetic energy density. Note that the cosmic ray adiabatic index, $\gamma_c = 4/3$, while the gas adiabatic index, $\gamma_g = 5/3$. The following terms are due to cosmic ray streaming: $\mathbf{F_c}$ is the cosmic ray flux due to streaming; H_c is the heating of the gas due to damping of waves generated by the streaming instability. It's crucial to note that these streaming terms depend on the Alfven speed, $V_A = B/\sqrt{4\pi\rho}$, so the magnetic field initial condition is an important parameter space to explore. $\dot{p}_{SN}$ and H_{SN} encode the momentum and heating from supernovae. Cosmic ray diffusion can also contribute to the flux, and we plan to test the effects of diffusion vs streaming with low-resolution simulations in the coming months.

Resource Usage Plan

Here we describe the proposed simulations that will address our research objectives. To briefly summarize our simulation setup, we generally follow [31], which defines the initial gas density as

$$\rho(R, z) = \frac{\mathrm{M_{gas}}}{2\pi \mathrm{a_{gas}^2 b_{gas}}} 0.5^2 \mathrm{sech}\Big(\frac{\mathrm{R}}{\mathrm{a_{gas}}}\Big) \mathrm{sech}\Big(\frac{|\mathrm{z}|}{\mathrm{b_{gas}}}\Big) \tag{6}$$

where a_{gas} and b_{gas} are the radial scale length and vertical scale height of the disk, and $M_{\mathrm{gas}} = 5 \times 10^8 \mathrm{M}_\odot$ for the LMC. This density is further cutoff at a radius R_{cut}, which we choose to be 10 kpc. This initial gas distribution matches well with the observed neutral hydrogen column as a function of radius and satisfies observational constraints on the total LMC mass. This density distribution is then put in vertical equilibrium with fixed stellar and dark matter gravitational potentials and spun in the azimuthal direction such that the centrifugal force balances the remaining radial gravitational force. The setup will be the same for SMC simulations; however, the gas mass and scale lengths differ and will follow the guidance of [31] as we did for the LMC in order to best compare to their RP stripping results.

The magnetic field is initially toroidal and follows the form of [32], in which the magnetic field peaks a few kpc from the galaxy center, falls off radially and vertically, and is purposely weak in the center to avoid magnetic field amplification due to the rapidly changing velocity field in that region. Following from [3], this peak magnetic field strength is a few μG within the galaxy (we will vary this exact value between 1 and 5 μG), and we choose the halo magnetic field strength to be a negligible 10^{-15} G. In future simulations we may include a larger halo field.

For simulations with RP, we sit in the frame of the LMC as it falls into the Milky Way halo; RP is modeled as a wind-tunnel boundary condition, and it varies in direction and magnitude according to simulated orbit and inclination angle of the LMC over the last Gyr.

LMC Simulations Without Ram Pressure

We first plan to address, at moderate resolution, how sensitive our results are to our main assumptions. The main free parameters we identify are 1) supernova "clustering", i.e. how the resulting outflows change if many small star cluster particles formed and exploded or if, instead, a few large clusters formed and exploded; 2) Magnetic field strength, which is crucial for assessing the role of cosmic ray streaming; 3) Minimum density for star formation, which sets the environment in which supernovae explode; 4) a temperature ceiling for feedback, which is necessary at moderate and high resolution for which most energy is deposited as thermal energy; 5) maximum star cluster mass draw from a probability distribution function, which we fiducially set to $10^5 M_\odot$, but we would like to try one lower value. Although we have a sense of these key parameters from observations, by testing a few values, we gain insight into their roles in shaping the simulated interstellar medium and in driving outflows. Depending on our results, this analysis alone could reasonably constitute the majority of a paper; therefore, we plan to test these assumptions at our target publication resolution of 39.5 pc. To do this, we will run our LMC setup without RP on a $(40\mathrm{kpc})^3$ domain with $(128)^3$ cells and 3 additional levels of adaptive mesh refinement. By varying each of our 5 parameters once, we plan to run 5 simulations at this resolution, each without cosmic rays.

After comparing to observations, we will settle on a fiducial simulation and add cosmic rays. One of these will have cosmic rays without streaming, and two will have cosmic rays with streaming (for two different peak magnetic field strengths of 1 and 5 μ G). These simulations will be sufficient to address the role of cosmic rays in driving outflows from the LMC, as well as their observational signatures when we make synthetic observations. We also plan to run one simulation with a maximum 4 levels of refinement (resolution of 19.75 pc) for our resolution study, which will not use cosmic ray streaming. This simulation will be critical to assess convergence, both in terms of the resulting outflow topology and also its multiphase structure. We expect the temperature and density of the outflow to depend partially on resolution because the active particle feedback prescription decides how much thermal or kinetic energy to inject based on resolution of the neighboring cells. A purely thermal instead of purely kinetic energy deposition could lead to different phases, even kpcs above the disk. This, in turn, affects the cooling rate and our mock observations. Because this simulation is very computationally expensive (we estimate $\approx 60,000$ SUs if we run for a full Gyr), we plan to only run this simulation for 250 Myrs. This should be sufficient to establish convergence.

