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Author(s)	Owen, Ellis R.
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Modeling diffuse signatures of cosmic ray processes in galaxies: extra-galactic gamma-ray background radiation

Ellis R. Owen
大阪大学 大学院理学研究科

1. Introduction

Cosmic rays are energetic, relativistic particles. Within our Galaxy, they contain a non-negligible fraction of the energy budget, with their total energy density being around 1 eV/cm^3 at the solar circle (this is comparable to thermal, turbulent, and magnetic energy densities; see e.g. 1). Cosmic rays are believed to originate from violent astrophysical environments, such as supernova remnants and young massive stellar clusters (2, 3), where strong shocks can boost charged particles to highly relativistic energies through diffusive acceleration processes (4). External galaxies undergoing intensive episodes of star-formation (starbursts) will have an abundance of these accelerator environments, so it is expected they will be rich in cosmic rays. It has been shown that the high abundance of cosmic rays in starbursts is able to modify their thermal and hydrodynamical properties (5), and drive significant high energy non-thermal emission, ranging from radio wavelengths to gamma-rays (6, 7).

Cosmic rays are therefore a potentially important physical component within galaxy ecosystems which can control their development. However, they are rarely included in detailed galaxy evolution models. While sophisticated treatments of mechanical and radiation physics are often included in these models (8, 9, 10), current approaches do not fully capture the observed evolutionary properties in populations of galaxies. In particular, model predictions for the abundance, halo-to-stellar mass ratios and star-forming histories of some galaxy types show particularly severe discrepancies from observations (e.g. very massive and intensively star-forming or primordial galaxies). As such, there are now renewed efforts to search for hidden agents shaping galaxy evolution, with cosmic rays being one clear candidate.

The non-thermal emission from populations of galaxies can be a useful way to test models of cosmic ray effects in galaxy evolution. One possibility is to use their gamma-ray emission. While gamma-rays have now been detected from a small number of spatially resolved nearby galaxies (7), extending these detections to large populations of distant galaxies is beyond the capability of current and near-future instruments, and is also subject to physical horizons.

Instead, it is possible to use the unresolved background gamma-ray emission from large populations of distant galaxies to probe cosmic ray activities. In this project, the contribution to this background emission was modelled using a novel MPI galaxy gamma-ray emission prototype code. This code post-processed outputs from galaxy formation and evolution simulations (11) and computed the expected gamma-ray background emission they contribute, as observed from Earth. The precise methodological set-up for this code is described in Ref (12). Developing these reliable models for the galaxy contribution to the gamma-ray background is essential to understand the physical information that can be obtained from future measurements, and to inform observational strategies and analysis techniques for up-coming facilities (e.g. the Cherenkov Telescope Array; see Ref. 13).

2. A new prototype model for cosmic ray containment in galaxies

In previous studies, it has been challenging to properly quantify precisely how well galaxies can contain their cosmic rays. Determining a correct treatment is essential to model the gamma-ray background intensity and spectral shape reliably. Earlier studies simply adopted a fiducial value to quantify the containment (or `calorimetry') of cosmic rays in these galaxies (see 12). The physics governing cosmic ray calorimetry in galaxies is a combination of attenuation by the interactions they undergo in the interstellar gases of their host system (so-called hadronic pp interactions – see Ref. 14), and cosmic ray transport effects. Existing models provide a relatively thorough treatment of the attenuation effect. However, the escape of cosmic rays by advection in bulk plasma flows out of a galaxy has received less attention.

2.1 Cosmic ray transport

Charged cosmic rays propagate through galactic ecosystems by diffusion and advection. The former dominates within a galaxy where turbulent magnetic fields suffuse interstellar gases, while the latter can be important for mid-energy cosmic rays entrained in fast, bulk flows. Such flows can arise from the confluence of energy and matter injection by concentrated star-forming activity in galaxies. They can be driven by thermal pressure gradients associated with gas heated by the processes associated with concentrated star-formation, or they can be driven by non-thermal pressure gradients associated with cosmic rays (15, 16). Thus, cosmic rays operate to drive large scale flows while also being redistributed by them.

