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Assessing the signatures imprinted by star-forming galaxies in the cosmic γ–ray background

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γ-ray emission has been detected from nearby star-forming galaxies in recent years, establishing such systems as a candidate source class for the extra-galactic γ-ray background. We investigate the spectral and anisotropic signatures such sources would imprint into the γ-ray background using a physically-motivated template model. We assess how these signatures can be modified by the properties and dynamics of star-forming galaxies over cosmic time.

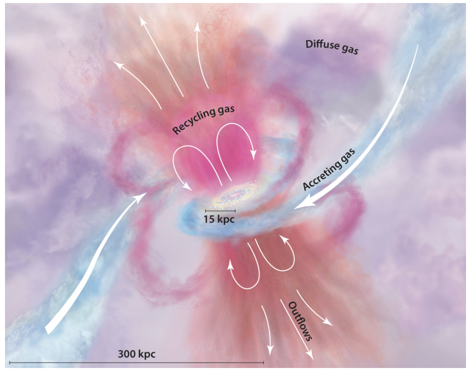
1 Introduction

Several nearby star-forming galaxies (SFGs) have been detected in γ-rays in recent years (Ajello et al. 2020), establishing such systems as a candidate source class for the extra-galactic γ-ray background (EGB). Their γ-ray emission is driven by an abundant reservoir of cosmic rays (CRs) which interact with interstellar gases to form pions and, subsequently, γ-rays.

The CRs within these systems are presumably accelerated by diffusive shock acceleration processes (e.g. Fermi 1949), boosting low energy charged seed particles to relativistic energies, operating in an abundance of violent shocked astrophysical environments. Such environments would be associated with the stellar end-products that arise soon after the onset of star-formation.

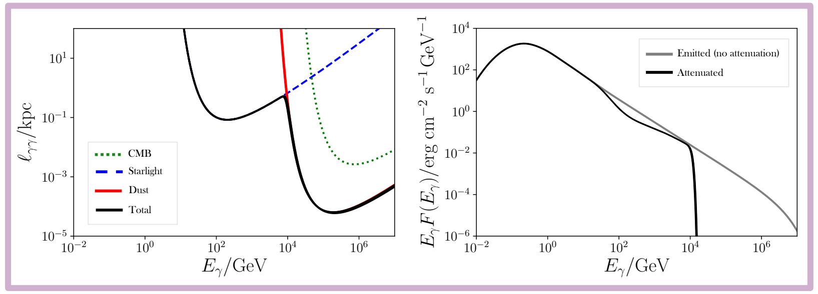
The impact of galactic outflows in removing CRs from a SFG has been argued to be substantial (Peretti et al. 2020), and this could have significant impacts for the resulting γ-ray emission from a source population. Given that outflows are ubiquitous among SFGs, they can greatly impact the possible SFG contribution to the EGB.

Figure 1: *Illustration of a galaxy in its circum-galactic environment (Tumlinson et al. 2017). Outflows and inflows are shown in red and blue respectively; these (in particular, outflows) can act to modify the containment of CRs within a galaxy, with advection removing CRs from a galaxy to reduce its γ-ray glow.*



Galactic outflows from SFGs can show evolutionary trends (Sugahara et al. 2017), with additional dependencies on star-formation rate and the stellar mass of a host galaxy (Sugahara et al. 2019). This would modify the CR containment fraction in host galaxies, according to the competition between transport processes (advection vs. diffusion). We introduce a simple parameterised CR containment model for SFGs hosting outflows, and assess their impacts on the resulting spectral and spatial properties of the EGB.

