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Gamma-ray emission from cosmic rays and interstellar medium interactions in star-forming galaxies

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Abstract. Star-forming galaxies generate gamma-rays in the GeV-TeV range through the interaction of their populations of cosmic rays with the interstellar medium. This diffuse emission can inform us about the origin and transport of cosmic rays, especially the hadronic component. Following the recent observations of six such objects, we present a systematic search of GeV-emitting star-forming galaxies using 29 months of *Fermi*/LAT data. The results are consistent with a nearly linear scaling relation between > 100 MeV gamma-ray luminosities and 8-1000 μm infrared luminosities. This relation was then used to estimate the contribution of unresolved star-forming galaxies to the gamma-ray extragalactic background.

Key words. Cosmic rays – Gamma rays: galaxies

1. Introduction

Cosmic rays (CRs) with energies < 10^{15} eV are commonly believed to be accelerated at strong shocks, especially those resulting from supernova explosions. In the ~GeV-TeV range, CRs have long enough lifetimes and ranges to propagate out from their sources and fill their entire galactic system. On their way, they illuminate the magnetic field, radiation and gas components of the interstellar medium (ISM), from the vicinity of their sources to more distant places. CR leptons produce radio emission through the synchrotron process, and gamma-ray emission through the Bremsstrahlung and inverse-Compton scattering mechanisms; CR nuclei produce high-energy emission through inelastic collisions with ambient gas particles, thereby creating neutral mesons that subsequently decay into gamma-rays, and the latter is thought to dominate in the ~1-10 GeV range.

The resulting galactic-scale diffuse emissions bear the marks of the cosmic-ray acceleration and transport processes. The comparison of the emissions from different galactic systems thus can provide insights into both aspects of the cosmic-ray phenomenon. Until recently the gamma-ray sky has remained nearly devoid of external galaxies whose high-energy emission results primarily from a galactic population of CRs interacting with the ISM. This was regrettable since this radiation can inform

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us about the hadronic component of CR populations in other galaxies, which cannot be directly inferred from the radio observations.

The launch of the *Fermi* satellite in 2008 and the advent of modern Atmospheric Cerenkov Telescopes (ACTs) are currently changing the situation. We review here the detections of external star-forming systems achieved so far by the *Fermi*/LAT in the GeV range, and by ACTs in the TeV range, and we present the outcome of a recent, systematic search for other GeV-emitting star-forming galaxies using the *Fermi*/LAT. The whole sample of studied objects is then used to explore the physics of galactic CR populations and predict the contribution of star-forming galaxies to the gamma-ray extragalactic background (EGB).

2. Currently-detected GeV/TeV star-forming galaxies

After about two years of operation, the *Fermi*/LAT data had allowed the detection of 6 external star-forming galaxies. Among these were the Small and Large Magellanic Clouds (hereafter SMC and LMC), and the starburst galaxies M82 and NGC253 (Abdo et al. 2010a,b,d). The latter two were also observed at TeV energies by VERITAS and HESS respectively (Acero et al. 2009; Acciari et al. 2009). The Andromeda galaxy M31 was observed just above the sensitivity limit of *Fermi*/LAT for about two years of data, while its neighbour the Triangulum galaxy M33 remained undetected (Abdo et al. 2010c). Gamma-ray emission from the composite starburst/Seyfert 2 galaxies NGC4945 and NGC1068 was reported by Lenain et al. (2010), but the authors concluded that the emission from NGC1068 may be dominated by the active nucleus activity. For our population study, we also considered the Milky Way (MW), whose diffuse emission actually dominates the >100 MeV gamma-ray sky. We used as its total gamma-ray luminosity the value computed from the GALPROP model, which is based on a large set of cosmic-ray experimental data (Strong et al. 2010).

In the LMC, the gamma-ray emission is poorly correlated with the gas distribution but instead strongly correlates with tracers of massive stars like ionised gas or WR stars. This establishes an unambiguous connection between CR acceleration sites and massive-star-forming regions and suggests a short diffusion length for 1-10 GeV protons. Related to that, the gamma-ray dimness of some gas-rich regions suggests that 1-10 GeV protons may not so easily diffuse through the gas (Abdo et al. 2010a).