2.2 Cosmic ray containment

To model an outflow driven by thermal gas pressure and cosmic rays, a two-fluid prescription was adopted. The first fluid is a thermal gas, while the second is a non-thermal cosmic ray fluid. This does not capture the energy spectrum of the cosmic rays, but it is sufficient for the purposes of this work, as it broadly incorporates the dynamical impacts of the total cosmic ray pressure gradients on the outflow and the spatial distribution of the cosmic ray energy density entrained in the flow. This allows the redistributive effects of an outflow on the cosmic rays in a galaxy halo to be modeled.

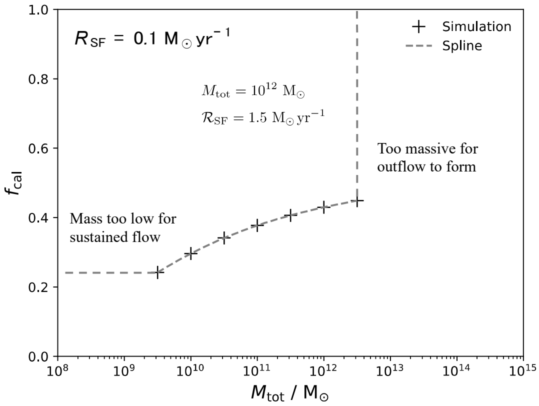

Figure 1 : The containment fraction of cosmic rays in a galaxy subject to an advective outflow. The strongest parameter dependency is on total galaxy halo mass. For most galaxies able to sustain an outflow, between 60-80 per cent of its cosmic rays are lost.

The energy, matter and cosmic ray injection rate at the base of an outflow can be parameterized by the star-formation rate of a galaxy. By solving the 1-dimensional (isotropic) fluid equations around a galaxy of a given mass, and coupling to the cosmic ray transport equation with fiducial parameters to capture cosmic ray diffusion in the magnetic fields of the flow (see 17 for details), the resulting distribution of cosmic rays can be obtained. To model the time evolution of the system, a numerical approach is required in solving the fluid and coupled cosmic ray transport equations. The Eulerian grid-based code FLASH4 (18) was used to do this, allowing the dependency of the flow properties and resulting cosmic ray distribution on model parameters to be explored. Cosmic ray transport physics is currently theoretically unsettled at the microphysical level (e.g. 19), and only fiducial, canonical transport parameters can currently be adopted. However, the exact choices for these (e.g. for the cosmic ray diffusion coefficient) do not strongly impact the results obtained in this work.

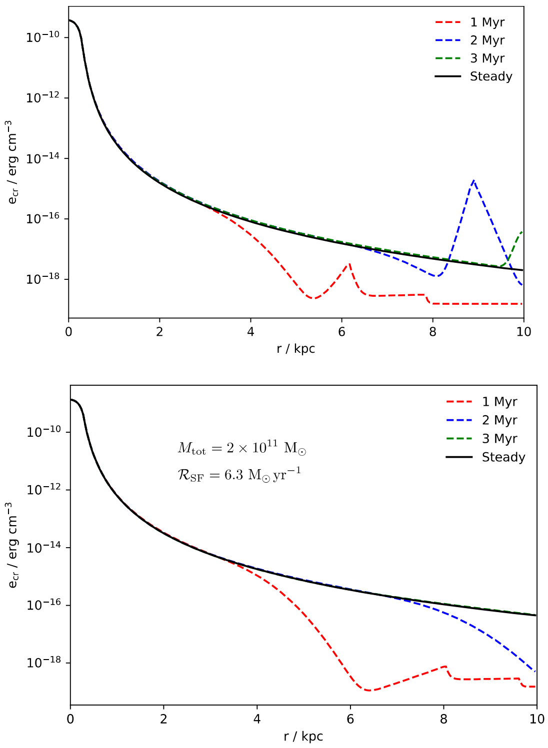

Figure 2 : Outflows evolve to a steady or unsteady state after their initial eruption. The starburst episode driving the flow is considered to persist for 10s of Myr. The flow evolution profile is affected strongly by the properties of the host galaxy, modifying the distribution and escape of cosmic rays through the halo. The top panel shows a less intensively star-forming galaxy in a strong gravitational potential, which can be compared with the bottom panel, showing a more intensively star-forming galaxy in a weak gravitational potential that is able to drive a faster, stronger outflow.