Figure 2 (below): *Adapted from Owen et al. (2021), with star-formation rate of 10 $M_{\odot}yr^{-1}$ and effective star-forming nucleus size taken as $R = 0.1$ kpc.* ***Left panel*** *shows effective path lengths of γ-rays in a SFG attenuated by the CMB, starlight and dust emission.* ***Right panel*** *shows γ-ray emission from the pp interaction (grey line), and the effective emitted spectrum from the galaxy when attenuation processes have been considered (black line). We use this as a basis for our parameterized galaxy emission model.*



2 Template model

The internal CR spectrum of a SFG is typically well-described by a simple power law, with a spectral index which has been found to take characteristic values of between -1.9 and -2.3 in nearby SFGs (Ajello et al. 2020). Here, we adopt a proton spectrum of $\Gamma = -2.1$, i.e. the mid-value of this range. The CR proton density within a SFG is estimated following the approach of Owen et al. (2021). A fraction of these CRs can be advected out of the host galaxy by outflows (Peretti et al. 2019). This is estimated as:

$$f_{\rm adv}(E_{\rm p}) \approx \left\{ \frac{V_{\rm f}(\ell)\,\tau_{\rm adv}^{-1}(\ell)}{\tau_{\rm d}^{-1}(E_{\rm p}) + \tau_{\rm adv}^{-1}(\ell)} \right\} \bigg|_{\ell=\ell_0}$$

V_f is the volume filling factor of an outflow, ℓ is the height from the starburst nucleus, $\tau_{\rm d}(E_{\rm p}) = \ell^2/4\,D(E_{\rm p})$ is the characteristic CR diffusion timescale, and $\tau_{\rm adv} \approx \ell/v_\infty$ is the characteristic CR advection timescale in the outflow where v_∞ is the terminal flow velocity. We use $\ell_0 = 1$ kpc.

For v_∞ , we adopt the scaling relation:

$$v_\infty(z, M^\star) \approx 320 \left(\frac{\rm sSFR}{0.316\ {\rm Gyr}^{-1}}\right)^{\beta_{\rm v}(z)} {\rm km\ s^{-1}}$$

For the function $\beta_{\rm v}(z)$, we consider three forms inspired by the best-fit values of Sugahara et al. (2017):

- Model 1: $\beta_{\rm v}(z) = 0.46$
- Model 2: $\beta_{\rm v}(z) = 0.58$
- Model 3: $\beta_{\rm v}(z) = 0.58\,\mathcal{H}(2 - z)$

The CRs which remain within the host galaxy undergo hadronic pp interactions (Owen et al. 2018). Their resulting γ-ray emission, accounting for attenuation in radiation fields, follows the template model of Owen et al. 2021 (see Figure 2).

For details see full paper:
Owen, Lee & Kong MNRAS advanced access (2021) *arXiv: 2106.07308*

3 γ-ray propagation

Over cosmological distances, the radiative transfer equation for γ-rays, is:

$$\frac{{\rm d}\mathcal{I}_\gamma}{{\rm d}z} = (1+z)\left[-\alpha_{\gamma\gamma}\mathcal{I}_\gamma + \frac{j_\gamma}{\nu^3}\right]\frac{{\rm d}s}{{\rm d}z}$$

Here, all quantities are Lorentz invariant, and a flat Friedmann-Robertson-Walker (FRW) Universe is adopted, with cosmological parameters from Planck Collaboration (2018). Over cosmological distances, γ-rays are reprocessed by pair-production in the extra-galactic background light (EBL) and subsequent inverse-Compton scattering off CMB photons. This is modelled by the absorption term as a function of γ-ray energy and cosmological redshift $\alpha_{\gamma\gamma}(E_\gamma, z)$, using the EBL model of Inoue et al. (2013). j_γ then includes contributions from inverse-Compton scattered CMB photons, and fresh γ-ray emission from populations of galaxies at a given redshift.

We solve the radiative transfer equation numerically over redshift, adopting the galaxy population model of Katsianis et al. (2017) and spatially distributing the sources (using a clustering length and bias factor determined in Hale et al. 2018) to model the EGB at z=0.

