Simulating Gamma-Ray Emission in Star-forming Galaxies

Christoph Pfrommer1,2, Rüdiger Pakmor2, Christine M. Simpson2, and Volker Springel2,3

1 Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany; c.pfrommer@iap.de
2 Heidelberg Institute for Theoretical Studies, Schloss-Wolfsbrunneweg 35, D-69118 Heidelberg, Germany
3 Zentrum für Astronomie der Universität Heidelberg, ARI, Mönchhofstr. 12-14, D-69120 Heidelberg, Germany

Received 2017 May 16; revised 2017 September 8; accepted 2017 September 11; published 2017 September 25

Abstract

Star-forming galaxies emit GeV and TeV gamma-rays that are thought to originate from hadronic interactions of cosmic-ray (CR) nuclei with the interstellar medium. To understand the emission, we have used the moving-mesh code AREPO to perform magnetohydrodynamical galaxy formation simulations with self-consistent CR physics. Our galaxy models exhibit a first burst of star formation that injects CRs at supernovae. Once CRs have sufficiently accumulated in our Milky Way–like galaxy, their buoyancy force overcomes the magnetic tension of the toroidal disk field. As field lines open up, they enable anisotropically diffusing CRs to escape into the halo and to accelerate a bubble-like, CR-dominated outflow. However, these bubbles are invisible in our simulated gamma-ray maps of hadronic pion-decay and secondary inverse-Compton emission because of low gas density in the outflows. By adopting a phenomenological relation between star formation rate (SFR) and far-infrared emission and assuming that gamma-rays mainly originate from decaying pions, our simulated galaxies can reproduce the observed tight relation between far-infrared and gamma-ray emission, independent of whether we account for anisotropic CR diffusion. This demonstrates that uncertainties in modeling active CR transport processes only play a minor role in predicting gamma-ray emission from galaxies. We find that in starbursts, most of the CR energy is “calorimetrically” lost to hadronic interactions. In contrast, the gamma-ray emission deviates from this calorimetric property at low SFRs due to adiabatic losses, which cannot be identified in traditional one-zone models.

Key words: cosmic rays – galaxies: formation – gamma rays: galaxies – magnetohydrodynamics (MHD) – methods: numerical – radiation mechanisms: non-thermal

1. Introduction

Cosmic rays (CRs), magnetic fields, and turbulent motions contribute equally to the total midplane pressure in the Milky Way (Boulares & Cox 1990). This could originate from a self-regulated feedback loop and may even suggest that CRs play an active role in shaping galaxies by altering the dynamics and driving galactic winds through their gradient pressure force, as suggested by theoretical works (Breitschwerdt et al. 1991; Everett et al. 2008), three-dimensional simulations of galaxies (Uhlig et al. 2012; Booth et al. 2013; Hanasz et al. 2013; Salem & Bryan 2014; Pakmor et al. 2016b), and the interstellar medium (ISM; Girichidis et al. 2016; Simpson et al. 2016). This idea can be scrutinized by studying CR-induced radiative processes with the goal to extract the CR pressure from the nonthermal emission at radio and gamma-ray energies.

Most of the galactic diffuse emission is generated by massive stars, preferentially in the beginning and at the end of their lives. Young massive stars emit mostly ultraviolet (UV) photons, which are absorbed by dust grains. This radiation is then re-emitted in the far-infrared (FIR) provided the dust is optically thick to UV photons. This is the case in actively star-forming galaxies, supporting the phenomenological correlation of the FIR emission with the SFR (Kennicutt 1998a). After their fuel is exhausted, massive stars explode as core-collapse supernovae, whose remnants are believed to accelerate CR protons and electrons in galaxies through diffusive shock acceleration.

CR electrons gyrate in the interstellar magnetic field and emit radio-synchrotron radiation that closely correlates with the total FIR luminosity of galaxies over five orders of magnitude in luminosity (Bell 2003). The same radio-emitting CR electrons can generate high-energy gamma-ray emission either through free–free transitions in the vicinity of gas nuclei (bremsstrahlung) or by inverse-Compton (IC) scattering off of radiation fields. Hadronic collisions between CR nuclei and the ISM also produce gamma-rays alongside other decay products via pion decay:

$$\pi^0 \rightarrow 2\gamma,$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu / \overline{\nu}_\mu \rightarrow e^\pm + \nu_e / \overline{\nu}_e + \nu_\mu + \overline{\nu}_\mu.$$

These secondary relativistic electrons and positrons (hereafter simply electrons) can emit radio-synchrotron emission in the presence of ubiquitous galactic magnetic fields as well as upscatter ambient photon fields into the gamma-ray regime through IC interactions.

Recently, nearby starburst galaxies have been detected in high-energy gamma-rays by space-based (Abdo et al. 2010) and imaging air-Cherenkov telescopes (Acero et al. 2009; VERITAS Collaboration et al. 2009). Upper limits and detections of the galactic gamma-ray emission by the Fermi telescope revealed a tight FIR–gamma-ray relation (Ackermann et al. 2012; Rojas-Bravo & Araya 2016). The gamma-ray emission enables testing whether starbursts act as proton “calorimeters” (where most of the CR energy is lost to hadronic interactions; Lacki et al. 2011; Wang & Fields 2016) and whether CRs are dynamically important in starbursts (Yoast-Hull et al. 2016).

