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Diffuse gamma-ray emission from local group galaxies

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Abstract. We systematically estimate the expected diffuse γ-ray flux from Local Group galaxies, and determine their detectability by new generation γ-ray observatories such as GLAST. For each galaxy, the expected γ-ray flux depends only on its total gas content and its cosmic ray flux. We present a method for calculating cosmic ray flux in these galaxies in terms of the observed rate of supernova explosions, where cosmic ray acceleration is believed to take place. We estimate the γ-ray flux for Local Group galaxies and find that our predictions are consistent with the observations for the LMC and with the observational upper limits for the Small Magellanic Cloud and M31. Both the Andromeda galaxy, with a flux of $\sim 1.0 \times 10^{-8}$ photons sec^{-1} cm^{-2} above 100 MeV, and the SMC, with a flux of $\sim 1.7 \times 10^{-8}$ photons sec^{-1} cm^{-2} above 100 MeV, are expected to be observable by GLAST. M33 is at the limit of detectability with a flux of $\sim 0.11 \times 10^{-8}$ sec^{-1} cm^{-2}. Other Local Group galaxies are at least two orders of magnitude below GLAST sensitivity.

1 Introduction

It has long beeen appreciated that diffuse gamma rays and cosmic rays are intimately connected. The γ-ray sky above 100 MeV (Hunter et al., 1997) is dominated by Galactic emission from cosmic ray interactions with the ISM, and has been modeled in detail (e.g., Strong (1996)). Extragalactic cosmic rays have proven much more elusive. In fact, the only extragalactic object detected in diffuse emission is the LMC (Hartman et al., 1999). Nonetheless, even the upper limits to γ-rays from the SMC have been enough to strongly establish that the origin of the bulk of cosmic rays is local rather than "universal" (Sreekumar et al., 1993).

Apart from the Magellanic Clouds, the only other Local Group galaxy for which there have been theoretical γ-ray flux predictions is M31. Özel and Berkhuijsen (1987) and Özel and Fichtel (1988), using observational data available at the time for the distance and gas content of M31, concluded that if the cosmic ray flux in the Andromeda galaxy is comparable to that in the Milky Way, then the galaxy should be detectable by EGRET. However, Blom, Paglione, and Carramiñana (1999) showed that EGRET has not detected M31, and have instead placed an upper limit for its γ-ray flux lower than the theoretically predicted value of Özel and Berkhuijsen (1987). Digel et al. (2000) base their recent study on this upper limit.

Here, we summarize a systematic study (Pavlidou and Fields, 2001) of the γ-ray emission from Local Group galaxies and its detectability; with the completion of EGRET observations and the prospect of the construction of new, more sensitive γ-ray observatories, such an investigation is timely. Our predictions for the Local Group will be testable by the forthcoming *Gamma-ray Large Area Space Telescope* (GLAST), which is predicted to be launched in 2005.

2 Formalism

The Galactic diffuse γ-ray emission > 100 MeV is dominated by π^0 decay, with additional contributions from cosmic ray electron bremsstrahlung, and inverse Compton scattering of interstellar radiation off a hard electron component. The Galatic emission has been studied in detail by many groups (Stecker, 1970, 1973, 1988; Dermer, 1986; Mori, 1997).

In order to extend these calculations to galaxies other than our own, we must relate the γ-ray production and hence cosmic ray flux, to observable properties of the galaxies. We therefore must account for both the acceleration and propagation of cosmic rays, and their dependence on the galactic environment. The assumption that supernova explosions are the engines of CR *acceleration* is encoded in simple and direct way. Specifically, we will impose a scaling of the CR source (injection) rate density q_p with $\mathcal{R}_{\rm G}$, the mean SN rate in a specific galaxy G:

$$q_p^G \propto \mathcal{R}_{\rm G}.$$

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Table 1. Observed Properties of Selected Local Group Galaxies

Galaxy	SN rate (century^{-1})	Adopted f	Σ ($10^4\ M_\odot$ kpc $^{-2}$) H I	H$_2$	Total
LMC	0.1, 0.23 ,0.49	0.14	22 ± 6	4.63	26.6
SMC	0.065, 0.12	0.04	17 ± 4	0.76	17.8
M31	0.9, 1.21, 1.25	0.45	0.9 ± 0.2	0.06	0.92
M33	0.28, 0.35, 0.68	0.17	0.26 ± 0.05	0.004	0.264
NGC6822	0.04	0.02	0.05 ± 0.02	0.006	0.056
IC10	0.082-0.11	0.04	0.016 ± 0.003	$\gtrsim 10^{-5}$	0.016

For references, see Pavlidou and Fields (2001).

