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Constraining Cosmic-Ray Transport through Synthetic Observations of the Circumgalactic Medium

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Cosmic-rays have been found to be potentially of great importance in galaxy formation in recent theoretical work. By establishing a substantial source of non-thermal pressure support in the circum-galactic medium (CGM), cosmic-rays alter the phase structure and spatial distribution of gas in the CGM, with notable ensuing effects on the star formation histories of galaxies. However, these effects rely heavily on the transport rate of cosmic-rays from the interstellar medium (ISM) into the CGM, and there remain order-of-magnitude uncertainties in the value of the macroscopic cosmic-ray diffusion coefficient from different plausible physical models. To place constraints on these theoretical models, we use high-resolution, magneto-hydrodynamic, cosmological simulations of galaxy formation from the Feedback in Realistic Environments (FIRE) project, and post process them with a novel code to compute the expected non-thermal synchrotron emission from the inner halo of these galaxies. By forward modeling the emission from simulations of galaxy formation which self-consistently evolve cosmic-rays, we are able to explore differences between models in non-thermal emission and place new constraints on models for cosmic-ray transport which may be investigated via future radio continuum observing missions.

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1. Introduction

Cosmic rays have long been known to be of dynamical importance in the interstellar medium (ISM) of galaxies, as they are in approximate energy equipartition with magnetic fields (**B**), starlight, and gas turbulence [1]. The dynamics of the mildly relativistic 1-10 GeV CR protons which dominate the energy budget of CRs in the Milky Way and similarly star-forming $\sim L_*$ galaxies has been of renewed interest in the past decade for potentially significant implications on galaxy evolution. Simulations of galaxy formation with varied physical and numerical prescriptions have shown that if CRs efficiently escape the ISM and establish quasi-static, CR-pressure dominated halos, galaxies' star formation can be significantly suppressed owing to CR-driven outflows and pressure support [2–7].

While these possibly important effects have been noted, they ultimately depend on the physics of CR transport through the ISM and into the CGM [8]. This transport is determined by scattering rates (ν) on "micro-scopic" plasma scales (on the order of CR gyro-radii, $\sim$ AU) which give rise to "macro-scopic" (on galactic $\gtrsim$ pc scales) effective diffusion coefficients ($\kappa_{\rm eff}$) or streaming speeds ($v_{\rm st}$). These "micro-scopic" transport parameters remain highly uncertain and plausible values from small-scale plasma physics arguments span orders of magnitude in typical ISM environments [9, 10]. Notably, two main model classes exist in the literature; those of "extrinsic turbulence" (ET) and "self-confinement" (SC), where CRs scatter off of gyro-resonant fluctuations in **B** determined by a turbulent cascade in the background fluid, and where CRs excite gyro-resonant Alfvén waves via streaming instabilities and subsequently scatter [11, 12].

Though these model classes predict qualitatively different scalings of the CR scattering rate as a function of plasma properties like gas density, strength of **B**, ionization fraction, temperature, etc., there are plausible variations within these classes that agree with the existing constraints we have on CR transport from Voyager and Fermi-LAT ([9]). To make further progress in this field, new observational constraints are crucial to determine the physics of CR transport in galaxies, particularly in the CGM, ultimately constraining CR effects on galaxy formation and evolution.

Here, we will describe synthetic synchrotron images from high-resolution, cosmological, magneto-hydrodynamic simulations of galaxy formation from the Feedback in Realistic Environments project (FIRE-2; [5, 9, 13]) which evolve CRs using varied models of CR transport described above. Preliminary results show that future radio surveys sensitive to the low-surface brightness emission from the inner regions of galactic halos may be able to provide new constraints on CR transport.

2. Methods

2.1 Simulations

We explore a subset of the simulations of $\sim L_*$ galaxies presented in [8, 9] which evolve a 'single-bin' of 1-10 GeV CRs and utilize FIRE-2 [14] physics. We defer to [9] for details, but these are all fully-dynamical, cosmological, magnetohydrodynamical(MHD)-cosmic ray galaxy formation simulations which self-consistently follow galaxy formation from cosmological initial conditions including both dark matter and baryons (in gas and stars). Magnetic fields are evolved self-consistently from arbitrarily small trace seed fields, with phase structure and thermo-chemistry in the galaxy emerging from explicit cooling functions with temperatures $T \sim 1 - 10^{10}$ K and self-gravity, fully-coupled to multi-band radiation transport, with star formation in the most dense gas ($\gtrsim 1000\,\mathrm{cm}^{-3}$), and those stars influencing the medium in turn via their injection of radiation, stellar mass-loss, and both Ia and core-collapse SNe explosions (followed self-consistently according to standard stellar evolution models). The cosmic ray physics is itself coupled directly to the dynamics from injection at SNe with a fixed fraction of 0.1 the initial ejecta kinetic energy. CRs propagate along magnetic field lines according to the fully general CR transport equations, and interacting with the gas via scattering, Lorentz forces, and losses.

These simulations utilize a set of scalings for the scattering rate ν which are motivated by ET and SC theory, which have been re-normalized at ~ 1 GeV to fit the Voyager, AMS-02, and Fermi data.

2.2 Synchrotron Forward Modeling

Our methodology to compute the synchrotron specific emissivities and subsequent images from our simulations follows the equations as derived in [15], and summarized again in [16].

