1 PROJECT PLANS FOR NEXT YEAR

1.1 Summarize the Project Plan

- Advances through the next award period, associate with the goals of the project.
- Relation between research Milestones, production simulations, and simulation time required.
- Do resource requirements change, and why?

By the end of Year 1, we will have accomplished the first two of our three research objectives: simulating galactic outflows with supersonic velocities, and quantifying the importance of radiative cooling for the multiphase structure seen in those outflows. Our original proposal specified a single research objective for Year 2: to determine the mass and energy coupling of ISM gas to supernova-driven outflows. While this objective is concise, the computational requirements to achieve it will be more demanding than those from our Year 1 simulations, largely because the resolution requirements will be greater than those for our current set of production simulations. Additional preparatory work will also be required in Semester 3 of our program, in order to calibrate a more realistic supernova feedback model than that being used in our Semester 2 simulations.
Year 1: High-Resolution Global Simulations of Radiatively-Cooling Galactic Winds A first important calculation for the program will be to simulate galactic outflows extending from the gain region in the inner 250pc of the disk to 10kpc above and below the disk at high resolution (2048x2048x4096). These simulations will allow us to model the multiphase structure of galactic outflows by capturing the radiative cooling radii expected for hot galactic winds (Thompson et al. 2016), as indicated by our initial test calculations performed at more moderate resolutions (shown in Figure 5). The goals of such simulations include a verification of analytical estimates of the cooling wind properties (e.g., the cooling radius), the density and temperature phase structure of the wind as a function of radius, and the bulk wind momentum and mass flux across the simulation boundary.
Years 1-2: Connecting Galactic Outflow Properties with Feedback Physics The main effort of the program will be to implement and test physical models for feedback from star formation, and study the resulting character of the galactic outflow. The goal of these studies is to understand how different physical considerations (thermal energy input, momentum driving, spatial and time-clustering of supernovae) change the detailed structure of the galactic wind including the mass-loading, wind velocity and temperature, and the ionization / phase structure of the outflowing gas. The critical new capability afforded by our calculations is the reliable tracking of the hydrodynamics and possible cooling of the outflow via fixed grid calculations with massive numbers of cells (>100 billion) densely sampling in the low-density CGM regions near the galactic disk. Lagrangian or AMR methods with resolutions that track the gas density provide no gain over Cholla in this regime, as such approaches purposefully sacrifice resolution in low-density CGM regions to more affordably reach high resolution in the star-forming disk

1.1.1 Research Milestones

As originally envisioned, all of the production simulations from Semester 2 were going to be quadrants of a galaxy, because the computing time required would have been too great to carry out a global simulation according to our original calculations. However, two factors have made it possible to carry out global simulations in Semester 2. First, we are able to use a more efficient hydrodynamics algorithm than the one used in our estimated time for the original proposal. Second, the simulations do not need to run as long as we initially estimated in order to set up a steady-state wind. While our original proposal specified 400 Myr of evolution, we have found that 100 Myr is sufficient to see the properties of the wind evolve on a global scale.

As a result, our original Research Milestone D: "Determine the role of full three-dimensionality on the velocity and density structure of galactic outflows" will be fulfilled by the simulations being carried out in Semester 2. Thus, we have restructured our milestone timeline somewhat, to better take advantage of the time awarded us in Year 1, and to progress through our proposed research objectives with an approach in which each builds naturally on the next. Despite this restructuring, our overall computational needs have not changed from the original proposal. Below we show the new set of Milestones for our project, along with their associated Research Objectives.

Table 1: On-going INCITE Proposal Research Objectives

RO.B	Quantify the importance of radiative cooling for the multiphase structure of observed galactic outflows (PARTIALLY COMPLETE).
RO.C	Determine the mass and energy coupling of ISM gas to supernova-driven outflows.

Table 2: On-going INCITE Proposal Research Milestones

Milestone		**Objective**
Semester 2		
RM.C	Model the multiphase structure and radiative cooling of galactic outflows on $\sim$ 10kpc scales (PARTIALLY COMPLETE).	RO.B
Semester 3		
RM.D	Determine the role of full three-dimensionality on the velocity and density structure of galactic outflows (PARTIALLY COMPLETE).	RO.B
Semester 4		
RM.E	Simulate galactic outflows at large dynamic range to generate *ab initio* $\sim$ 10kpc-scale winds from $\sim$pc-scale supernovae bubbles.	RO.B, RO.C

Because we have restructured the timeline somewhat, we have updated set of proposed simulations for Year 2. In Table 2, we list the simulations that will be completed in Year 1 and 2, along with the research objectives and milestones being addressed by each. Note that the total allocation request has not changed for Year 2.

