FERMILAB-PUB-13-352-A

The Astrophysical Journal Letters, 777:L16 (5pp), 2013 November 1 doi:10.1088/2041-8205/777/1/L16

SIMULATIONS OF DISK GALAXIES WITH COSMIC RAY DRIVEN GALACTIC WINDS

C. M. Booth[1], Oscar Agertz[1,2], Andrey V. Kravtsov[1,3,4], and Nickolay Y. Gnedin[1,3,5]

[1] Department of Astronomy & Astrophysics, The University of Chicago, Chicago, IL 60637, USA; cmbooth@oddjob.uchicago.edu

[2] Department of Physics, University of Surrey, Guildford, GU2 7XH, UK

[3] Kavli Institute for Cosmological Physics, The University of Chicago, Chicago, IL 60637, USA

[4] Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA

[5] Particle Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

Received 2013 August 22; accepted 2013 September 30; published 2013 October 18

ABSTRACT

We present results from high-resolution hydrodynamic simulations of isolated Small Magellanic Cloud (SMC)- and Milky-Way-sized galaxies that include a model for feedback from galactic cosmic rays (CRs). We find that CRs are naturally able to drive winds with mass loading factors of up to ∼10 in dwarf systems. The scaling of the mass loading factor with circular velocity between the two simulated systems is consistent with $\eta \propto v_{\rm circ}^{1-2}$ required to reproduce the faint end of the galaxy luminosity function. In addition, simulations with CR feedback reproduce both the normalization and the slope of the observed trend of wind velocity with galaxy circular velocity. We find that winds in simulations with CR feedback exhibit qualitatively different properties compared to supernova-driven winds, where most of acceleration happens violently in situ near star forming sites. The CR-driven winds are accelerated gently by the large-scale pressure gradient established by CRs diffusing from the star-forming galaxy disk out into the halo. The CR-driven winds also exhibit much cooler temperatures and, in the SMC-sized system, warm ($T \sim 10^4$ K) gas dominates the outflow. The prevalence of warm gas in such outflows may provide a clue as to the origin of ubiquitous warm gas in the gaseous halos of galaxies detected via absorption lines in quasar spectra.

Key words: cosmic rays – galaxies: formation – methods: numerical

1. INTRODUCTION

Galactic winds are observed to be ubiquitous in galaxies that have recently experienced significant amounts star formation (see, e.g., Veilleux et al. 2005 for a review). These outflows represent a fundamental part of galaxy formation models, because the absence of outflows galaxy star formation rates (SFRs) are much higher than those observed (e.g., Stinson et al. 2013) and baryon fractions in the disk are close to the universal value (e.g., Crain et al. 2007), much higher than inferred from observations. In contrast, models that include a variety of feedback effects predict much lower SFRs and baryon fractions. Additionally, outflows are required to drive metal-enriched gas out of galaxies, as suggested by both observational (e.g., Steidel et al. 2010) and theoretical (e.g., Booth et al. 2012) work.

However, despite their key role in galaxy formation, the exact processes driving winds remain an open question. Plausible driving mechanisms include core collapse supernovae (SNe; Martin 1999) and radiation pressure (Murray et al. 2005; Hopkins et al. 2012; Agertz et al. 2013). SN-driven winds are now routinely included in semi-analytic and numerical simulations. However, it has long been known that in the disk of the Galaxy there is a rough equipartition of the magnetic and cosmic ray (CR) energy densities (e.g., Beck & Krause 2005). This indicates that CRs play a significant role in dynamics of interstellar medium (ISM). Only relatively recently have the effects of CRs have been considered in the context of galaxy formation (e.g., Jubelgas et al. 2008; Uhlig et al. 2012; Wadepuhl & Springel 2011; Salem & Bryan 2013) and galaxy cluster (Enßlin et al. 2007; Sijacki et al. 2008; Guo & Oh 2008) simulations.

A tight link between CRs and star formation is evidenced by the correlation between a galaxy's infrared luminosity, closely related to its SFR, and the luminosity of its radio halo (e.g., Helou et al. 1985; Lacki et al. 2010). The relationship is almost linear, has very little scatter, and does not evolve with redshift (Mao et al. 2011), indicating that the coupling between star formation and CRs is robust over a wide variety of conditions.