Here, we present high-resolution MHD simulations with CR physics of forming disk galaxies and compute the gamma-ray emission. This enables us to critically assess simplifying
assumptions made in previous one-zone analyses. We describe our simulations in Section 2 and lay out our methodology to compute pion-decay and IC emission in Section 3. We analyze gamma-ray emission maps and the FIR–gamma-ray relation in Section 4 and conclude in Section 5.

2. Simulations

We simulate the formation of isolated disks in dark-matter (DM) halos that range in mass from $10^{10}$ to $10^{12} \, M_\odot$. We use the second-order accurate, adaptive moving-mesh code AREPO (Springel 2010; Pakmor et al. 2016c). We model the ISM with an effective equation of state with radiative cooling and star formation using a probabilistic approach (Springel & Hernquist 2003). Magnetic fields are treated with ideal MHD (Pakmor & Springel 2013).

CRs are modeled as a relativistic fluid with a constant adiabatic index of $4/3$ in a two-fluid approximation (Pfrommer et al. 2017). We describe CR generation at remnants of core-collapse supernovae by instantaneously injecting all CR energy produced by a stellar particles population through this channel with an energy efficiency of $\zeta_{\text{SN}} = 0.1$ into its surroundings immediately after birth. We account for adiabatic changes of the CR energy as well as CR cooling via Coulomb and hadronic CR interactions, assuming an equilibrium momentum distribution (Pfrommer et al. 2017). To bracket the uncertainty regarding CR transport, we simulate two models. In model CR adv, we only advect CRs with the gas while model CR diff additionally accounts for anisotropic diffusion relative to the rest frame of the gas with a diffusion coefficient of $10^{28} \, \text{cm}^2 \, \text{s}^{-1}$ along the magnetic field and no diffusion perpendicular to it (Pakmor et al. 2016a). Our simulations do not include CR streaming (unlike Wiener et al. 2017).

DM halos are modeled as static NFW (Navarro et al. 1997) profiles with a fixed concentration parameter of $c_{200} = 12$ across our halo mass range and one $10^{12} \, M_\odot$ halo with $c_{200} = 7$. The gas is initially in hydrostatic equilibrium with the DM potential. The halo carries a small amount of angular momentum, parameterized by the spin parameter $\lambda = 0.05$. In all cases, we adopt a baryon mass fraction of $\Omega_b/\Omega_m = 0.155$. We assume a uniform, homogeneous seed field along the z-axis with strength $10^{-12} \, \text{G}$ and no CRs in the initial conditions.

We start our simulations with $10^7$ gas cells inside the virial radius, each of which has a target mass of $155 \, M_\odot \times M_{10}$, where $M_{10} = M_{200}/(10^{10} \, M_\odot)$. This target gas mass corresponds to the typical mass of a stellar population particle. We require that the mass of all cells is within a factor of two of the target mass by explicitly refining and de-refining cells. We additionally require adjacent cells to differ in volume by less than a factor of 10 and refine the larger cell if this condition is violated.

3. Radiative Processes

3.1. Pion-decay Gamma-Rays

Pion-decay gamma-rays arise from inelastic CR interactions with thermal nuclei. We assume that the one-dimensional CR momentum spectrum per volume element, $d^3x$, follows a power law:

$$\frac{d^4 N}{dp \, d^3x} = f_p(p) = 4\pi p^2 f_p^{(3)}(p) = C_p p^{-\alpha} \theta(p-q),$$

where $p = p_i/(m_p c)$ is the dimensionless proton momentum, $\theta(p-q)$ denotes the Heaviside step function, $q$ is the low-momentum cutoff, and $\alpha$ is the CR spectral index. The normalization is determined by solving the CR energy density ($\varepsilon_{\gamma}$) for $C_p$:

$$\varepsilon_{\gamma} = \int_0^\infty f_p(p)E(p)dp = \frac{C_p \, m_p c^2}{\alpha - 1} \times \left[ \frac{1}{2} B_{1+q}(\frac{\alpha - 2}{2}, \frac{3 - \alpha}{2}) + q^{\alpha-1}(\sqrt{1+q^2} - 1) \right],$$

where $E(p) = (\sqrt{1+p^2} - 1) m_p c^2$ is the kinetic proton energy and $B_j(a, b)$ denotes the incomplete beta function (Abramowitz & Stegun 1965), assuming $\alpha > 2$.

