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THE COSMIC-RAY POPULATION OF NEARBY GALAXIES

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Abstract. Every star-forming galaxy is thought to host a large-scale population of cosmic rays accelerated in the various astrophysical shocks that accompany the evolution of massive stars from the main sequence to the compact remnant. As they propagate in the interstellar medium, these non-thermal particles radiate in the radio and gamma-ray bands through interactions with matter and radiation fields. The resulting diffuse glow bears the marks of the cosmic-ray acceleration and transport processes, and the comparison of the emissions from different galactic systems thus can provide insights into both aspects of the cosmic-ray phenomenon. Such a study was however not possible before the LAT gamma-ray telescope onboard the *Fermi* satellite came into operation about two years ago. In this paper, we review the detections of some external star-forming systems achieved by the *Fermi*/LAT so far, and we emphasise how these observations hold potential for improving our understanding of galactic cosmic rays.

Keywords: cosmic rays, galaxies: Milky Way, LMC, SMC, M82, NGC253, gamma rays: galaxies

1 Introduction

Cosmic rays (CRs) with energies $< 10^{15}$ eV are very likely energised by the powerful outflows that accompany massive star evolution, from main-sequence stellar winds to supernova explosions and even beyond with the fast rotation/accretion-driven plasma ejections from compact objects. Yet, CRs are not simply a side-product confined to these phenomena. They actually diffuse out from their sources to eventually form an essential component of the entire Milky Way (MW) and as such, they have observational consequences on quite large scales. The sky in gamma rays with energies >100 MeV is dominated at the 80-90% level by diffuse emission from CRs illuminating the interstellar medium (ISM) of our Galaxy through the processes of Bremsstrahlung and inverse-Compton scattering for CR leptons, and neutral pion production and decay for CR nuclei. In the same time, at the other end of the electromagnetic spectrum, the <1 GHz radio flux is dominated by synchrotron emission from CR leptons spiralling in the Galactic magnetic field.

Extended radio emission of that nature has been observed in countless galaxies and the relation to the massive-star-forming activity seems to be evidenced by the so-called FIR-radio correlation, at least to first order (Helou et al. 1985; Yun et al. 2001; Murphy et al. 2006). Conversely, the gamma-ray sky has remained nearly devoid of external galaxies whose emission in the >100 MeV range result primarily from stellar activity and the associated CR-ISM interactions. At the end of the 1990s, the LMC was the only such source of high-energy gamma-rays detected by the EGRET telescope onboard the CGRO satellite (Sreekumar et al. 1992).

This was regrettable since the characteristics of the diffuse gamma-ray emission from a given galaxy can inform us about its CR population and particularly about its hadronic component, which cannot be directly inferred from the radio observations, and so comparing the emission from galactic systems with different geometries, contents, and physical conditions provide the possibility to make further progress understanding the origin and propagation of CRs. In addition, studying externally-viewed systems allows to get rid from the complications inherent to line-of-sight accumulation in the Milky Way and from the possible bias due to our particular position in the Galactic disk and in the local bubble especially (Grenier 2004; Putze et al. 2010).

The higher sensitivity of the LAT telescope onboard the *Fermi* satellite launched in 2008 was predicted to

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extend the sample of star-forming gamma-ray-emitting galaxies to several nearby objects, thus allowing for the first time a population study. In this paper, we review some of the detections achieved by the *Fermi*/LAT over its first two years of operation and we emphasise how these observations hold potential for challenging and/or improving our understanding of galactic cosmic rays.

2 Star-forming galaxies detected in high-energy gamma-rays

External galaxies actually are a major source class in the >100 MeV sky, as they account for about half of the entries in the 1FGL catalog, the rest being unassociated objects (Abdo et al. 2010a). Yet, the vast majority of these galaxies emit in gamma-rays through the activity of an accreting central black hole or so-called galactic nucleus. In this work, we are interested only in galaxies that emit in gamma-rays through CR-ISM interactions resulting from stellar activity and in the following we will therefore refer to these systems as star-forming galaxies.

After slightly less than two years of operation, the *Fermi*/LAT observations have allowed the detection of 4 external star-forming galaxies. Among these are the Small and Large Magellanic Clouds (hereafter SMC and LMC), on which we will focus for the most part of this paper (Abdo et al. 2009, 2010b). The two other objects detected so far are the starburst galaxies M82 and NGC253 (Abdo et al. 2010d).

3 Morphological information

The proximity of the Magellanic Clouds (hereafter MCs) and their relatively large angular sizes (about 6-8° and 8-10° in optical for the SMC and LMC respectively) allowed to unambiguously resolve their gamma-ray emission using the *Fermi*/LAT. From only 11 months of data, the LMC was already spatially resolved at a level enabling to correlate the gamma-ray emission with known structures in the galaxy, while 17 months of data did not provide enough statistics for such correlations to be conclusively established in the SMC. The emission from M82 and NGC253 is consistent with point-source emission, so the morphological information on the gamma-ray diffuse emission from external star-forming galaxies comes from the MCs only.