To describe the cosmic ray *propagation* we adopt a simple leaky box model. This can be further simplified by at the high energies of interest, at which ionization and inelastic losses are negligible compare to escape losses. If a steady state also holds, then we arrive at

$$\phi(E) = \ell_{\rm esc}\, q(E) \tag{1}$$

at each point, where $\ell_{\rm esc}$ is the mean free path against escape (sometimes quoted in terms of the escape pathlength $\Lambda_{\rm esc} = \rho\ell_{\rm esc}$).

Thus, to make further progress in estimating the CR flux $\phi_p(T)$ in the galaxy G, we need to have some understanding of the CR confinement in that galaxy, which enters in eq. (1) through $\ell_{\rm esc}$. This depends on the details of the magnetic field strength and configuration in these galaxies, but we will provisionally assume $\ell_{\rm esc}$ is the same as in the Milky Way. This amounts to an *Ansatz* that the physical properties that determine $\ell_{\rm esc}$ are dominated by local rather than global properties of the host galaxy. This assumption becomes more plausible the more similar G is to the MW, so we expect our approach to yield better results in the cases of M31 and M33 rather than in the cases of the Magellanic Clouds and other irregular galaxies. (Alternatively, one could turn the problem around, and with γ-ray observations of these objects, one can measure or limit the cosmic ray confinement in these objects.)

Under this assumption, the CR flux is proportional to the SN rate in G:

$$\frac{\phi_p^G}{\phi_p^{MW}} = \frac{\mathcal{R}_{\rm G}}{\mathcal{R}_{\rm MW}} = f_{\rm G} \tag{2}$$

We then simply apply the inverse square law to arrive at the γ-ray flux of photons > 100 MeV from galaxy G

$$F_\gamma^G = 2.34 \times 10^{-8} f_{\rm G} \left(\frac{\Sigma}{10^4 M_\odot {\rm kpc}^{-2}} \right) {\rm cm}^{-2}\ {\rm s}^{-1}\,. \tag{3}$$

where in terms of the ratio $f_{\rm G}$ of the supernova rate in G to that of the Milky Way. We note that the gas mass-to-distance squared ratio $\Sigma = M_{\rm gas}/d^2$ can be determined directly from observed gas column densities and is independent of the distance to the galaxy.

3 Data

Equation (3) shows that the information we need to calculate the expected γ-ray flux from each galaxy is the SN rate of the galaxy, and the ratio Σ. A summary of these data and the relevant references are presented in Table 1; references are too numerous to quote here but appear fully in Pavlidou and Fields (2001). The indicated ranges are the span in the published observational data and are not representative of the error of each measurement as estimated by the corresponding authors. This should give a sense of the systematic uncertainties, but one should bear in mind that the overall error could be larger, particularly for the supernova rates. The value quoted in the Σ column is the mean value of all the measurements found in the indicated references while the error is just the square root of the sample variance.

In order to calculate $f_{\rm G}$ we also need the SN rate of the Milky Way. Different authors have produced results which cover a range of roughly an order of magnitude, depending on the method of calculation. The three main methods used are extragalactic SN discoveries, SN-related Galactic data relating to massive star formation, chemical evolution, and nuclear γ-ray lines, and analysis of the historical record of Galactic SN explosions. Dragicevich, Blair, and Burman (1999) critically surveyed $\mathcal{R}_{\rm MW}$ determinations by different methods. As a "best bet" we will adopt the Dragicevich, Blair, and Burman (1999) recommended value of $\mathcal{R}_{\rm MW} = 2.5$ SN per century.

4 Results

We now combine eq. (3) with the data presented in Table 1 to predict $\gamma-$ray flux levels for photons with energies above 100 MeV originating in the interaction between cosmic rays and interstellar medium in galaxies of the Local Group.