4 Results

Spectrum

We solve γ-ray cosmological radiative transfer equation for the 3 outflow velocity models, and for a fixed for a fixed outflow loss fraction of 50% (thus reproducing the result of Owen et al. 2021). The resulting total spectrum is shown in Figure 3, where the impact of each of the outflow models is demonstrated to be significant and sensitive to the particular outflow model adopted. This demonstrates that **outflow activity in populations of SFGs can modify their contribution to the EGB spectrum**, and **more sophisticated approaches thoroughly considering CR transport in and around SFGs is crucial** to correctly assess their EGB contribution.

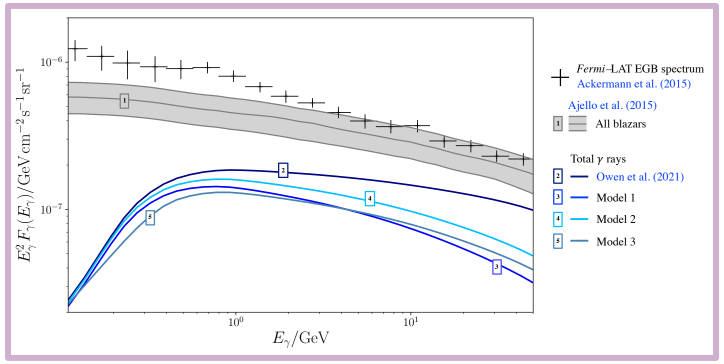
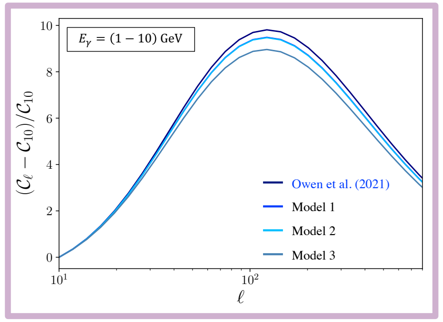


Figure 3: *EGB spectrum from SFGs under the 3 outflow models, compared to the result from Owen et al. (2021). While CR advection in outflows is important at lower energies, diffusive propagation starts to become more competitive at higher energies, introducing the observed energy dependence. For all 3 outflow models, the EGB flux is reduced at all energies compared to the Owen et al. (2021) result, which adopted a simple fixed CR outflow loss fraction of 50%.*

Anisotropies

The spatial distribution of SFGs, set by their power spectrum, would imprint a spatial signature in the EGB, even though individual contributing sources would not typically be resolved. The distribution of spatial scales of this signature would depend on z, and the strength of the contribution from sources at a particular epoch. **The imprinted signatures could be accessed in the EGB using the intensity fluctuation power spectrum** (see Figure 4) providing an **alternative window to study EGB source populations** and their **evolution** over cosmic time**. This could be used to gain crucial new insights about CR activity in EGB source populations and its co-evolution with galaxy populations.**

Figure 4 (right): *EGB intensity fluctuation power spectrum $\mathcal{C}_\ell$, normalized to $\mathcal{C}_{10}$, plotted against multipole ℓ in the energy band $E_\gamma = (1-10)$ GeV. This shows the result of Owen et al. (2021), compared to the 3 outflow models, as labelled, which all show a slightly broader power spectrum. This is most noticeable in the case of Model 3, where the broadening is stronger, particularly towards larger scales (smaller ℓ).*



References*: Ackermann et al. 2015 ApJ 799, 86; Ajello et al. 2015 ApJ 800, L27; Ajello et al. 2020, ApJ 894, 88; Fermi 1949 Phys. Rev. 75, 1169; Hale et al. 2018 MNRAS 474, 4133; Inoue et al. 2013 ApJ 768, 197; Katsianis et al. 2017 MNRAS 472, 919; Owen et al. 2018 MNRAS 481, 666; Owen et al. 2021 MNRAS, in press, arXiv: 2106.07308; Planck Collaboration 2018 A&A 641, A6; Peretti et al. 2019 MNRAS 487, 168; Peretti et al. 2020 MNRAS 493, 5880; Sugahara et al. 2017 ApJ 850, 51; Sugahara et al. 2019 ApJ 886, 29; Tumlinson et al. 2017 ARA&A 55, 389*