Although the energy injection rate of CRs is small compared to the other sources of energy from star formation, the rate at which they inject momentum is not (Socrates et al. 2008). This is because the CRs that supply most of the pressure in the galaxy generate Alfvén waves in the ISM (Wentzel 1968), which then scatter the CRs with a mean free path of ∼1 pc. Thus, CRs are "self-confined" (e.g., Cesarsky 1980), and it takes ≈250 Myr for a typical CR to escape its parent galaxy. Theoretical models of dynamical haloes in which CRs diffuse and are advected out in a galactic wind predict steady, supersonic galaxy-scale outflows driven by a combination of CR and thermal pressure (Breitschwerdt et al. 1991; Everett et al. 2008).

In this Letter, we present high-resolution hydrodynamical simulations of isolated disk galaxies, including a model for the injection, transport and decay of CRs, to investigate how outflows are driven by CRs and the properties of the outflowing gas.

2. METHOD

Our simulations are performed with the adaptive-mesh-refinement (AMR) code RAMSES, described in Teyssier (2002). The detailed description of physical processes included in our simulations—star formation, radiative cooling, and metal enrichment from Type Ia, Type II SNe, and intermediate mass stars—can be found in Agertz et al. (2013). SN feedback is modeled by injecting a total of 10^{51} erg of thermal energy per SN into the cells neighboring the star particle. We do not employ any delay of dissipation for the injected energy in these runs (the runs are equivalent to the "Energy only" run in Agertz et al. 2013).

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

A full description of the CR field would require modeling the distribution function of CRs as a function of position, momentum, and time. However, if the CR mean free path is shorter than the length scale of the problem, the CR field can be described as a fluid (Skilling 1975). We thus take the approach of modeling the CR energy density, $E_{\rm CR}$, as an additional energy field that advects passively with the gas density (e.g., Jones & Kang 1990) and exerts a pressure $p_{\rm CR} = (\gamma_{\rm CR} - 1)E_{\rm CR}$. Thus, the total pressure entering the momentum and energy equations governing gas evolution is $p_{\rm tot} = p_{\rm gas} + p_{\rm CR}$. We assume throughout that the CR fluid is an ultrarelativistic ideal gas with $\gamma_{\rm CR} = 4/3$. CRs undergo a random walk through the ISM after their injection. Their evolution is thus a combination of advection with the ambient gas and diffusion, which we parameterize by the diffusion coefficient, $\kappa = 3 \times 10^{27}$ cm^2 s^{-1}.

The evolution of baryon and CR fluids is thus governed by the standard continuity and momentum equations and the following energy equations:

$$\frac{\partial e_{\rm gas}}{\partial t} + \nabla \cdot (e_{\rm gas} v_{\rm gas}) = -p_{\rm gas} \nabla \cdot v_{\rm gas} + \Gamma - \Lambda_{\rm rad} + (1 - \xi_{\rm CR}) \Delta e_{\rm SN}\,, \quad (1)$$

$$\frac{\partial e_{\rm CR}}{\partial t} + \nabla \cdot (e_{\rm CR} v_{\rm gas}) = -p_{\rm CR} \nabla \cdot v_{\rm gas} + \nabla \cdot (\kappa \cdot \nabla E_{\rm cr}) - \Lambda_{\rm CRcool} + \xi_{\rm CR} \Delta e_{\rm SN}\,, \quad (2)$$

where $v_{\rm gas}$ is gas velocity, $p_{\rm gas}$, $e_{\rm gas}$ and $p_{\rm CR}$, $e_{\rm CR}$ are the pressure and internal energy of gas and CRs, respectively. The $\Delta e_{\rm SN}$ indicates energy injection by SN, and $\xi_{\rm CR}$ is the fraction of this energy that is injected in the form of CRs. $\Lambda_{\rm rad}$ indicates radiative cooling of gas, while Γ indicates the heating of gas by both CRs and UV radiation. Finally, $\Lambda_{\rm CRcool}$ corresponds to energy losses by CRs both due to decays and Coulomb interactions with gas mediated by magnetic fields (e.g., Völk et al. 1996; Ensslin et al. 1997). Following Guo & Oh (2008), we assume that the CR cooling rate is:

$$\Lambda_{\rm CRcool} = -7.51 \times 10^{-16}\, n_{\rm e} e_{\rm CR}\ {\rm erg\, s^{-1}\, cm^{-3}}, \quad (3)$$

where $n_{\rm e}$ is the local electron number density. The ratio of the catastrophic cooling rate to the Coulomb cooling rate for our CR population is 3.55. Some fraction of the energy lost by the CR population heats the thermal gas (e.g., Mannheim & Schlickeiser 1994) at a rate given by Guo & Oh (2008)

$$\Gamma_{\rm CRHeat} = 2.63 \times 10^{-16}\, n_{\rm e} e_{\rm CR}\ {\rm erg\, s^{-1}\, cm^{-3}}. \quad (4)$$

Equations (3) and (4) are solved to calculate the rate of decay of the CR energy density along with the corresponding gain in the gas thermal energy.

We have tested our CR implementation using a standard CR and gas shock-tube test (Pfrommer et al. 2006) and found that results accurately match the analytic solution. Results of this and other tests will be presented in a forthcoming paper.

Strong shock waves associated with SN explosions have long been recognized as a likely source of Galactic CRs (e.g., Baade & Zwicky 1934). Empirically, in order to match the galactic energy density in CRs, SNe must be capable of transferring a fraction $\Delta e_{\rm SN} \sim 10\%$ of the explosion kinetic energy into the form of CR energy (Hillas 2005). In our models we make the assumption that a certain fraction, $\xi_{\rm CR} = 0.1$, of the SN energy is injected to the CR fluid energy density. The remaining fraction $1 - \xi_{\rm CR}$ is injected thermally into the gas field.

We note that the assumption that the diffusion of CRs is isotropic is a necessary simplification in our models, which track neither the direction nor the strength of the magnetic field. On small scales ($\sim$100 pc), the strength of the random component of the galactic magnetic field is several times higher than the average field strength (e.g., Jansson & Farrar 2012) because galaxy formation processes (e.g., SNe and hydrodynamical turbulence) in the disk (Breitschwerdt et al. 1991) and the turbulent dynamo effect and CR buoyancy in the halo (Breitschwerdt et al. 1993) tangle the magnetic field to the extent that isotropic diffusion is a good approximation (e.g., Strong et al. 2007). Codes that assume isotropic diffusion are able to predict CR-emitted spectral data down to the few percent level (Orlando & Strong 2013). Therefore, for the purposes of this exploratory work, we employ the isotropic diffusion model, but note that investigation of complex models represents an interesting future direction.

2.1. *The Simulation Set*

We simulate isolated model galaxies of two different masses representing a dwarf galaxy and a Milky-Way-(MW)-sized disk galaxy with three different feedback models: no feedback, thermal feedback only, and thermal feedback plus CR feedback. The "thermal feedback" runs inject 100% of the energy released by each SN blast into the gas thermal energy. The "CR feedback" runs inject 90% of the SN energy into the gas thermal energy and the remaining 10% into the CR energy density field. Every simulation models radiative cooling, star-formation, and metal enrichment. All runs are evolved for 0.5 Gyr and throughout this Letter we report results for the final time.

Following Hernquist (1993) and Springel (2000), the galaxy model consists of a dark matter halo, a stellar bulge and an exponential disc of stars and gas. The dark matter halo is modeled as an NFW halo (Navarro et al. 1997). The gas and stars are then initialized into an exponential disk, and the bulge is assumed to have a Hernquist (1990) profile with a scale length that is 10% of the disk scale length. The relevant parameters for each set of initial conditions are given in Table 1. Each simulation is run with a maximum spatial resolution of 75 pc (37.5 pc) for the MW (SMC) runs.

3. RESULTS

We begin by considering the SFRs of the simulated galaxies in Figure 1. The SFR in simulations without feedback is higher than in simulations with feedback and is higher than typically observed SFRs of galaxies of these sizes. Simulations with CRs suppress SFR compared to simulations with thermal SN feedback only, especially in the Small-Magellanic-Cloud-(SMC)-sized galaxy. This is because CRs act as a source of pressure in the galaxy disk. This significantly changes the density probability distribution function (PDF) of the gas in the disk reducing the fraction of mass in star forming regions.