The omnidirectional gamma-ray source function from decaying pions ($s_{\gamma^{\pi^0-\gamma}}$) is (Pfrommer & Enßlin 2004)

$$\frac{d^2N_{\gamma}}{dE_{\gamma} \, dt \, d^3x} = s_{\gamma^{\pi^0-\gamma}}(E_{\gamma}) \sim \frac{2C_p \, \sigma_{\gamma p} \, n_A}{3\alpha \, m_p c^2 \left( \frac{2m_p}{m_A} \right)^\alpha} \times \left[ f_{\gamma_{\gamma}} \left[ 2E_{\gamma} \delta \left( \frac{m_p}{m_A} \right) \left( \frac{m_A}{m_p} c^2 \right)^2 \right] + f_{\gamma_{\gamma}} \left( \frac{2E_{\gamma}}{m_A c^2} \right)^{-\alpha/\delta} \right],$$

where $m_p$ is the pion rest mass and $n_A = n_H + 4n_{\text{He}} = \rho/m_p$ is the target density of nucleons, neglecting metals. This treatment accounts for all physical processes at the pion production threshold, which are parameterized by the shape parameter $\delta$ and the effective cross-section $\sigma_{\gamma p}$ in terms of the photon index $\alpha_\gamma = \alpha$ according to

$$\delta \approx 0.14 \, \alpha^{-1.6} + 0.44 \quad \text{and} \quad \sigma_{\gamma p} \approx 32 \times (0.96 + e^{4.4 - 2.4\alpha}) \, \text{mbarn}.$$ (4)

The energy-integrated gamma-ray emissivity for the energy band $[E_i, E_f]$ (in units of erg cm$^{-3}$) that results from pion decay is given by

$$\Lambda_{\gamma^{\pi^0-\gamma}}(E_i, E_f) = \int_{E_i}^{E_f} s_{\gamma^{\pi^0-\gamma}}(E_{\gamma}) E_{\gamma} \, dE_{\gamma},$$

$$= \frac{2C_p \, m_p^3 e^2 \sigma_{\gamma p} n_A}{3\alpha \delta \, m_p} \left( \frac{m_p}{2m_A} \right)^\alpha \left[ B_j \left( \frac{\alpha + 2}{2\delta}, \frac{\alpha - 2}{2\delta} \right) \right]^y_i,$

$$\gamma_i = \left[ 1 + \left( \frac{m_p e^2}{2E_i} \right)^{2\delta-1} \right]^{-1} \text{for } i \in \{1, 2\}.$$ (7)

3.2. Secondary IC Emission

The mean energies of isotropically scattered IC photons and scattering CR electrons are related by

$$h\nu_{\text{IC}} = \frac{4}{3} h\nu_{\text{init}} \gamma_i^2 \approx 1 \, \text{GeV} \, \nu_{\text{init}} \nu_{\text{CMB}} \left( \frac{\gamma_i}{10^6} \right)^2, $$ (8)

where the particle kinetic energy $E/(m_e c^2) = \gamma - 1$ is defined in terms of the Lorentz factor $\gamma$. We adopt cosmic microwave background (CMB) photons with a characteristic energy $h\nu_{\text{CMB}} = 0.66 \, \text{meV}$ as the source for IC emission using Wien’s displacement law. The IC cooling time of these relativistic
electrons is $t_{IC} \sim 2$ Myr and thus shorter than both the CR residency time in our Galaxy and the dynamical timescales in the warm and coronal phases of the ISM. Hence, the steady-state approximation for modeling secondary IC emission is justified. Note that we neglect IC interactions with starlight and FIR photons: including them would not change any conclusions since the steady-state IC emissivity does not depend on the photon energy density (in the IC-dominated scattering regime), which solely depends on the CR electron energy density. Throughout the Letter, we neglect primary IC emission, which has a subdominant contribution to the Fermi-band luminosity (but may be important outside the disk; Selig et al. 2015).

At high momenta ($P_e > \text{GeV}/c$), the injection of secondaries is balanced by IC and synchrotron cooling, which results in an equilibrium distribution of secondary CR electrons (Pfrommer et al. 2008),

$$f_{eq}(p) dp = C_e p^{-\alpha_e} dp,$$

where we redefined $p = P_e / (m_e c)$ as the dimensionless electron momentum, $\alpha_e = \alpha + 1$ is the electron spectral index, $\sigma_T$ is the Thomson cross-section, and $\varepsilon_B$ and $\varepsilon_{ph}$ are the energy densities of the magnetic and photon fields, respectively.

The energy-integrated gamma-ray emissivity for an isotropic power-law distribution of CR electrons of Equation (9) that Compton-upts-scatters CMB photons is (derived from Equation (7.31) in Rybicki & Lightman 1979, in the case of Thomson scattering)

$$\Lambda_{IC,\rightarrow}(E_1, E_2) = \int_{E_1}^{E_2} s_{IC,\rightarrow}(E_{\gamma}) E_{\gamma} dE_{\gamma},$$

where $s_{IC,\rightarrow} = \alpha_e f_{IC}(\alpha_e) \left( \frac{E_{\gamma}}{kT_{CMB}} \right)^{\alpha_e - 3} \Gamma(\alpha_e + 5/2) \zeta(\alpha_e + 5/2) / \zeta(\alpha_e - 1)$.

and $\Lambda_0 = 16 \pi e^2 c^2 \zeta(\alpha_e - 1) / (\alpha_e - 3) h^3 e^2$.