LMC Simulations With Ram Pressure

With RP, we will increase our box size to $(60\text{kpc})^3$ with a base grid of $(192)^3$ cells and an additional 3 AMR levels. We will run 5 total simulations at this resolution: one without any active particles or feedback, one with feedback but without cosmic rays, one with cosmic rays but no streaming, and two with streaming (again using two different magnetic field strengths). Using two different magnetic field strengths is important not only because the streaming speed and gas heating depend on the magnetic field strength but also because we expect the magnetic field to play a large role in suppressing mixing between the expelled filament and the background halo gas. Overall, these RP simulations will address many of the main goals of our study, including magnetization of the surrounding medium, the energy budget of cosmic rays ejected from the galaxy and into the surrounding medium, and how the composition of thermal and non-thermal particles affects observational signatures of this expelled gas. This will also directly further our understanding of the Trailing Stream.

SMC Simulations

To further test our outflow model, we can easily extend this work to the SMC by loading in the star formation history of the SMC, transforming from the LMC to the SMC frame to model the RP headwind, and modifying our initial galaxy density, gravity, etc. We plan to run a total of 4 SMC simulations on Stampede2 with lower resolution tests done on our local cluster. The Stampede2 simulations will use the same $(60\text{kpc})^3$ box with RP included with a base grid of $(192)^3$ cells and an additional 3 AMR levels. Two simulations, one with and one without RP, will include feedback without cosmic rays while the other two simulations will include cosmic rays with streaming. This will probe the viability of galactic wind driving and filament formation from the SMC, for which there is new observational evidence [8], and will provide a crucial second test for our feedback model.

Justification And Appropriateness Of Resources

Here, we take the computational experiments described in the Resource Usage Plan and calculate, based on our timing tests, how that translates to SUs for each simulation. In total, we estimate that our main proposed simulations will require 187,750 SUs on Stampede2 and 5.5 TB of storage on Ranch. Adding in lower resolution test simulations and a small amount of node-hours for data visualization, **we request 200,000 SUs on Stampede2 and 6 TB of storage on Ranch**.

To estimate the time taken for each of our runs, we need to estimate the number of blocks and, hence, the work load of our simulations. We can do this using eqn. 7 of the Scaling and Performance document, for which we need to estimate the covering fraction of gas above our threshold density. We know that the Clouds are likely losing no more than $10^8 M_\odot$ of gas through the combined outflow and stripping process, based on our past B2018 simulations of RP stripping and the observationally determined outflow rates from Cloud winds. Since our simulations will be purposely tailored not to exceed such large outflow rates, we can estimate the number of blocks that need to be refined by assuming the entire $10^8 M_\odot$ is spread out at the threshold density for refinement. We calculate that no more than 42 additional base-level blocks will be refined to k levels, corresponding to a volume of $(8.7\text{kpc})^3$ gas at the 10^{-26}g/cm^3 threshold density. At $k = 2$, this results in an additional 4688 blocks, while for $k = 3$ and $k = 4$, it is 21504 and 172032 blocks, respectively. Adding this to the initial number of blocks for each AMR level, **the total number of blocks expected for the $(40\text{kpc})^3$ box runs are 17488, 69056, and 415232 for AMR levels of 2, 3, and 4, respectively. For the $(60\text{kpc})^3$ box runs, the estimated number of blocks are are 27216, 78848 for AMR levels of 2 and 3, respectively.** We will use these block numbers combined with eqns. 3-6 of our Scaling and Performance document to estimate the run-time for each proposed simulation.

To get the total number of steps per simulation, we must estimate the timestep. For our target resolution of 39.5 pc, the stable streaming timestep from eqn. 2 of the Scaling and Performance document would be 1.44×10^{10} s using a cosmic ray pressure scale length of $L = 10$ kpc, as in Ruszkowski et al. 2017; however, we find that a scale length of 5 kpc gives sufficiently converged results in our low resolution tests. This would make our streaming timestep, which is almost always the most restrictive timestep in our simulation, $\approx 3 \times 10^{10}$ s, at worst. In low-resolution test simulations, we find a maximum Alfven speed of 470 km/s at one of ten snapshots within the first 100 Myrs, but at the other snapshots, the Alfven speed peaks around 250 km/s. To run for a full Gyr, then, would require a maximum of $\approx 1,000,000$ steps, with a more likely estimate being $500,000 - 750,000$ steps. Using eqn. 4 from the Scaling and Performance document, with a timestep of 5×10^{10} seconds, an efficiency of 80%, 1024 cpus, and 69000 blocks (for AMR level of 3), we estimate a standard unit requirement of $\approx 16,500$ SUs. For the analogous simulation with RP stripping on the larger domain, we estimate $18,750$ SUs.