Outflow efficiency can be parameterized by the mass loading factor, η, defined as the ratio of the gas outflow rate to the SFR. The solid curves in Figure 1 show η as a function of time for different simulations. Outflow rates are measured as the instantaneous mass flux through the plane parallel to the galactic disk at a height of 20 kpc. In the MW simulation the mass loading is approximately 0.5 in both simulations, whereas in the SMC simulation the mass loading is $\sim$10 in the simulation with CRs and $\sim$1 in the simulation with thermal feedback only.

Table 1
Parameters of the Galaxy Models

Identifier[(1)]	Halo Properties				Disk Properties					
	$m_{200}^{(2)}$ ($M_\odot$)	$v_{200}^{(3)}$ (km s^{-1})	c[(4)]	$\lambda^{(5)}$	$f_g^{(6)}$	$M_{\rm gas,disk}^{(7)}$ ($M_\odot$)	$M_{\rm star,disk}^{(8)}$ ($M_\odot$)	$M_{\rm star,bulge}^{(9)}$ ($M_\odot$)	$r_d^{(10)}$ (kpc)	$h_d^{(11)}$ (kpc)
MW	1.1×10^{12}	150.0	10	0.02	0.20	9.0×10^9	3.3×10^{10}	3.3×10^9	3.6	0.36
SMC	2.0×10^9	40.0	15	0.04	0.75	4.0×10^8	4.0×10^8	1.0×10^7	0.9	0.2

Notes. From left to right the columns contain: (1) Simulation set name; (2) Spherical overdensity dark matter halo mass defined relative to the 200 times the critical density at $z = 0$; (3) Circular velocity at the virial radius; (4) Concentration of NFW halo; (5) Halo spin parameter; (6) Disk gas fraction; (7) Mass of gas in the disk; (8) Mass of stars in the disk; (9) Mass of stars in the bulge; (10) Scale length of exponential disk; (11) Scale height of gas disk.

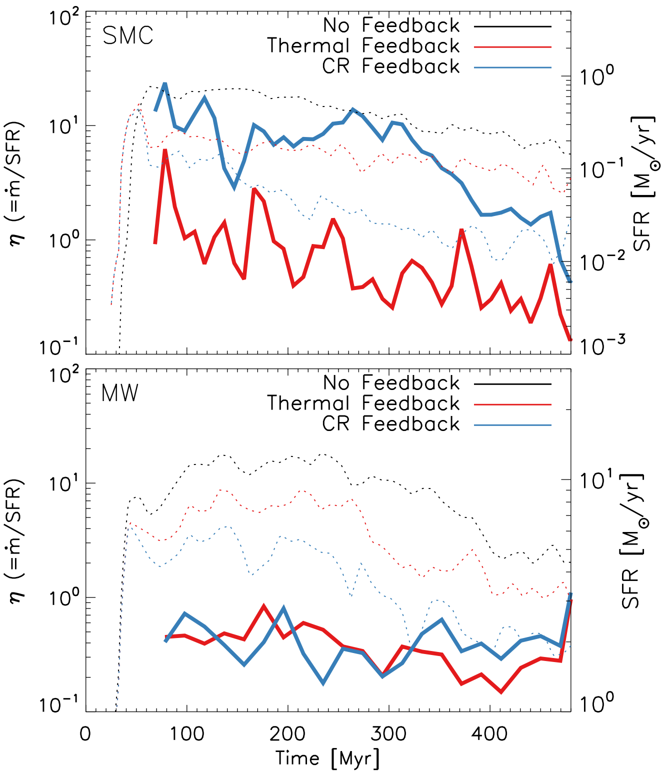

Figure 1. Solid curves show the mass loading factor, η, of the galactic wind, defined as the ratio of the SFR to the gas outflow rate, as a function of time (left-hand axis). The dotted curves show the galaxy SFR (right-hand axis). The color of each curve denotes the feedback model and the top (bottom) panel shows results for the SMC (MW) simulation. The no-feedback model (black curves) is not shown on the mass-loading plot because there is a net inflow of gas at all times. Both feedback models predict mass loadings of ∼0.5 for the MW galaxy, but the CR feedback is capable of suppressing the SFR by a larger fraction than the thermal feedback model. In the SMC galaxy the CR feedback model is capable of driving galactic winds with large (∼10) mass loadings and suppresses the SFR significantly more than thermal feedback alone.