4. Results

4.1. CR-driven Outflows in a Milky Way–like Galaxy

We first analyze our simulation of the Milky Way–like galaxy using the model CR diff $(M_{200} = 10^{12} M_\odot, c_{200} = 7)$. At the beginning of our simulation, radiative cooling diminishes pressure support of the central dense gas, starting to collapse while conserving the specific angular momentum of the gas. After settling into a rotationally supported disk, gas is compressed by self-gravity to sufficiently high densities for star formation. During the first collapse phase, a turbulent dynamo quickly grows a small-scale magnetic field, which is further amplified by a large-scale dynamo that preferentially grows a toroidal field in the disk (Pakmor et al. 2016b, 2017).

CRs are injected into the ambient ISM surrounding stellar macroparticles, providing the gas with additional nonthermal pressure. As CRs are advected and diffused, they collect in the disk and start to dominate the pressure, especially in the outer midplane of the disk and everywhere at the disk–halo interface (Figure 1). This result points to the importance of modeling CRs in simulations of galaxy formation that aim to capture their dynamical evolution. While our SFRs significantly vary over the simulation, our galaxy properties are not changing too quickly on the timescale over which the CRs lose energy and hence can be considered a reasonable proxy for observed systems.

However, the CR pressure falls short of the thermal pressure in the inner part of the disk. This is caused by overcooling of our steady-state CR fluid in the densest regions since the simulations assume a softer CR spectral index ($\alpha = 2.2$) than the analysis ($\alpha = 2.05$). This will be improved upon with future simulations that dynamically follow the CR spectrum. Moreover, we adopt a single-phase ISM rather than a realistic multiphase ISM. The latter would minimize CR losses since CRs spend more time in the lower-density warm and coronal phases, which dominate the volume.

After 1 Gyr, the CR pressure has increased to the point where the buoyancy force overcomes the magnetic tension of the toroidal magnetic field that bends and opens. CRs diffuse ahead of the gas into the halo and accelerate the gas, thereby driving a bubble-like outflow (Figure 1). The total pressure, composed of thermal, CR, and magnetic pressures, declines smoothly outward, which demonstrates that the bubble edges are contact discontinuities and not shocks.

We project the pion-decay and secondary IC emissivities along the line of sight into face-on and edge-on views (Figure 1) according to $S_{i,\rightarrow}(\hat{n}) = \int L_{i,\rightarrow} dr$, where $i \in \{\pi^0, IC\}$ and $\hat{n}$ is a unit vector perpendicular to the line of sight. Despite the high CR load of the outflow, neither pion-decay nor IC gamma-ray emission show signatures of hadronic gamma-ray bubbles because the fast outflow ($v_{\perp} \lesssim 150$ km s$^{-1}$) evacuates the gas in the bubble region. This is consistent with findings by Bayesian nonparametric reconstructions of the Fermi sky, which suggests that the Fermi bubbles are of leptonic origin (Selig et al. 2015).

Figure 2 compares the pion-decay-induced gamma-ray spectra to the IC spectra from an equilibrium secondary CR electron population in the weak-field regime ($B = 0$). This choice maximizes the IC yield of the cooling electron population and keeps the pion-decay-to-IC photon ratio at a constant value that solely depends on the spectral index. Increasing the field strength above the CMB equivalent field strength of $B_{CMB} = 3.24$ $\mu$G causes the electrons to cool preferentially by emitting radio-synchrotron radiation. Less energy is then emitted via IC interactions. This happens in our Milky Way–like galaxy for radii $r \lesssim 3$ kpc at $t = 1$ Gyr and the field strength increases with time to tens of $\mu$G in the center due to the ongoing magnetic dynamo. At larger radii in the
Figure 1. Properties of the gas disk in our Milky Way–like galaxy ($M_{200} = 10^{13} M_{\odot}$) at 1 Gyr, shortly after the onset of a CR-driven central outflow. The MHD simulations account for CR injection at supernova remnants and follow their advection with the gas and anisotropic diffusion along the magnetic fields relative to the gas. In the top panels, we show cross-sections of gas properties in the midplane of the disk (face-on views) and vertical cut-planes through the center (edge-on views) of the gas density (left), CR energy density (middle), and CR-to-thermal pressure ratio (right). In the bottom panels, we show face-on and edge-on projections of observables: gas surface mass density (left), pion-decay-induced gamma-ray surface brightness from 0.1 to 100 GeV (middle), and secondary IC surface brightness in the same energy band (right). Both gamma-ray maps do not show the CR-loaded outflow in the form of hadronic gamma-ray bubbles.
The Astrophysical Journal Letters, 847:L13 (8pp), 2017 October 1

Pfrommer et al.