For simulations without streaming, the hydrodynamic timestep determines our simulation run-time. We utilize FLASH's hybridorder option, which adaptively varies the reconstruction order scheme depending on monotonicity constraints; this consequently decreases the CFL number (from a fiducial CFL number of 0.6) down to 0.25 when needed. For a fastest propagation speed of 2600 km/s (the sound speed for a 5×10^8 K gas) and a grid spacing of 39.5 pc, this corresponds to a time step of $\approx 1.2 \times 10^{11}$ seconds. For an AMR level of 3 without streaming, we calculate this node-hour requirement to be ≈ 5000 SUs. For an AMR level of 3 *with* RP, and without streaming, this is ≈ 7600 SUs per run, so we budget for 8000 SUs per run.

As we expect to output ≈ 200 plot files per simulation and 3 checkpoint files that will be overwritten during the run, each simulation at 3 AMR levels will require ≈ 300 GB, since each plot file will be between 1.3-2 GB in size. In total, this corresponds to 17*300 GB, which is 5.1 TB of storage space. Accounting for a few extra plot files for our resolution study run, we expect to need ≈ 6 TB of storage space on Ranch.

Appropriateness Of Resources

Here we describe our code optimizations, memory considerations, and architecture choice to execute our research plan. Stampede2, specifically the Skylake nodes that have a larger 192 GB RAM than

Type	Simulation Number and Details	SUs (x 1000)
LMC *without* RP	5 without CRs: **3 AMR levels**	25
	1 without CRs: **4 AMR levels (res. study)**	15 (250 Myrs)
	1 with CRs, no streaming: **3 AMR levels**	5
	2 with CRs, streaming (vary B field): **3 AMR levels**	33
LMC *with* RP	1 without feedback: **3 AMR levels**	8
	1 without CRs: **3 AMR levels**	8
	1 with CRs, no streaming: **3 AMR levels**	8
	2 with CRs, streaming (vary B field): **3 AMR levels**	37.5
SMC *without* RP	1 without CRs: **3 AMR levels**	5
	1 with CRs, streaming: **3 AMR levels**	16.5
SMC *with* RP	1 without CRs: **3 AMR levels**	8
	1 with CRs, streaming: **3 AMR levels**	18.75
Total	**18 simulations**	**187.75**

Table 1: Outline of our planned simulation runs, separated by type, and with estimated SUs.

the 96 GB RAM on the Knights Landing nodes, is our preferred machine to get the most efficient use per SU. This choice is driven by the fairly memory-intensive nature of our simulations, which can be varied within reason by changing the maximum number of blocks (defined as 8^3 cells) per processor. We have experimented with this MAXBLOCKS array parameter and find that setting it to 400 gives a good trade-off between the minimum number of cores required to run a given simulation and the memory per processor, which depends on the number of stored variables and number of blocks per processor. For our LMC simulations with MAXBLOCKS = 400, this translates to ≈ 3.5 GB per processor, which fits within the 192 GB RAM per node on the Stampede2 Skylake nodes if we use under ≈ 54 processors per node. In past simulations run on Stampede2, we encountered MPI deadlock errors during refinement/derefinement steps. We (and other FLASH users) were able to alleviate these issues by reducing the MAXBLOCKS value, hence the memory per processor. Therefore, we choose in our scaling studies and for our proposed simulations to use 32 processors per node (instead of the maximum 54 that we estimate could fit within the 192 GB RAM) in order to safely avoid these issues.

As outlined in our Scaling and Performance document, we find that FLASH scales very well on Stampede2 up to 1024 cores, which is the largest number of cores we tested, with strong scaling efficiencies above 80%. Weak scaling, i.e. how FLASH scales if we increase the workload and the number of processors by the same factor, is generally very good, as well.

Other Supercomputing Support

We have modest supercomputing support provided by our local HPC cluster at UW-Madison. Specifically the Astronomy Department has an exclusive partition on this cluster comprised of 320 cores. As this is shared for the entire department, it is frequently over-subscribed, and we are limited to using this cluster for low-resolution simulations, scaling studies, and code development. Higher resolution simulations easily exceed the capacity of these local resources in processor availability and even more so in data storage. This local cluster, however, will be our main tool for code development and testing.

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