COSMOLOGICAL SIMULATIONS OF GALAXY FORMATION WITH COSMIC RAYS

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ABSTRACT

We investigate the dynamical impact of cosmic rays (CR) in cosmological simulations of galaxy formation using adaptive-mesh refinement simulations of a $10^{12} M_\odot$ halo. In agreement with previous work, a run with only our standard thermal energy feedback model results in a massive spheroid and unrealistically peaked rotation curves. However, the addition of a simple two-fluid model for CRs drastically changes the morphology of the forming disk. We include an isotropic diffusive term and a source term tied to star formation due to (unresolved) supernova-driven shocks. Over a wide range of diffusion coefficients, the CRs generate thin, extended disks with a significantly more realistic (although still not flat) rotation curve. We find that the diffusion of CRs is key to this process, as they escape dense star-forming clumps and drive outflows within the more diffuse interstellar medium.

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

Online-only material: color figures

1. INTRODUCTION

The formation of realistic disk galaxies in cosmological simulations has proven a considerable challenge over the years, largely due to the tendency for energetic feedback from star formation (SF) to be radiated away (e.g., Navarro & Benz 1991; Thacker & Couchman 2000; Abadi et al. 2003; Governato et al. 2007; Hummels & Bryan 2012, and references therein). Recently, however, significant progress has been made by a number of groups, producing thin disks with nearly flat rotation curves (e.g., Governato et al. 2010; Guedel et al. 2011; Stinson et al. 2013; Agertz et al. 2013; Aumer et al. 2013; Brooks et al. 2011; Marinacci et al. 2014). While methodology has varied, these successes have generally involved a sub-grid model tuned to generate large winds, either explicitly or via a technique to reduce radiative losses in dense, star-forming gas. Although this approach is certainly useful, the detailed physical nature of the feedback in these models is imposed as a sub-grid model and generally tuned to match observations. Complementary work to produce a sub-grid model from first principles is still in early stages—preliminary efforts have found it remarkably difficult to drive highly mass-loaded winds from baryon-rich disks (e.g., Mac Low & Ferrara 1999; Joung et al. 2009; Creasey et al. 2013).

Here, we take a somewhat different approach, and explore the impact of cosmic-ray (CR) pressure on the formation of disks in cosmological simulations. Although the detailed dynamics of CRs are complicated, we adopt a simple two-fluid approach that has been widely used, and which, we argue, captures the key effects of CR dynamics. We assume that CRs are accelerated by supernovae (SNe) blast waves, retaining a significant fraction of the SN energy, that the CRs are tightly coupled to the thermal gas (via magnetic interactions) except for a diffusive term. This work builds on previous efforts to model CR pressure in previous one-dimensional (1D) and three-dimensional (3D) galaxy models, and is a direct (cosmological) follow-up to our previous work (Salem & Bryan 2014, hereafter SB14). Early work (Breitschwerdt et al. 1991, 1993; Zirakashvili et al. 1996; Everett et al. 2008) showed that CRs could drive significant winds in 1D steady-state models, a conclusion that was extended to time-dependent cases by Dorfi & Breitschwerdt (2013). Full 3D galaxy simulations including CRs have only recently been explored (Enßlin et al. 2007; Jubelgas et al. 2008; Siejkowski et al. 2014), affirming that CRs can influence galactic structure but generally did not include streaming or diffusion, which turns out to be a key ingredient in driving winds (Uhlig et al. 2012; SB14).

In SB14, we simulated an idealized galactic disk, demonstrating that CRs with diffusion generically drove outflows, with mass-loading factors approaching unity. The precise results depended mostly on the CR diffusion coefficient, but also had a dependency on the amount of energy injected. This result, first submitted in 2013 July, was confirmed by two Letters both submitted a month after SB14 (Booth et al. 2013; Hanasz et al. 2013), the latter of which explicitly included magnetic fields and anisotropic diffusion. In this Letter, we apply our CR model to galaxy formation in a cosmological context, demonstrating that it has a dramatic effect on the disk dynamics, resulting in systems much closer to those observed than our standard (pure thermal) feedback model.