This indicates that CRs greatly enhance efficiency of outflows from dwarf galaxies.

Figure 2 shows velocity of the outflowing gas, $v_{\rm wind}$, as a function of the circular velocity of the halo, $v_{\rm circ}$, compared to observational measurements of cool wind gas around dwarf galaxies (Schwartz & Martin 2004) and $z < 0.5$ starburst-dominated galaxies (Rupke et al. 2005). We measure outflow velocities by projecting the gas field perpendicular to the disk and calculating the velocity that contains 90% of the cool ($T < 10^5$ K) gas. In each galaxy the thermal feedback simulation predicts outflow velocities that are significantly

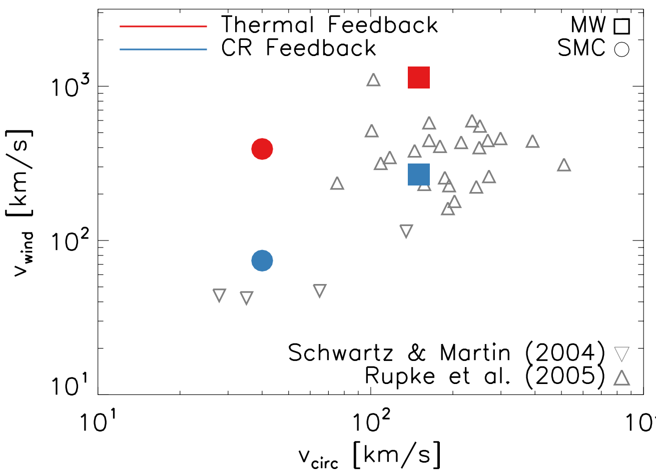

Figure 2. Velocity of the outflowing gas ($w_{\rm wind}$) as a function of halo circular velocity. The gray points show the observations of Schwartz & Martin (2004; downward pointing triangles) and Rupke et al. (2005; upward pointing triangles). The solid points show simulation predictions. The squares (circles) show the MW (SMC) simulations and the colors denote the feedback model. In both galaxies, the outflows in the CR feedback models (blue points) have velocities comparable to the observations, whereas the thermal feedback models (red points) overestimate the wind velocity by a large factor.

larger than those observed whereas the CR runs are comparable to the observations.

Finally, Figure 3 shows the temperature of the outflowing gas in a thin slice through the center of the simulated galaxies (left). The notable difference between simulations is that wind in the CR simulation is considerably cooler, especially in the SMC simulation. The panels to the right of this figure show the profiles of velocity and outward pressure gradient. The thermal feedback run has winds that accelerate abruptly from the galactic disk up to ∼700 km s^{-1} and thereafter have a constant velocity. The CR simulations, however, show a wind that accelerates smoothly into the halo. The reason for this is revealed in the right-hand panels, where it is immediately apparent that the pressure gradient in the halo with CRs is a factor of 3–10 larger in the CR simulation than in the thermal feedback simulation (the difference is particularly striking in the SMC simulation). These results illustrate that the wind properties in the simulations with CRs are qualitatively different properties to the wind driven by thermal SN feedback.

4. DISCUSSION AND CONCLUSIONS

Our simulations show that energy injection in the form of CRs is a promising feedback process that can substantially aid in driving outflows from star-forming galaxies. First, we find