In the LMC, the distribution of the gamma-rays reveals a strong emission from the 30 Doradus direction. An estimated ∼25% of the total >100 MeV flux indeed come from a rather compact region ∼ 200 pc in size coincident with this very active star-forming region, one of the most active of the Local Group of galaxies. On a larger scale, 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. These observations therefore establish an unambiguous connection between CR acceleration sites and massive-star-forming regions. They also suggest a short diffusion length for 1-10 GeV protons, which apparently remain confined close to their production sites. Related to that, it is also interesting to note that the gas ridge south of 30 Doradus, which hosts ∼20% of the total gas mass of the galaxy, is definitely not a bright source of high-energy emission, thereby suggesting that 1-10 GeV protons do not so easily diffuse through the gas.

In the SMC, the situation is less clear-cut because of the more limited statistics. The emission is not clearly correlated with the gas distribution or with the active star-forming regions or known pulsars and supernova remnants, but a certain correlation with supergiant shells is observed, as in the case of the LMC. The maximum of the emission does not correspond to the highest gas column density in the galaxy or to the most active star-forming region NGC602, but more *Fermi*/LAT data are needed here to firmly establish the morphology of the gamma-ray emission from the SMC.

4 Spectrometric information

The spectra derived for the MCs look quite similar and are actually rather flat, with a spectral index ~2. A dedicated spectral modelling was done from a one-zone model, taking into account the specificities of the MCs in terms of gas mass, size...etc, but assuming a electron-to-proton ratio and CR spectrum similar to the local MW. The modelled spectra fit the data quite well (with an underdensity of CRs compared to locally, see further down) and the distribution of the different spectral component is similar to what is obtained for the MW. In both cases, the assumptions of electron-to-proton ratio and CR spectrum similar to the local MW do not conflict with the radio synchrotron measurements, but the uncertainties are large.

The spectra, however, are not really constraining above ~10 GeV because of limited statistics and so the slope of the spectrum up to TeV energies remains rather ill-defined from *Fermi* measurements. We emphasise here the importance of the spectral slope over the GeV-TeV range for constraining the transport processes (see for instance Lacki et al. 2010, about M82 and NGC253, which were detected at TeV energies by VERITAS and HESS, respectively).

5 Photometric information

From the observed > 100 MeV photon fluxes, it is possible to estimate the average CR density in the galaxies under consideration. Under the assumption that the gas content of a galaxy is uniformly irradiated by CRs, the > 100 MeV emissivity can be derived. Then, a comparison to the locally measured value gives an upper-limit on the average CR nuclei density in the galaxy, under the implicit assumption that the CR nuclei spectrum is similar (which appears to be the case from the spectral measurements, see above).

The inferred average CR densities for the SMC and LMC are smaller than the value measured locally in the MW by factors of 6-7 and 2-4 respectively. In the case of the SMC, such a lower CR density is likely to be due to a smaller CR confinement volume because the CR injection rate per unit volume in the SMC does not appear to be lower than in the MW (as inferred for instance from the average temperature of the dust, which is observed to be higher in the SMC than in the MW, hence indicating that the star formation rate per unit volume is at least similar to the MW). The same conclusion can probably be reached for the LMC. In contrast, M82 and NGC253 have average CR densities that are larger than the local one by factors of ~100-1000.

Yet, the resolved emission from the LMC seems to show a more complicated picture than these average estimates. In the Fig. 10 of Abdo et al. (2010b), which shows the emissivity (or equivalently CR density) distribution across the LMC, it can be seen that, although the emissivity in the LMC is on average 2-4 times smaller than the local value, it can reach values twice as high over a significant fraction of the galaxy. This naturally comes from the poor correlation of the gamma-ray emission with the gas distribution, which means that in places the emissivity should be pushed to high values to compensate for the low gas column density.

6 Conclusions

After less than two years of operation, the LAT instrument onboard the *Fermi* satellite has allowed the detection of 4 star-forming galaxies emitting in high-energy, GeV gamma-rays as a result of their stellar activity and the associated CR-ISM interactions. The current sample of such objects includes the SMC, the LMC, M82, and NGC253, with the Magellanic Clouds being spatially resolved at GeV energies. These observations allow for the first time to compare the emission from CR-ISM interactions in galactic systems with different geometries, contents, and physical conditions, hence providing the possibility to make further progress in our understanding of the origin and propagation of CRs.

The LMC displays a gamma-ray emission that is poorly correlated with the gas distribution but instead strongly correlates with massive stars, and in particular with the very active 30 Doradus region. This confirms the role of massive stars in CR acceleration and suggest a short diffusion length of ~1-10 GeV CR protons around their injection sites. The emission from the SMC does not seem to be correlated with neither the gas or the massive star forming regions, but the current photon statistics are too limited to conclusively relate the gamma-ray emission with particular features in the galaxy. The spectra of the galaxies in our sample are quite similar in the GeV range and consistent with that of our Galaxy in terms of underlying CR spectrum, electron-to-proton ratio, and relative contribution of the various spectral components. The average CR densities in the Magellanic Clouds objects are lower than the local Galactic value, but the resolved emission from the LMC shows that such average estimates may not be representative.

The ongoing survey of the sky by *Fermi*/LAT will probably lead to the detection of other nearby objects like M31 or M33, and very likely allow defining upper limits on others. A real population study will then be possible, which will inform us about how CR populations are affected by the global galactic properties. Beyond constraining the CR production and transport processes, the outcomes of such a study may be relevant to the FIR-radio correlation, the extragalactic gamma-ray background, or the prospects for neutrino astronomy.

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