Our predictions, and their implications for GLAST, are summarized in Table 2, with detailed discussion of each galaxy appearing below. In Table 2, all values refer to γ-rays > 100 MeV. The "GLAST Significance" column refers to the formal significance expected to be achieved after a 2-year (nominal GLAST duty cycle) and 10-year (GLAST lifetime goal) all-sky survey. The "On-Target 5 σ Exposure Time" column refers to the total exposure *of the object* needed to achieve a 5 σ detection. When GLAST is operating in the normal sky-scanning mode, each individual source is in the field of view for only $\sim 20\%$ of the time for each duty cycle, so the GLAST operation time required to achieve a detection of the same significance is typically 5-6 times the on-target exposure time quoted (assuming a field of view for GLAST between 2 and 2.4 sr). All significances and exposure times were calculated according to the GLAST specifications as described in De Angelis (2000), and we recover their limits on point source sensitivity.

4.0.1 Large Magellanic Cloud

The LMC is the only galaxy other than the Milky Way for which there has been a positive detection of its diffuse $\gamma-$ray emission, and is therefore the only one of the systems of interest for which any prediction can be directly tested against observations.

For the LMC, Table 1 suggests a mean Σ equal to $26.6 \times 10^4 M_\odot\,\mathrm{kpc}^{-2}$ and a mean SN rate of 0.27 $\mathrm{century}^{-1}$ which, combined with a Galactic SN rate of 2.5 $\mathrm{century}^{-1}$, gives $f_{\mathrm{LMC}} = 0.11$. Inserting these data in eq. (3) we derive a γ-ray flux for photons with energies > 100 MeV of 6.8×10^{-8} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

However, of the 3 references quoted in Table 1 for the SN rate of the LMC, the lowest one (ref. (2) in the table, equal to 0.1 SN $\mathrm{century}^{-1}$), which is based on a count of observed SN remnants, is derived only as a lower limit to the LMC SN rate. The other two estimates are based on extragalactic SN discoveries in morphologically similar galaxies (ref. 4 in Table 1) and on the massive star formation rate (ref. 3 in Table 1). If we use the mean value of the latter two as our best estimate for $\mathcal{R}_{\mathrm{LMC}}$ we get $f_{\mathrm{LMC}} = 0.14$.

As far as the gas mass is concerned, although the more recent 21cm surveys tend to give rather low values for Σ (Luks & Rohlfs 1992, Kim et al. 1998), the gas mass estimates in those cases are assuming an optically thin medium. However, recent studies of the cool gas in the LMC by Marx-Zimmer et al. (2000) are not in favor of this assumption, which indicates that the gas masses might in fact be significantly underestimated. On this basis, we will adopt for our calculation the higher estimate from Westerlund (1997), which predicts a $\Sigma_{\mathrm{H\ I}} = 28 \times 10^4 M_\odot\,\mathrm{kpc}^{-2}$, and thus $\Sigma_{\mathrm{tot}} = 32.6 \times 10^4 M_\odot\,\mathrm{kpc}^{-2}$.

These values of f and Σ, if used in eq. (3), yield a total γ-ray flux of

$$F_\gamma^{\mathrm{LMC}} = 11 \times 10^{-8}\ \text{photons cm}^{-2}\ \text{s}^{-1}\,.$$

This value is in excellent agreement with the observed value of $(14.4 \pm 4.7) \times 10^{-8}$ photons cm^{-2} s^{-1} (Hartman et al. 1999). This consistency gives us confidence in our method of computing galactic cosmic ray fluxes.

Our best estimate for the flux gives a very strong detection (formally, at the 42σ level) in the first 2 years of sky-scanning GLAST operation, with the 5-σ detection feasible after an on-target observation time of less than 2 days.

4.0.2 Small Magellanic Cloud

The $\gamma-$ray flux level of the Small Magellanic Cloud has been the object of both theoretical and observational studies in the past, which have been used to resolve the debate of the origin of the cosmic rays: if the origin of the cosmic rays were cosmological and the level of the CR flux were universal the $\gamma-$ray flux should have been easily detectable by EGRET (Sreekumar & Fichtel, 1991). However, the SMC was not detected by EGRET, and an observational upper limit was placed instead on its $\gamma-$ray flux. (Sreekumar et al. 1993, Lin et al. 1996).