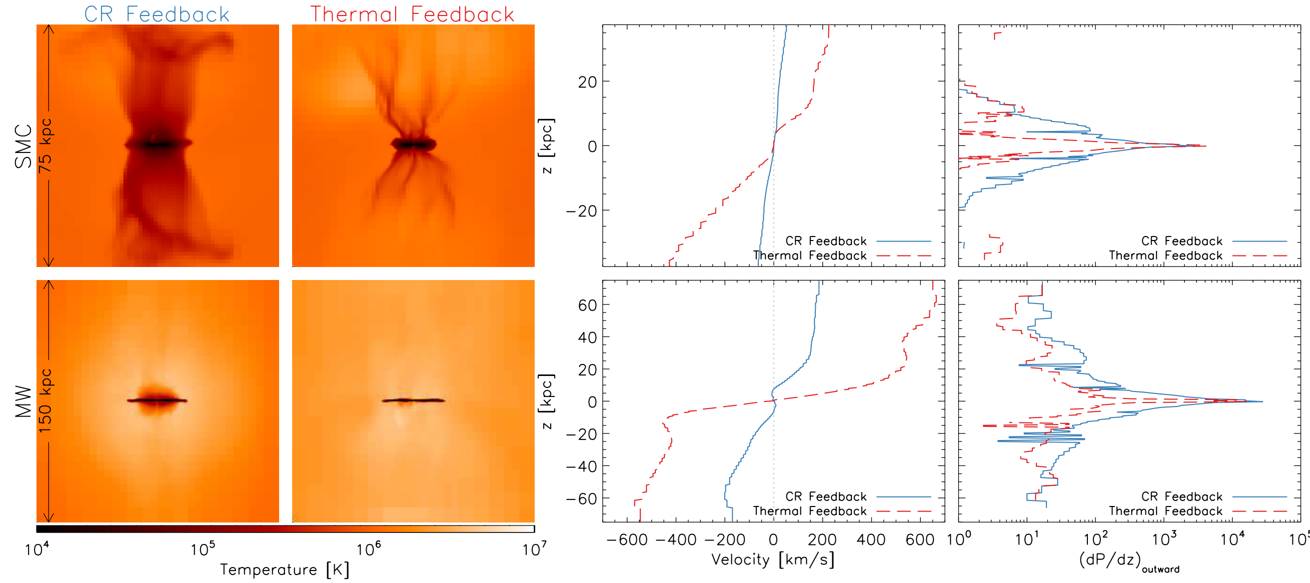

Figure 3. Edge-on maps of the temperature in a thin slice around the MW (top panels) and SMC galaxies (bottom panels) for both the thermal feedback (left panels) and CR feedback (right panels). CR feedback has a large effect on the temperature structure of the halo gas. The plots show the median velocity (left panels) and outward pressure force (right panels) as a function of height from the disk for the same two simulations. All quantities are calculated in a cylinder of radius 3 kpc, centered on the galactic disk. It is clear that the effect of the CRs is to increase the outward pressure forces in the halo by a factor of 3–5 at all z. This pressure gradient slowly accelerates the wind into the halo. The wind in the thermal feedback simulations is accelerated abruptly from the disk and maintains a constant velocity thereafter.

that CR injection can suppress the SFR by providing an extra source of pressure that stabilizes the disk. Turbulent and CR pressure are in equipartition in the disk, thus the CR pressure can significantly affect most of the volume of the disk, but will be sub-dominant inside supersonic molecular clouds, where turbulent pressure dominates over both CR and thermal pressure. This effect is particularly strong in our simulated SMC-sized dwarf galaxy. The SFRs measured in our galaxies with CR feedback are comparable to observed SFRs for both the MW and the SMC.

Second, we find that addition of the CR feedback increases the mass loading factor, η, in the dwarf galaxy by a factor of 10 compared to the simulation with SN-only feedback. As a result, the SMC- and MW-sized galaxies (circular velocities of 40 and 150 km s^{-1}, respectively) have mass loading factors that differ by a factor of $\sim$3–10, depending on the stage of evolution. This is in rough agreement with expectations from theoretical models based on simulations and semi-analytic models, which show that dependence $\eta \propto v_{\rm circ}^{\alpha}$ with $\alpha \sim 1$–2 is needed to reproduce the observed faint end of the stellar mass function of galaxies and other properties of the galaxy population (e.g., Somerville et al. 2008; Schaye et al. 2010; Oppenheimer et al. 2010; Dutton 2012). Moreover, the wind velocities in the SMC- and MW-sized simulated galaxies are consistent with the observed trend for galaxies in this mass range (Schwartz & Martin 2004; Rupke et al. 2005) both in normalization and slope. Although we have reported only two models, these results are encouraging, especially because simulation parameters have not been tuned in any way to reproduce these observations.