The gamma-ray spectra derived for Local Group galaxies look quite similar and seem consistent with the spectrum of our Galaxy. The only difference is the inferred average CR densities, which for the SMC, LMC and M31 are smaller than the local value by factors of 6-7, 2-4 and 3 respectively, which may be due to smaller CR confinement volumes and/or lower CR injection rates. In contrast, M82 and NGC253 appear to have a GeV-TeV gamma-ray spectrum with spectral slope of $\sim 2.2-2.3$ (Abdo et al. 2010d; Lacki et al. 2011), significantly harder than the ~ 2.7 of the MW. If the gamma-ray emission in this energy range is dominated by meson decay (as is thought to be the case), this suggests that the galactic CR populations in M82 and NGC253 have a spectral distribution close to the one expected for injection (slope ~2.2-2.4), which may be indicative of a different transport scenario, such as energy-independent convection by strong galactic winds instead of energy-dependent diffusion. In addition, the average CR densities inferred for these two objects are a few orders of magnitude above the local value.

From this sample, a strong correlation of gamma-ray luminosity with star formation rate was found (Abdo et al. 2010c). Such a scaling relation holds potential for constraints on the origin and transport of galactic CRs and therefore needed to be further investigated.

3. Search for other GeV star-forming galaxies

We performed a systematic search for GeV emission from star-forming galaxies beyond the Local Group using the *Fermi*/LAT. We selected galaxies with globally-measured HCN line emission, which is a tracer of dense molecular gas, hence star formation. We used for the most part the HCN survey of Gao & Solomon (2004) and ended up with 64 objects in our candidate list. The sample includes more than a dozen large nearby spiral galaxies, 22 LIRGs, and 9 ULIRGs (luminous and ultra-luminous infrared galaxies). Nine objects host active galactic nuclei, as indicated in the *Swift*/BAT 58-month catalog.

We analysed 29 months of *Diffuse* class LAT data with reconstructed energies in the range 0.2-100 GeV, photon zenith angles $< 100°$ and spacecraft rocking angles $< 52°$. We used P6V11 instrument response functions and version 09-21-00 of the LAT Science Tools. For each galaxy in the sample, the data in a $15° \times 15°$ region of interest about the object were modelled using templates for foreground Galactic emission and isotropic emission (both publicly-available), point sources from a preliminary version of the 2FGL catalog, and a point-like source at the optically-determined position of the galaxy. A power-law spectral model was assumed for the candidate galaxies and its parameters were determined with a binned likelihood procedure, using 0.1° pixels and 27 logarithmically-spaced energy bins.

Significant gamma-ray excesses above background were detected in directions coinciding with the galaxies M82, NGC253, NGC1068 and NGC4945, thereby confirming previous results. None of the 4 sources shows significant time variability over the 29 months of LAT observations for 80-day time bins. The spectral distributions over the studied energy range were found to be well represented by power-laws with photon indices in the range 2.1-2.4. For the galaxies not significantly detected by the LAT, integral flux upper limits in the energy range 0.1-100 GeV were determined.

4. Insights from a population study

4.1. Origin and transport of galactic cosmic rays

Figure 1 shows how the total gamma-ray luminosity L_γ above 100 MeV correlates with the total infrared luminosity L_{IR} in the 8-1000 μm band (which is considered as a tracer of the massive stars, the ultimate sources of cosmic-ray acceleration). There appears to be a trend of increasing L_γ with increasing L_{IR}. Using the full sample of 69 objects (the 64 in our candidate list plus the Local Group galaxies), the P-value of the correlation is $\sim 2.10^{-4}$, which increases to $\sim 2.10^{-3}$ if we exclude the AGN-contaminated galaxies[1]. Fitting this relationship by a simple power law, we found an index of order 1.0-1.2, consistent with that determined for the Local Group objects only. Interestingly, the non-detection of the LIRGs and ULIRGs disfavor a strongly non-linear scaling relation.