For each gas cell in the simulation, we utilize the internally-evolved **B** and CR energy density (e_{cr}), scaling the CRe spectrum of [17] by $\frac{e_{\mathrm{CR,sim}}}{e_{\mathrm{CR,B19}}}$. From these, we follow the procedure of computing critical frequencies of emission and integrating over the CRe spectrum, utilizing pre-tabulated Bessel functions, to get the total specific emissivity at a given frequency from each gas cell. The subsequent emissivities are then integrated along the line-of-sight to compute the total specific intensity (I_ν; Stokes I) in each pixel.

3. Results

The resulting synthetic synchrotron images (edge-on) and vertical emission profiles for a simulated L_* galaxy with varied CR transport physics (all other initial conditions held constant) are shown in Figure 1. A few differences are evident from visual inspection: namely that the simulation run with SC-motivated scalings for CR transport exhibits brighter and more extended emission relative to the ET run.

These differences are not solely due to the spatial distribution of CRs according to the the CR-transport scalings, though they are related to the non-linear dynamical interplay of the CRs and gas. One characteristic feature of SC-motivated transport scalings is a scaling between the scattering rate ν and e_{cr}, meaning that the effective local diffusivity $\kappa_{\mathrm{eff}} \sim 1/e_{cr}$. This scaling of the diffusivity can lead to efficient trapping of CRs in regions of e_{cr} over-density, which continues to runaway until the pressure buildup is enough to drive e_{cr}- and e_B-loaded winds out of the galaxy up to kpc scales from the disk midplane, resulting in the brighter and more extended synchrotron profiles. This effect is described in more detail in [9, 10], and we see that this type of CR-driven feedback can lead to interesting and potentially observationally discernable predictions in synchrotron emission.

While the current observational sample of spatially resolved, edge-on spiral galaxies remains limited [18], future radio surveys like DSA-2000 [19] will be able to image this low surface brightness emission out to ~few kpc scales for many more edge-on systems, and provide crucial observations to compare with theory predictions.

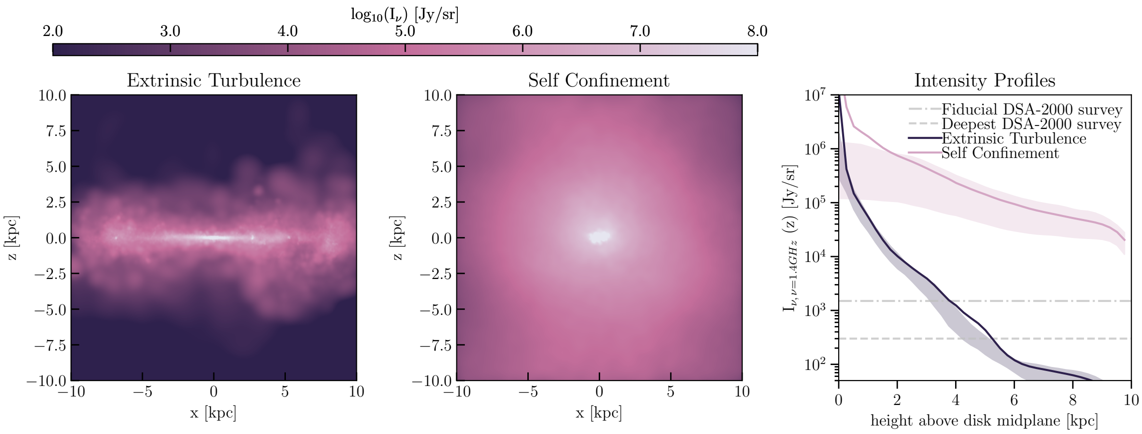

Figure 1: *Predicted synchrotron specific intensity at 1.4 GHz for an edge-on projection simulated L_* galaxy at redshift 0.* **Left and Middle:** image of a simulation with an extrinsic-turbulence (*left*) and self-confinement (*middle*) motivated treatment of CR transport. **Right:** Vertical intensity profiles (*solid lines*) of the ET (*navy*) and SC model variant simulations (*pink*), with lines showing means in radial vertical bins, and scatter showing approximate 1σ scatter.

4. Discussion and Conclusion

Utilizing a set of high-resolution, cosmological simulations of L_* galaxies from the FIRE-2 project which self-consistenly evolve **B** and a single-bin of 1-10 GeV CRs, we generate new predictions of non-thermal radio continuum emission from the inner halos of galaxies for different physically-motivated CR transport models. We find that there are marked differences between extrinsic-turbulence and self-confinement motivated emission profiles in the inner halos, with SC-motivated transport producing galaxies with brighter and more extended synchrotron emission profiles.

Though we only show two examples here, we have explored a larger subset and find that this qualitative trend appears on average, we stress that this does not mean that SC-motivated scalings *always* produce these differences, as the behavior is driven by a highly non-linear process of the 'SC runaway.' Despite the CR-physics appearing to drive these differences, the other FIRE-2 feedback physics and numerical treatments are also interdependent, and so changing physics and numerical modules may lead to different results. These results do, however, emphasize the need to model the dynamical interactions of CRs with the background medium in simulations of galaxy formation to capture the full effects and observable implications of CR transport. As shown in [10], different physically motivated CR transport scalings also predict highly variant CR spectra, and so investigating these non-thermal emission differences using spectrally-resolved CR-MHD will be crucial for more detailed predictions, as loss terms and corresponding spectral shapes in the inner halo can substantially differ from the local ISM conditions and spectra utilized here.

More detailed predictions expanding upon the preliminary results presented here will be crucial to constrain CR transport in the ISM and CGM of ~L_* galaxies. These can be compared to the existing samples of spatially resolved ~L_* galaxies [18] as well as future radio missions [19], which will greatly expand the sample of galaxies with low-surface brightness imaging in the inner halo.

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