Figure 2. Spectral distribution of the differential gamma-ray source function (top) and the energy-integrated gamma-ray emissivity, \( \Lambda_{\Gamma} \), vs. energy (middle) that results from hadronic CR interactions for different CR spectral indices, \( \alpha \) (colored differently). We also present \( \Lambda_{\Gamma} \) vs. spectral index in the Fermi-energy band (bottom) for various low-momentum cutoffs \( q \) of the distribution function (colored differently). Shown are pion-decay-induced gamma-ray spectra (solid) and IC spectra from a steady-state secondary CR electron population (dashed–dotted) in the weak-field regime (\( B = 0 \)). The model calculations assume a fixed CR energy density of \( \varepsilon_{\text{CR}} = 10^{-11} \text{erg cm}^{-3} \) and target nucleon density \( n_n = 1 \text{ cm}^{-3} \), which both impact the absolute normalization of the spectra in equal measures.

low-\( B \) regime, \( \Lambda_{\pi^- \gamma}/\Lambda_{\text{IC} \gamma} = 4.3 \) for \( \alpha = 2.05 \). Due to the strong IC suppression in the center, the pion-decay luminosity (3.2 \( \times \) \( 10^{49} \) erg s\(^{-1}\)) dominates over the secondary IC luminosity (5.6 \( \times \) \( 10^{39} \) erg s\(^{-1}\)) by a factor of 5.7. Hence, we neglect the IC contribution to the gamma-ray luminosity in what follows.

Throughout this Letter, we adopt \( \alpha = 2.05 \) and \( q = 0.5 \), which yields an average value of \( \Lambda_{\pi^- \gamma} \) that is within a factor of 2.5 from the extreme outliers for a broad variety of physically motivated values for \( \alpha \) and \( q \) (see the bottom panel of Figure 2). The observed photon index is expected to be somewhat steeper (matching the observed range of \( \alpha_\gamma = 2.1\textnormal{--}2.4 \); Ackermann et al. 2012) due to a combination of energy-dependent CR streaming and diffusion in Kolmogorov turbulence.

4.2. FIR-Gamma-Ray Relation

We now analyze our entire galaxy sample for both models CR adv and CR diff while fixing \( c_{\text{200}} = 12 \) to ensure self-similarly evolving galaxies. We believe that each of our galaxy simulations are good analogs of observed galaxies as they go through different evolutionary phases: initial gas collapse is immediately followed by a starburst that transitions to an intense star-forming thick disk, which eventually settles to a quiescently star-forming thin-disk galaxy.

After 100 Myr, the \( 10^{12} \) M\(_{\odot}\) halo enters a starburst phase with a central density of \( 3 \) M\(_{\odot}\) pc\(^{-3}\) (averaged within a radius of 300 pc). Line-of-sight integration over this central region yields a central surface mass density of \( 1.8 \times 10^5 \) M\(_{\odot}\) pc\(^{-2}\) or 0.4 g cm\(^{-2}\), amounting to 1.6 (2.6) times the surface mass density inferred from M 82 (NGC 253); see Lacki et al. (2011). The corresponding simulated SFR density is \( \approx 40 \) M\(_{\odot}\) yr\(^{-1}\) kpc\(^{-2}\), which integrates to a global SFR of \( \approx 120 \) M\(_{\odot}\) yr\(^{-1}\), substantially larger than the SFRs in M 82 and NGC 253. The simulations reach a peak resolution (minimum cell radius) of \( \approx 5 \) pc, sufficient to resolve the central starburst region.

The total FIR luminosity (8–1000 \( \mu \)m) is a well-established tracer of the SFR of spiral galaxies (Kennicutt 1998b) with a conversion rate (Kennicutt 1998a)

\[
\frac{\text{SFR}}{M_{\odot}\text{yr}^{-1}} = \epsilon \times 10^{-10} \frac{L_{8–1000 \mu m}}{L_{\odot}}. \tag{15}
\]

This assumes that thermal dust emission is a calorimetric measure of the radiation of young stars, and the factor \( \epsilon = 0.79 \) derives from the Chabrier (2003) initial mass function (IMF; Crain et al. 2010). While this conversion is reliable at \( L_{8–1000 \mu m} > 10^9 L_{\odot} \), it becomes progressively worse at smaller FIR luminosities due to the lower metallicity and dust content, which implies a low optical depth to IR photons and invalidates the calorimetric assumption (Bell 2003). Blindly applying the conversion yields the gray data points in Figure 3 for the Small and Large Magellanic Clouds (SMC, LMC). More reliable SFR estimates for the SMC range from 0.036 M\(_{\odot}\) yr\(^{-1}\) (combining H\(_\alpha\) and FIR emission, assuming a Chabrier IMF; Wilke et al. 2004) to 0.1 M\(_{\odot}\) yr\(^{-1}\) (UVBI photometry, Harris & Zaritsky 2004) and yield 0.2 M\(_{\odot}\) yr\(^{-1}\) for the LMC (UVBI photometry; Harris & Zaritsky 2009).