1.2 Developmental Work

- Developmental work has been carried out? What was the outcome?
- Additional developmental work to be executed and when?
- Estimate a percentage of project time spent on developmental computing?

RM.E: Discrete supernova feedback models. We will implement and test two or more supernovae feedback models. The first model will input stochastic energy sources in 10pc Œ 10pc regions with a spatial sampling following the expected star formation rate density in the disk and a time sampling appropriate of averages over the lifetimes and initial mass function of massive stars in stellar clusters. Given that these supernova-heated regions will marginally resolve the size of the supernovae remnants as they enter the momentum-conserving phase, we will use the local density around the supernovae to estimate any missing momentum deposition and add that as a radially-diverging kinetic feedback. A second model will combine a smooth volumetric heating of the disk gas from a time-averaged supernovae rate with stochastic momentum feedback from star formation [40], which is expected to have a similar net effect. Given that the disk gas will be allowed to cool radiatively, heating from supernovae directly or secondary heating from supernova-driven turbulence will be required to maintain the observed disk

Table 2: Research Simulations

Simulation Type and Details		**Objective / Milestone**	**Resolution**	**Titan Nodes**	**Titan Core Hours**
		Semester 1: 2M core hours			
RS.A	Initial Conditions Test Simulations	RO.A	$N = 1024^3$	512	0.5M
RS.B	Feedback Model Calibration Simulations	RO.A	$N = 1024^2 \times 2048$	1024	1.5M
		Semester 2: 44M core hours			
RS.C	Adiabatic Wind Simulation	RO.A, RO.B	$N = 2048^2 \times 4096$	8192	11M
RS.D	3 Radiative Wind Simulations	RO.A, RO.B	$N = 2048^2 \times 4096$	8192	33M
		Semester 3: 22M core hours			
RS.F	2 Radiative Simulations with discrete SN feedback	RO.A, RO.B, RO.C	$N = 2048^2 \times 4096$	8192	36M
		Semester 4: 32M core hours			
RS.G	High-Res Radiative Simulation	RO.A, RO.B, RO.C	$N = 4096^3$	16,384	32M
	Core Hour Budget for Analysis and Data Manipulation				5M
Two-Year Program Total Titan Core Hour Request:					**104M**

thickness of M82. We will perform a series of resolution studies (RS.B) focused on the disk to verify the implementation of each feedback prescription, calibrate its efficiency to drive galactic winds, and develop yet further prescriptions if they prove unsuccessful. We have extensive experience implementing ISM and feedback models [62] that are widely used in galaxy simulations, and correspondingly this phase of the program poses little risk to our research objectives.

We will implement several supernovae feedback models and simulate the resulting galactic winds. The first model will model thermal feedback, using stochastic energy sources in 10pc Œ 10pc regions with a spatial sampling following the expected star formation rate density in the disk and a time sampling appropriate of averages over the lifetimes and initial mass function of massive stars in stellar clusters (e.g., Gentry et al. 2017). Given that these supernova-heated regions will marginally resolve the size of the supernovae remnants as they enter the momentum-conserving phase, we will use the local density around the supernovae to estimate any missing momentum deposition and add that as a radially-diverging kinetic feedback. A second model will combine a smooth volumetric heating of the disk gas from a time-averaged supernovae rate with stochastic momentum feedback from star formation (Ostriker et al. 2010), which is expected to have a similar net effect but may lead to differing temperature, momentum, and ionization structure in the wind. Given that the disk gas will be allowed to cool radiatively, heating from supernovae directly or secondary heating from supernova-driven turbulence will be required to maintain the observed disk thickness of M82. We will perform a series of resolution studies focused on the disk to verify the implementation of each feedback prescription, calibrate its efficiency to drive galactic winds, and develop yet further prescriptions if they prove unsuccessful. We have extensive experience implementing ISM and feedback models (Robertson and Kravtsov 2008), and correspondingly this phase of the program poses little risk to our research objectives.

1.3 New Code Applications (where relevant)

We do not plan to use any new codes in Year 2. We will continue to update and improve our primary hydrodynamics code, *Cholla*, used to carry out all of the described simulations. We do not require additional resources beyond those requested in our original proposal.