2. METHODOLOGY

Our cosmological galaxy simulation is based very closely on Hummels & Bryan (2012, hereafter HB12), who performed a “zoom” simulation of a forming $1.2 \times 10^{12} M_\odot$ halo within a $(20 \, \text{Mpc}/h)^3$ box with cosmological parameters from the WMAP5 year results (Komatsu et al. 2009; see Table 1), evolved from $z = 99$ to the present day. We zoom on the same relatively isolated $\sim 10^{12} M_\odot$ halo (denoted halo 26 in that work), using the adaptive-mesh refinement (AMR) code Enzo—see Bryan et al. (2014) for a description, and the same initial conditions and refinement strategy. In particular, we use a base grid of 128$^3$ cells per side, two levels of initial refinement (resulting in a dark matter (DM) particle mass of $4.9 \times 10^8 M_\odot$) and a maximum of nine levels of AMR, thus providing a maximum comoving resolution of 305 $h^{-1}$ pc.

We integrate CR physics into Enzo via a two-fluid model (Jun et al. 1994; Drury 1985; Drury & Falle 1986), whose features, limitations, and implementation are described in SB14.
Figure 1. Surface gas density at the center of our $\sim 10^{12} M_\odot$ halo. Each column is a distinct simulation, where the cosmic-ray (CR) fluid becomes increasingly diffusive from left to right. The rightmost column is a run devoid of CRs. The top two rows are a face-on view at redshifts 1 and 0, whereas the bottom two rows are edge-on. A $z = 0$ view of a highly diffusive run with a factor of two higher spatial resolution (see the text) at $z = 0$ is shown in the bottom panel. (A color version of this figure is available in the online journal.)

Table 1

| CR Physics | SF/Feedback | Cosmology | Numerics |
|------------|-------------|-----------|----------|
| $\kappa_{\text{CR}}$ | $\epsilon_{\text{SF}}$ | $\Omega_0$ | $\Delta x_{\text{min}}$ |
| $\gamma_{\text{CR}}$ | $\epsilon_{\text{SN}}$ | $h$ | 425 pc |
| $c_{\text{r,max}}$ | $f_{\text{CR}}$ | $\Omega_\Lambda$ | Size |

Briefly, this model assumes a relativistic population of a few GeV protons treated as an ideal gas with $\gamma_{\text{CR}} = 4/3$. Inhomogeneities in the interstellar medium’s (ISM) magnetic field (not explicitly modeled) scatter the CR’s motion, tying them to the thermal plasma except for a diffusion term modeled with a homogeneous, scalar diffusion coefficient, $\kappa_{\text{CR}}$. Bulk motions of the thermal gas transport the CRs and perform adiabatic work on the CR fluid. In turn, the CR fluid exerts a scalar pressure on the thermal ISM. This model neglects diffusion of the CRs in energy, non-adiabatic CR energy loss terms and any attempt to directly model magnetic fields.

This prescription necessitated the inclusion in Enzo of a new conserved fluid quantity, $\epsilon_{\text{CR}}$, evolved with the robust ZEUS hydro method (Stone & Norman 1992), as described and tested in SB14. That work explored various diffusion coefficients, $\kappa_{\text{CR}} \in [0, 10^{29}] \text{ cm}^2 \text{ s}^{-1}$. We again vary the scalar diffusion coefficient across runs, including $\kappa_{\text{CR}} \in [0, 3\times10^{27}, 10^{28}, 3\times10^{28}] \text{ cm}^2 \text{ s}^{-1}$. Within galactic disks, both CR propagation models and observations motivate a value of a few times $10^{28} \text{ cm}^2 \text{ s}^{-1}$ (e.g., Ptuskin et al. 2006; Ackermann et al. 2012; Strong & Moskalenko 1998; Tabatabaei et al. 2013), although a more detailed model would treat this coefficient as an anisotropic tensor dependent on details of the magnetic field and CR momentum distribution.

The present work occurs over cosmological timescales, during which our comoving grid cells expand in size appreciably in physical units. This adiabatic expansion manifests as a decay in the fluid’s energy density. For the ultra-relativistic ray gas, with...
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Figure 2. Stellar surface density across our simulations in the center of our $\sim 10^{12} M_\odot$ halo; see Figure 1 for an explanation of the layout.