In Figure 3, we correlate the gamma-ray luminosity in the Fermi band (0.1–100 GeV) to the SFR for all simulated galaxies at various times (see Table 1, and relate them to the FIR luminosity via Equation (15)). We find very similar gamma-ray luminosities in our models CR adv and CR diff, which both match the observed relation \( L_\gamma/\text{erg s}^{-1} = 8.9 \times 10^{27} (L_{8–1000 \mu m}/L_{\odot})^{1/12} \) (Rojas-Bravo & Araya 2016) for \( L_{8–1000 \mu m} > 10^9 L_{\odot} \). The simulations appear to overpredict the gamma-ray luminosity at the lowest SFRs. The match may be improved by lowering the gas density in these halos or by adopting a realistic multiphase ISM, which becomes more porous toward lower SFRs.
The Astrophysical Journal Letters, 847:L13 (8pp), 2017 October 1

Pfrommer et al.

Those dominate over the adiabatic CR losses at late times and thus move the lowest two (light blue) simulation points in Figure 3 closer to the calorimetric relation.

So far, we choose the canonical value for the CR injection efficiency at supernovae of $\zeta_{\text{SN}} = 0.1$. Varying this value by a factor of three results in a similar change in $L_\gamma$ (Table 1). In all of these cases, the CR injection and adiabatic gains are balanced by the total CR cooling rate, indicating self-regulation. Hence, $L_\gamma$ and—by extension—the FIR–gamma-ray relation remain invariant if $\zeta_{\text{SN}}$ decreases by a factor of two and the CR spectral index is increased to $\alpha = 2.15$ (Figure 2).

5. Concluding Remarks

For the first time, we have calculated the gamma-ray emission in galaxy simulations that span four orders of magnitude in SFRs and by modeling ideal MHD and CR physics self-consistently. We identify the influence of different CR gain and loss processes on the gamma-ray emission.

In agreement with previous literature, we find that the gamma-ray luminosity from decaying pions dominates over the IC emission by at least a factor of 5.7 in the Fermi-energy band 0.1–100 GeV. This dominance increases significantly for spectral indices steeper than $\alpha = 2.05$. The continuous injection of CR energy at supernova remnants increases CR pressure to the point where the buoyancy force overcomes the magnetic tension of the dominant toroidal field after 1 Gyr. This enables CRs to diffuse into the halo and to accelerate the gas in a bubble-like, CR-dominated outflow. However, these bubbles are invisible in our simulated gamma-ray maps of hadronic pion-decay and IC emission because of low gas density in the outflows. This suggests that morphological features such as the Fermi bubbles in the Milky Way may be generated by leptonic IC emission.

We find that most CR energy is lost to hadronic interactions at high SFRs. However, the gamma-ray emission deviates from this calorimetric property at low SFRs due to adiabatic losses, which cannot be identified in traditional one-zone models. Assuming that gamma-rays mainly originate from decaying pions, we show that our simulated galaxies exactly reproduce the observed FIR–gamma-ray relation at FIR luminosities $L_\text{FIR} > 10^9 L_\odot$. This nontrivial finding comes about because we adopt a phenomenological relation between SFR and CR injection and because $L_\gamma \propto f_{\text{cal}} L_{\text{CR}} \propto f_{\text{cal}} SFR$, where the calorimetric factor $f_{\text{cal}}$ smoothly decreases toward smaller SFRs due to the increasing importance of adiabatic losses. At small FIR luminosities ($L_\text{FIR} < 10^9 L_\odot$), the Magellanic Clouds emit fewer gamma-rays in comparison to our simulated analogs. We speculate that this is either due to a too dense ISM or due to a missing multiphase, porous ISM in our simulations, which would lower the hadronic gamma-ray yield at fixed gas mass, provided the CR density is (anti-)correlated with the thermal gas.

Most importantly, the simulated gamma-ray emission does not depend on whether we account for anisotropic CR diffusion in addition to CR advection. The somewhat higher CR energy is compensated by the lower gas density in our CR diff model in comparison to the CR adv model. This demonstrates that uncertainties in modeling active CR transport processes only play a minor role in predicting gamma-ray emission from galaxies and emphasizes the importance of dynamic simulations of galaxy formation to understand nonthermal processes.

The relative contribution of hadronic losses to the total CR loss rate, $\Gamma_{\text{had}}/\Gamma_{\text{tot}}$, sets the normalization of the calorimetric relation, $L_\gamma \propto L_{\text{CR}} \propto SFR$ ($L_{\text{CR}}$ is the CR luminosity). Star-forming galaxies with SFR $\geq 10 M_\odot$ yr$^{-1}$ are close to the calorimetric relation (see Figure 3). Instead, galaxies with lower SFRs fall below this relation, indicating that non-hadronic CR energy losses start to become relevant.

We explore different CR energy gain and loss processes in Figure 4. In the Milky Way–like halo, the nonadiabatic CR loss processes (hadronic and Coulomb interactions) cool most of the CR energy that is injected, with cooling rates of $\Gamma_{\text{had}} = 7.44 \times 10^{-16}$ s$^{-1}$ and $\Gamma_{\text{cont}} = 2.78 \times 10^{-16}$ s$^{-1}$, respectively (Pfrommer et al. 2017). The (sub)dominant) adiabatic gains in the CR diff model are twice those of the CR adv model as CRs that are diffusing from the dense ISM into the halo are caught by the accretion flow and get advected back onto the disk. Hence, the calorimetric assumption for these high-mass galaxies is justified.