The dependency of the cosmic ray distribution in a flow on the most important galaxy parameters (found to be galaxy halo mass and star-formation rate) is shown in Figure 1, with corresponding examples of the development of a galaxy outflow over time shown in Figure 2. These results show that galactic outflows can reach a steady-scenario relatively quickly (a few Myr compared to the 100 Myr evolutionary timescale of the system), and tend to attain a cosmic ray containment fraction of around 20-40 per cent.

2.3 Post-processing model and gamma-ray background

To obtain an overall determination of the galaxy contribution to the extra-galactic gamma-ray background, a prototype model was constructed. This uses information about the star-formation rate, mass, redshift and effective size of a galaxy to determine the steady-state cosmic ray distribution therein, corrected for the effects of outflows (see section 2.3). By adopting appropriate cross sections for the production of gamma-rays via hadronic pp collisions between cosmic rays and interstellar gas (provided by Ref. 14), a corresponding gamma-ray spectrum can be calculated for a broad range of galaxy types. A full description of the prototype model adopted is available in Ref. (12). By interfacing this prototype model with the distribution of galaxy sizes, masses, star-formation rates and over redshift from the outputs of the EAGLE simulations (described in Ref. 11), the overall galaxy contribution to the extra-galactic gamma-ray background could be estimated.

In computing the gamma-ray background flux received on Earth, a co-variant radiative transport formulation was adopted that ensures the conservation of photon number and phase space volume during cosmological transport, and accounts self-consistently for gamma-gamma pair creation and the subsequent inverse-Compton scattering of high energy photons with soft background radiation fields from galaxies.

3. Results

The total contribution from star-formation in galaxies to the gamma-ray background is shown in Figure 3. This indicates a contribution ranging from 10-50 per cent of the flux, depending on energy. By splitting the contribution according to the star-formation intensity of the contributing galaxies, it was found that more than 95 per cent of the emission is contributed by rare galaxies undergoing very intensive starburst episodes.

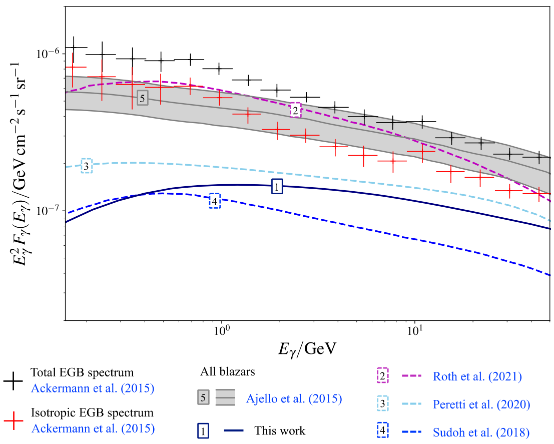

Figure 3 : Total gamma-ray background contribution at z=0, predicted by this work (line 1), compared to other studies and observational constraints.

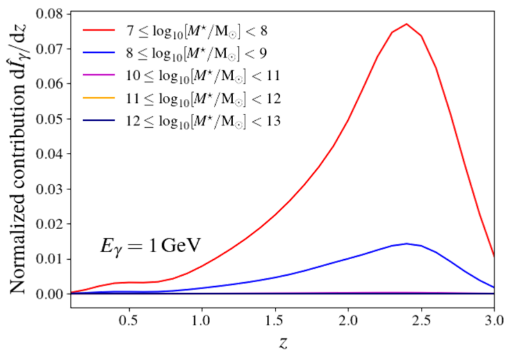

Figure 4 : Gamma-ray background contributions, showing the originating redshift of the received flux at z=0, segregated according to galaxy mass.

Figure 4 separates the total contribution according to galaxy mass and redshift. This shows that much of the emission originates from low mass galaxies, residing around redshift 2-2.5. This represents an epoch where many galaxies were growing and building up their stellar mass.

4. Discussion and conclusions

This work has shown that a significant portion of the unresolved extra-galactic gamma-ray background can be attributed to populations of star-forming galaxies. Most of the emission originates from low-mass galaxies undergoing very intensive star-formation activities, meaning gamma-ray background radiation is a biased tracer of cosmic ray feedback activities, and is particularly sensitive to cosmic rays in young galaxies building-up their stellar masses for the first time. Such galaxies are relatively rare in the Universe, which indicates new considerations may be required to establish robust statistical methods able to differentiate between contributions from various source populations, as the relative dominance of the shot noise (often used to make such distinctions) may be smaller than generally expected.

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