$\gamma_{CR} = 4/3$, the decay follows $\partial_t \epsilon_{CR} = -(\dot{a}/a)\epsilon_{CR}$ where $a(t)$ is the cosmic scale factor.

Our resolution fails to resolve the formation of molecular clouds and stars. Thus to capture this physics, we create collisionless “star particles” of mass $M_* \geq 10^5 M_\odot$. To determine the star formation rate (SFR), we follow the prescription of Cen & Ostriker (1992), updated as first described in O'Shea et al. (2004), which essentially adopted a SFR $\dot{\rho}_{SF} = \epsilon_{SF} \rho / t_{dyn}$. Here $\epsilon_{SF}$ is the SF efficiency, and $t_{dyn}$ is the dynamical time; a detailed explanation of parameters and their choices (listed in Table 1) can be found in HB12, which employed an identical prescription without CRs.

We also include stellar feedback from Type II supernovae, which deposit a portion of the star particle’s mass and energy back into the fluid quantities of the cell it occupies over a dynamical time, following

$$\Delta M_{gas} = f_* m_*, \quad (1)$$

$$\Delta E_{gas} = (1 - f_{CR}) \epsilon_{SN} m_* c^2, \quad (2)$$

$$\Delta E_{CR} = f_{CR} \epsilon_{SN} m_* c^2, \quad (3)$$

where $f_* = 0.25$ is the mass fraction of the star ejected as winds and SN ejecta, $\epsilon_{SN} = 3 \times 10^{-6}$ is the Type II supernovae efficiency and $f_{CR}$ is the fraction of this energy feedback donated to the relativistic CR fluid. The choice of this latter CR feedback was explored in SB14. Following that work’s fiducial run, we set $\epsilon_{SN} = 3 \times 10^{-6}$.

3. RESULTS

We begin by presenting a brief analysis of the distribution of baryons in our $1.2 \times 10^{12} M_\odot$ halo across our five simulations (four which vary the CR diffusion coefficient and a control run without CRs). Figures 1 and 2 display gas and stellar column densities within a central 10 kpc$^2$ region at the center of the DM halo. The top two rows show face-on views of the baryonic disk at both $z = 1$ and $z = 0$, the former epoch featuring substantially higher physical resolution. The bottom two rows show the edge-on view. Each column of these figures represents a different simulation, where, from left to right, our CRs run from zero-diffusion to very diffusive.

The rightmost column of Figures 1 and 2 shows a run with the traditional (purely thermal) feedback of Cen & Ostriker (1992) but no CR physics. Face- and edge-on views at $z = 1$ show that this approach has concentrated the gas and stars within a massive, central, kiloparsec-scale bulge. A rotationally supported disk of roughly 5 kpc in diameter is visible in the gaseous component, although this feature is mostly washed out in the stellar maps, particularly at $z = 0$. As is well-
known, purely thermal energy injection is not an efficient feedback mechanism for such simulations, as the energy is rapidly radiated away.

At the opposite extreme of behavior is our run with CRs but no CR diffusion, plotted in the leftmost column of Figures 1 and 2. SB14 showed in an isolated galaxy that the pressure support of the CRs injected in SF regions led to a puffed up disk with the lowest SFRs among all runs considered but failed to launch any galactic winds to redistribute the baryons. In this cosmological setting we find these earlier results corroborated. Like the
no-CR run, this no-diffusion simulation has failed to produce a thin disk of stars down to z = 0, although it did manage to lower the resulting stellar mass by ∼30%, lowering the rotation curve peak by over 100 km s\(^{-1}\). Finally, the baryon fraction throughout the central 10 kpc has been lowered by ∼10%, though this is somewhat due to a higher concentration of DM at the center, where less SF (and thus local feedback) has occurred compared somewhat due to a higher concentration of DM at the center, where less SF (and thus local feedback) has occurred compared to the no-CR run.