This is in stark contrast to the dwarf-galaxy simulation ($10^{10} M_\odot$ halo), where adiabatic and nonadiabatic losses are equally strong in the CR diff model. This is the main reason why these slowly simmering star-forming galaxies deviate from the calorimetric relation. In our dwarf-galaxy simulation in the CR adv model, the SFR levels off after 0.3 Gyr. This causes an almost linear increase of the CR injection rate that is counteracted by the increasing nonadiabatic CR cooling rates.
Table 1

SFRs and Gamma-Ray Luminosity $L_{\gamma,0.1-100\text{GeV}}$ for Our Simulated Galaxies

| $M_{200}$ ($M_\odot$) | $c_{200}$ | $\zeta_{\text{SN}}$ | $t$ (Gyr) | SFR ($M_\odot$ yr$^{-1}$) | $L_{\gamma,0.1-100\text{GeV}}$ (erg s$^{-1}$) | $t$ (Gyr) | SFR ($M_\odot$ yr$^{-1}$) | $L_{\gamma,0.1-100\text{GeV}}$ (erg s$^{-1}$) |
|-----------------|----------|-----------------|----------|-------------------------|-----------------------------|----------|-------------------------|-----------------------------|
| $10^{12}$       | 12       | 0.10            | 0.1      | $2.76 \times 10^4$      |                             | 0.1      | $3.6 \times 10^5$       |                             |
| $10^{12}$       | 12       | 0.10            | 0.3      | $1.01 \times 10^4$      |                             | 0.4      | $3.8 \times 10^5$       |                             |
| $10^{12}$       | 12       | 0.10            | 1.0      | $3.91 \times 10^5$      |                             | 1.2      | $1.3 \times 10^5$       |                             |
| $10^{12}$       | 12       | 0.10            | 2.3      | $1.31 \times 10^6$      |                             | 2.5      | $4.5 \times 10^6$       |                             |
| $10^{12}$       | 12       | 0.10            | 4.8      | $5.19 \times 10^6$      |                             | 4.5      | $1.7 \times 10^6$       |                             |
| $10^{12}$       | 12       | 0.10            | 0.2      | $1.45 \times 10^6$      |                             | 0.4      | $5.3 \times 10^6$       |                             |
| $10^{12}$       | 12       | 0.10            | 0.7      | $4.04 \times 10^6$      |                             | 0.9      | $1.8 \times 10^6$       |                             |
| $10^{12}$       | 12       | 0.10            | 1.3      | $1.08 \times 10^7$      |                             | 1.8      | $7.2 \times 10^7$       |                             |
| $10^{12}$       | 12       | 0.10            | 2.2      | $4.08 \times 10^7$      |                             | 3.0      | $3.2 \times 10^7$       |                             |
| $10^{12}$       | 12       | 0.10            | 0.1      | $1.31 \times 10^8$      |                             | 0.2      | $1.9 \times 10^7$       |                             |
| $10^{12}$       | 12       | 0.10            | 0.6      | $6.13 \times 10^8$      |                             | 2.0      | $7.1 \times 10^7$       |                             |
| $10^{12}$       | 12       | 0.10            | 1.2      | $1.63 \times 10^9$      |                             | 12.0     | $3.0 \times 10^8$       |                             |
| $10^{12}$       | 12       | 0.10            | 0.2      | $3.93 \times 10^9$      |                             |         |                         |                             |
| $10^{12}$       | 7        | 0.03            | 0.2      | $1.78 \times 10^9$      |                             |         |                         |                             |
| $10^{12}$       | 7        | 0.03            | 0.8      | $6.31 \times 10^9$      |                             |         |                         |                             |
| $10^{12}$       | 7        | 0.03            | 2.3      | $6.36 \times 10^9$      |                             |         |                         |                             |
| $10^{12}$       | 7        | 0.05            | 0.7      | $2.80 \times 10^9$      |                             |         |                         |                             |
| $10^{12}$       | 7        | 0.05            | 2.1      | $8.64 \times 10^9$      |                             |         |                         |                             |
| $10^{12}$       | 7        | 0.10            | 0.2      | $1.33 \times 10^9$      |                             |         |                         |                             |
| $10^{12}$       | 7        | 0.10            | 0.6      | $5.01 \times 10^9$      |                             |         |                         |                             |
| $10^{12}$       | 7        | 0.10            | 1.9      | $1.54 \times 10^9$      |                             |         |                         |                             |
| $10^{12}$       | 7        | 0.30            | 0.2      | $3.31 \times 10^9$      |                             |         |                         |                             |
| $10^{12}$       | 7        | 0.30            | 0.5      | $1.22 \times 10^9$      |                             |         |                         |                             |
| $10^{12}$       | 7        | 0.30            | 1.6      | $4.72 \times 10^9$      |                             |         |                         |                             |

Figure 4. Time evolution of different CR energy gain and loss processes for a dwarf galaxy of mass $10^{10} M_\odot$ (left) and a Milky Way–like galaxy of mass $10^{12} M_\odot$ (right). We contrast our model of advective CR transport (dashed) to the model in which we additionally follow anisotropic CR diffusion (solid). While CRs experience a modest adiabatic energy gain in the Milky Way–like galaxy, they suffer a substantial adiabatic loss in the dwarf galaxy that even matches the nonadiabatic CR loss in model CR diff. This causes the FIR–gamma-ray relation to deviate from the calorimetric relation.