Perhaps the most intriguing difference of the CR-driven winds compared to the winds driven by thermal SN feedback is that they contain significantly more "warm" $T \sim 10^4$ K gas. This is especially true for the dwarf galaxy, which develops a wind strikingly colder than in the SN-only simulation (see Figure 3). The CR-driven wind has a lower velocity, and is accelerated gradually with vertical distance from the disk. The reason for these differences is that the gas ejected from the disk is accelerated not only near star-forming regions, as is the case in SN-only simulations, but is continuously accelerated by the pressure gradient established by CRs diffused outside of the disk (see Figure 3). The diffusion of CRs is thus a key factor in ejecting winds and in their resulting colder temperatures. The cooler temperatures of the ejected gas may be one of the most intriguing new features of the CR-driven winds, as this may provide a clue on the origin of ubiquitous warm gas in gaseous halos of galaxies (e.g., Chen 2012 and references therein). Detailed predictions of circumgalactic medium properties will require cosmological galaxy formation simulations incorporating CR feedback, which we will pursue in future work.

Several studies have explored effects of CR injection on galaxies. Jubelgas et al. (2008) found that CRs suppress the SFR in dwarf galaxies by an amount comparable to that observed in our simulations, but have almost no effect on the SFR- of MW-sized systems. We find significant SFR suppression for both masses. Additionally, Jubelgas et al. (2008) found that CRs did not generate winds with diffusion alone and in a recent study using a similar model Uhlig et al. (2012) argued that to launch winds CR streaming is crucial. In contrast, we find that CR-driven winds are established for both SMC- and MW-sized systems with CR diffusion alone. These differences likely arise due to assumption of equilibrium between the sources of CRs (star formation $\propto \rho^{1.5}$) and the sinks (catastrophic losses $\propto \rho^{-1}$) in the subgrid model of Jubelgas et al. (2008). The subgrid model thus predicts that CR pressure scales as $\sqrt{\rho}$ and is subdominant to the thermal ISM pressure at densities $n_{\rm H} > 0.2$ $\rm cm^{-3}$ (see Figure 7 of Jubelgas et al. 2008). This assumption of equilibrium, which is likely true only in the deepest parts of the galaxy potential well (see, e.g., the discussion in Socrates et al. 2008), breaks down in lower density gas. In our simulations we do not assume such equilibrium and we find significant contributions to the pressure from CRs up to much higher densities. Our results thus indicate that CRs, even in the diffusion only limit, not only suppress star formation but also drive outflows efficiently. Thus, the effects of CR feedback on the properties of galaxies of different masses should be significantly stronger and span a wider range of masses than simulations that use the Jubelgas et al. (2008) model (e.g., Wadepuhl & Springel 2011).

While this manuscript was in a late stage of preparation, Salem & Bryan (2013) appeared as a preprint. These authors have presented simulations of an MW-sized galaxy, similar to the model presented here, albeit without accounting for CR cooling losses and with a much larger SFR in their model galaxy (up to ∼200–300 $M_{\odot}$ yr^{-1}). Where our results do overlap (e.g., mass loading factor) with those of Salem & Bryan (2013) we find remarkably good agreement. These authors also find that outflows are efficiently generated with CR diffusion alone. Our study extends the results of Salem & Bryan (2013) by presenting the differences between wind properties in dwarf- and MW-sized systems. The results of Salem & Bryan (2013) and our study indicate that CRs can significantly suppress star formation in galaxies and efficiently drive outflows with significant mass loading factors and velocities comparable to observed outflows. A detailed exploration of the effects of such feedback on the galaxy population in a full cosmological setting is therefore extremely interesting.

N.G. and A.K. were supported via NSF grant OCI-0904482. A.K. was supported by NASA ATP grant NNH12ZDA001N and by the Kavli Institute for Cosmological Physics at the University of Chicago through grants NSF PHY-0551142 and PHY-1125897 and an endowment from the Kavli Foundation and its founder Fred Kavli.