Some correlation of L_γ with L_{IR} can be expected as the latter can be taken as a first-order tracer of CR injection. An almost-linear dependence would be expected if all galaxies were CR calorimeters, where most CR energy would be converted to radiation and especially gamma-rays since CR nuclei dominate the energy budget. But although this might be the case for CR leptons, most systems are very likely inefficient CR nuclei calorimeters (see for instance Strong et al. 2010). The observed correlation might then be indicative of a slight increase of the calorimetric efficiency across the galaxy range. While this could be due to an increase of the average gas density from dwarf galaxies to dense starbursts, many subtleties also need to be considered: possible transition from diffusion-dominated to convection-dominated CR transport, relative contribution of synchrotron to inverse-Compton losses, contribution of secondary leptons,...etc. In addition, it should be

[1] The significance of correlation was assessed using Kendall-tau rank correlation test, by comparing to simulated uncorrelated data sets, taking into account errors on distance measurements of up to 20%.

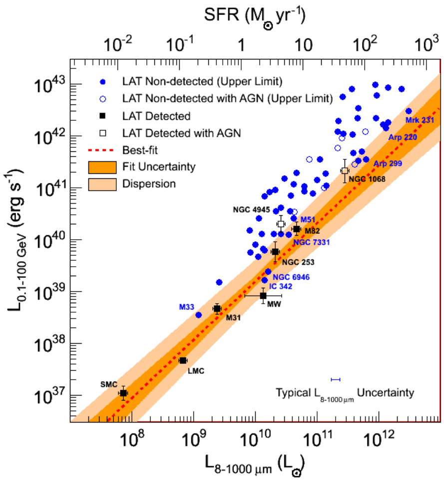

Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).

noted that the above gamma-ray luminosities include (except for the MW value) a contribution from discrete sources like pulsars or supernova remnants, and a potential contribution from dark matter, both in unknown proportions. This complicates the interpretation of the observed correlation.

4.2. Contribution to the extragalactic background

Using the above-mentioned L_γ-L_{IR} relation and the IR luminosity function for non-AGN dominated star-forming galaxies determined from *Spitzer* data (Rodighiero et al. 2010), the collective gamma-ray intensity of unresolved star-forming galaxies can be estimated through an integration over redshift and luminosity range. The calculation was performed assuming that the L_γ-L_{IR} relation does not vary over redshifts and using two bracketing spectral shapes for the gamma-ray spectrum.

Figure 2 shows this estimated contribution of star-forming galaxies to the EGB measured by the *Fermi*/LAT, together with the estimated contribution of unresolved blazars. It appears that star-forming galaxies with redshifts $0 < z < 2.5$ can contribute 3-25% of the EGB in terms of integral photon intensity

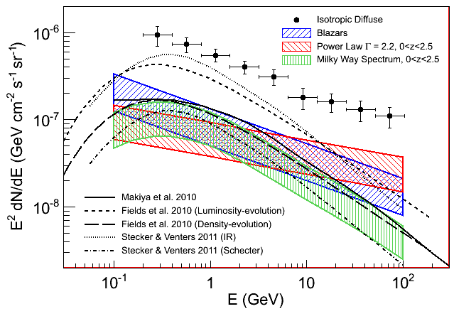

Fig. 2. Contribution of star-forming galaxies and blazars to the isotropic diffuse gamma-ray emission measured by the *Fermi*/LAT.

in the energy range 0.1-100 GeV. Unresolved blazars and star-forming galaxies cannot account for the entire EGB intensity, suggesting that our understanding of both populations may need to be improved and/or leaving room for other high-energy source classes (see Dermer 2007).

5. Conclusion

The *Fermi* satellite and modern ACTs have allowed the detection of six external star-forming galaxies emitting in the GeV-TeV range as a result of CRs interacting with the ISM. This new class of gamma-ray sources already provided us with promising constraints on the origin and transport of galactic CRs. From a systematic search of GeV-emitting star-forming galaxies using 29 months of *Fermi*/LAT data, it was possible to confirm a previously-suggested correlation between gamma-ray and infrared global luminosities. The observed relation could then be used to estimate the contribution of unresolved star-forming galaxies to the gamma-ray extragalactic background.

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