We thank Else Starkenburg, Annette Ferguson, and Alice Quillen for useful discussions and an anonymous referee for a constructive report. C.P., R.P., C.S., and V.S. acknowledge support by the European Research Council under ERC-CoG grant CRAGSMAN-646955, ERC-StG grant EXAGAL 308037, and from the Klaus Tschira Foundation.
References

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJL, 709, L152
Abramowicz, M., & Stegun, I. A. 1965, Handbook of Mathematical Functions (New York: Dover)
Acero, F., Aharonian, F., Akhperjanian, A. G., et al. 2009, Sci, 326, 1080
Ackermann, M., Ajello, M., Allafort, A., et al. 2012, ApJ, 755, 164
Bell, E. F. 2003, ApJ, 586, 794
Booth, C. M., Agertz, O., Kravtsov, A. V., & Gnedin, N. Y. 2013, ApJL, 777, L16
Boulares, A., & Cox, D. P. 1990, ApJ, 365, 544
Breitschwerdt, D., McKenzie, J. F., & Voelk, H. J. 1991, A&A, 245, 79
Chabrier, G. 2003, ApJL, 586, L133
Crain, R. A., McCarthy, I. G., Frenk, C. S., Theuns, T., & Schaye, J. 2010, MNRAS, 407, 1403
Everett, J. E., Zweibel, E. G., Benjamman, R. A., et al. 2008, ApJ, 674, 258
Griffiths, P., Naab, T., Walch, S., et al. 2016, ApJL, 816, L19
Griffin, R. D., Dai, X., & Thompson, V. A. 2016, ApJL, 823, L17
Hanasz, M., Lesch, H., Naab, T., et al. 2013, ApJL, 777, L38
Harris, J., & Zaritsky, D. 2004, AJ, 127, 1531
Harris, J., & Zaritsky, D. 2009, AJ, 138, 1243
Kennicutt, R. C., Jr. 1998a, ARA&A, 36, 189
Kennicutt, R. C., Jr. 1998b, ApJ, 498, 541
Lacki, B. C., Thompson, T. A., Quataert, E., Loeb, A., & Waxman, E. 2011, ApJ, 734, 107
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Pakmor, R., Gómez, F. A., Grand, R. J. J., et al. 2017, MNRAS, 469, 3185
Pakmor, R., Pfrommer, C., Simpson, C. M., Kannan, R., & Springel, V. 2016a, MNRAS, 462, 2603
Pakmor, R., Pfrommer, C., Simpson, C. M., & Springel, V. 2016b, ApJL, 824, L30
Pakmor, R., & Springel, V. 2013, MNRAS, 432, 176
Pakmor, R., Springel, V., Bauer, A., et al. 2016c, MNRAS, 455, 1134
Peng, F.-K., Wang, X.-Y., Liu, R.-Y., Tang, Q.-W., & Wang, J.-F. 2016, ApJL, 821, L20
Pfrommer, C., & Enßlin, T. A. 2004, A&A, 413, 17
Pfrommer, C., Enßlin, T. A., & Springel, V. 2008, MNRAS, 385, 1211
Pfrommer, C., Pakmor, R., Schaal, K., Simpson, C. M., & Springel, V. 2017, MNRAS, 465, 4500
Rojas-Bravo, C., & Araya, M. 2016, MNRAS, 463, 1068
Rybicki, G. B., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York: Wiley-Interscience)
Salem, M., & Bryan, G. L. 2014, MNRAS, 437, 3312
Selig, M., Vacca, V., Oppermann, N., & Enßlin, T. A. 2015, A&A, 581, A126
Simpson, C. M., Pakmor, R., Marinacci, F., et al. 2016, ApJL, 827, L29
Springel, V. 2010, MNRAS, 401, 791
Springel, V., & Hernquist, L. 2003, MNRAS, 339, 289
Tang, Q.-W., Wang, X.-Y., & Tam, P.-H. T. 2014, ApJ, 794, 26
Uhlig, M., Pfrommer, C., Sharma, M., et al. 2012, MNRAS, 423, 2374
VERITAS Collaboration, Acciari, V. A., Aliu, E., et al. 2009, Natur, 462, 770
Wang, X., & Fields, B. D. 2016, arXiv:1612.07290
Wiener, J., Pfrommer, C., & Peng, Oh, S. 2017, MNRAS, 467, 906
Wilke, K., Klaas, U., Lemke, D., et al. 2004, A&A, 414, 69
Yoast-Hull, T. M., Gallagher, J. S., & Zweibel, E. G. 2016, MNRAS, 457, L29