REFERENCES

Agertz, O., Kravtsov, A. V., Leitner, S. N., & Gnedin, N. Y. 2013, ApJ, 770, 25
Baade, W., & Zwicky, F. 1934, PhRv, 46, 76
Beck, R., & Krause, M. 2005, AN, 326, 414
Booth, C. M., Schaye, J., Delgado, J. D., & Dalla Vecchia, C. 2012, MNRAS, 420, 1053
Breitschwerdt, D., McKenzie, J. F., & Voelk, H. J. 1991, A&A, 245, 79
Breitschwerdt, D., McKenzie, J. F., & Voelk, H. J. 1993, A&A, 269, 54
Cesarsky, C. J. 1980, ARA&A, 18, 289
Chen, H.-W. 2012, MNRAS, 427, 1238
Crain, R. A., Eke, V. R., Frenk, C. S., et al. 2007, MNRAS, 377, 41
Dutton, A. A. 2012, MNRAS, 424, 3123
Ensslin, T. A., Biermann, P. L., Kronberg, P. P., & Wu, X.-P. 1997, ApJ, 477, 560
Enßlin, T. A., Pfrommer, C., Springel, V., & Jubelgas, M. 2007, A&A, 473, 41
Everett, J. E., Zweibel, E. G., Benjamin, R. A., et al. 2008, ApJ, 674, 258
Guo, F., & Oh, S. P. 2008, MNRAS, 384, 251
Helou, G., Soifer, B. T., & Rowan-Robinson, M. 1985, ApJL, 298, L7
Hernquist, L. 1990, ApJ, 356, 359
Hernquist, L. 1993, ApJS, 86, 389
Hillas, A. M. 2005, JPhG, 31, 95
Hopkins, P. F., Quataert, E., & Murray, N. 2012, MNRAS, 421, 3522
Jansson, R., & Farrar, G. R. 2012, ApJL, 761, L11
Jones, T. W., & Kang, H. 1990, ApJ, 363, 499
Jubelgas, M., Springel, V., Enßlin, T., & Pfrommer, C. 2008, A&A, 481, 33
Lacki, B. C., Thompson, T. A., & Quataert, E. 2010, ApJ, 717, 1
Mannheim, K., & Schlickeiser, R. 1994, A&A, 286, 983
Mao, M. Y., Huynh, M. T., Norris, R. P., et al. 2011, ApJ, 731, 79
Martin, C. L. 1999, ApJ, 513, 156
Murray, N., Quataert, E., & Thompson, T. A. 2005, ApJ, 618, 569
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Oppenheimer, B. D., Davé, R., Kereš, D., et al. 2010, MNRAS, 406, 2325
Orlando, E., & Strong, A. W. 2013, MNRAS, 1718
Pfrommer, C., Springel, V., Enßlin, T. A., & Jubelgas, M. 2006, MNRAS, 367, 113
Rupke, D. S., Veilleux, S., & Sanders, D. B. 2005, ApJS, 160, 115
Salem, M., & Bryan, G. L. 2013, arXiv:1307.6215
Schaye, J., Dalla Vecchia, C., Booth, C. M., et al. 2010, MNRAS, 402, 1536
Schwartz, C. M., & Martin, C. L. 2004, ApJ, 610, 201
Sijacki, D., Pfrommer, C., Springel, V., & Enßlin, T. A. 2008, MNRAS, 387, 1403
Skilling, J. 1975, MNRAS, 172, 557
Socrates, A., Davis, S. W., & Ramirez-Ruiz, E. 2008, ApJ, 687, 202
Somerville, R. S., Hopkins, P. F., Cox, T. J., Robertson, B. E., & Hernquist, L. 2008, MNRAS, 391, 481
Springel, V. 2000, MNRAS, 312, 859
Steidel, C. C., Erb, D. K., Shapley, A. E., et al. 2010, ApJ, 717, 289
Stinson, G. S., Brook, C., Macciò, A. V., et al. 2013, MNRAS, 428, 129
Strong, A. W., Moskalenko, I. V., & Ptuskin, V. S. 2007, ARNPS, 57, 285
Teyssier, R. 2002, A&A, 385, 337
Uhlig, M., Pfrommer, C., Sharma, M., et al. 2012, MNRAS, 423, 2374
Veilleux, S., Cecil, G., & Bland-Hawthorn, J. 2005, ARA&A, 43, 769
Völk, H. J., Aharonian, F. A., & Breitschwerdt, D. 1996, SSRv, 75, 279
Wadepuhl, M., & Springel, V. 2011, MNRAS, 410, 1975
Wentzel, D. G. 1968, ApJ, 152, 987