Our final three runs include not only CRs but also CR diffusion, shown in the middle three columns of Figures 1 and 2. These runs feature thin gaseous disks from high redshift down past z = 1, complete with large, coherent spiral features in the more diffusive runs at z = 1. By z = 0, the disks are gas-poor, with the “middle” \(\kappa_{\text{CR}} = 10^{28} \text{ cm}^2 \text{s}^{-1}\) run showing the least residual gas. The ratio of CR pressure to gas pressure in the disk varies mostly between a factor of roughly unity and 100 for these runs. At a radius of 10 kpc from the disk center, the CR energy density is about \(4 \times 10^{12} \text{ erg cm}^{-2}\), within a factor of two of the value observed in the solar neighborhood. This value is relatively constant across our simulations with non-zero-diffusion coefficients.

In the stellar maps, we see all three of these runs have extended, thin stellar disks, with the thickness decreasing for more diffuse runs, to a fraction of a kiloparsec even more. Finally, these runs were also the most effective at reducing the ratio of CR pressure to gas pressure in the disk, with mass-loading factors (normalized by the SFR) of the order of unity. Their less diffusive runs lifted more mass from the disk, ultimately processing more ISM into the circumgalactic medium than into stars. Figure 4 shows edge-on cutaway “slices” of gas density and CR energy density for our halos at z = 1, with poloidal velocity vectors superimposed showing transport of the two fluid. All three diffusion-inclusive runs (middle three columns) feature robust flows above and below the disk, with velocities well above 100 km s\(^{-1}\). For the most diffusive run, the speed of these winds exceeds 1000 km s\(^{-1}\), although the flows become increasingly evacuated, leading to a lower mass flux. These flows first appear at substantially higher redshift and persist down to z = 0 (indeed, they are stronger at higher redshift).

From Figure 3, we find substantially lower stellar masses throughout the halo for our diffusion-inclusive runs (blue, green, and red). The run most effective at suppressing SF is the least diffusive \(\kappa_{\text{CR}} = 3 \times 10^{27} \text{ cm}^2 \text{s}^{-1}\) run, consistent with the results of SB14. This run produced roughly half as many stars as the no-CR run. All three diffusive runs perform better in this respect than the non-diffusive case. All CR-inclusive runs lower the cumulative baryon fraction by 30% or more in the central 10 kpc, with the less diffuse runs decreasing the fraction at larger radii even more. Finally, these runs were also the most effective at driving down the rotation curve peak, with the least diffusive run dropping below 400 km s\(^{-1}\).

4. CONCLUSION

Our diffusive CR model successfully produces thin, extended baryonic disks that persist to low redshift, with fewer stars, a lower baryon fraction and a less pronounced peak in their rotation curves than in our thermal-only feedback models. The details depend on the precise diffusion coefficient chosen, but, the overall result holds over a wide range of coefficients.
Although CR physics dramatically improves the realism of the resulting disks, these runs could not completely disband the unnaturally large spheroid of gas and stars at the center of the simulated galaxy, as the reflected in their peaked rotation curves. In fact, the runs with the most extended disks (the most the simulated galaxy, as the reflected in their peaked rotation curves. In fact, the runs with the most extended disks (the most

The runs with the most extended disks (the most extended disks) were also the runs with the largest central bulge. This suggests the precise role of CRs in feedback, and the spatial scales on which they are relevant, depend on the details of CR streaming and diffusion. A more diffusive CR gas may play a less critical role in small scale feedback, on the level of SF clumps, than in global flows. This is in agreement with the higher resolution work of SB14, where strongly mass-loaded winds arose from the disk, but failed to regulate fragmentation and SF. This problem is likely due to the absence of other feedback processes, such as radiation and stellar winds, that play an important role in dense molecular gas which are unaffected by CR feedback. We also may be impacted by the relatively poor resolution of these cosmological runs, which still do not resolve the disk scale height. As shown in the higher resolution runs of SB14, we see a bulk transport of the multiphase ISM rising buoyantly, and gaining speed, beyond the sites of SF. The flows are primarily driven not by a hot, evacuated cavity of thermal gas, but by the pressure support of a relativistic component that is everywhere intermixed with the fluid.

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