For the SMC, the mean value of Σ is equal to $17.8 \times 10^4 M_\odot\ \mathrm{kpc}^{-2}$ and the average of the quoted SN rates is 0.09 SN per century (Table 1). Thus, eq. 3 (using again a $\mathcal{R}_{\mathrm{MW}}$ equal to 2.5 $\mathrm{century}^{-1}$) predicts a γ-ray flux of

$$F_\gamma^{\mathrm{SMC}} = 1.7 \times 10^{-8}\ \mathrm{photons\ \ cm^{-2}\,s^{-1}}\,. \tag{4}$$

This value is consistent with the current observational upper limit of 4×10^{-8} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ of Lin et al. (1996). Using this “best bet” value for the SMC $\gamma-$ray flux, we find that GLAST will detect the SMC with a 19 σ significance after a 2-year all-sky survey. The total exposure time needed to achieve a 5 σ detection is only 8 days.

4.1 M31

The mean observed value of Σ for M31 is $0.92{\times}10^4 M_\odot\ \mathrm{kpc}^{-2}$ while the average of $\mathcal{R}_{\mathrm{M31}}$ as measured with all 3 different methods (observations of SN remnants, star formation rates and morphology arguments) is 1.12 per century (Table 1). The average $\mathcal{R}_{\mathrm{M31}}$ corresponds to an M31/MW supernova rate ratio $f_{\mathrm{M31}} = 0.45$. It is worth pointing out that M31 has an unusually low Hα and far infrared emission (e.g., Pagani et al. (1999)), which imply a low star formation rate, and hence a low Type II supernova rate for such a large galaxy. As we will see, GLAST should detect M31, an thus provide an important new measure of the M31 supernova rate.

Using our adopted gas content and supernova rate for M31, eq. (3) then predicts a total γ-ray flux for energies above 100 MeV

$$F_\gamma^{\mathrm{M31}} = 1.0 \times 10^{-8}\,\text{photons cm}^{-2}\ \text{s}^{-1}\,. \tag{5}$$

This value is consistent with the observational upper limit of 1.6×10^{-8} photons cm^{-2} s^{-1} set by Blom, Paglione, and Carramiñana (1999), but only slightly lower than the EGRET sensitivity. As we see in Table 2, our predicted $\gamma-$ray flux for M31 would be detected by GLAST in its first 2-year all-sky survey with a 14 σ significance. After a projected lifetime of 10 years, and assuming continuous sky-scanning operation, this significance would rise to 31 σ.

4.2 Other Local Group Galaxies

Using the mean values for the gas content-related Σ and the supernova rate shown in Table 1 for the case of M33, eq. (3) gives a $\gamma-$ray flux of

$$F_\gamma^{\mathrm{M33}} = 0.11 \times 10^{-8}\ \mathrm{photons\ \ cm^{-2}\ s^{-1}}\,, \tag{6}$$

Table 2. Predicted Gamma-Ray Flux and GLAST Requirements for Selected Local Group Galaxies

Galaxy	Flux > 100 MeV (photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$) Prediction	EGRET Value/Limit	GLAST Significance 2 years	10 years	GLAST On-Target 5σ Exposure Time
LMC	11×10^{-8}	$(14.4 \pm 4.7) \times 10^{-8}$	$42\ \sigma$	$93\ \sigma$	4.6×10^{-3} yr
SMC	1.7×10^{-8}	$< 4 \times 10^{-8}$	$19\ \sigma$	$43\ \sigma$	2.1×10^{-2} yr
M31	1.0×10^{-8}	$< 1.6 \times 10^{-8}$	$13\ \sigma$	$31\ \sigma$	4.1×10^{-2} yr
M33	0.11×10^{-8}	N/A	$1.9\ \sigma$	$4.1\ \sigma$	2.31 yr
NGC6822	2.6×10^{-11}	N/A	$0.04\ \sigma$	$0.09\ \sigma$	$\gg 10$ yr
IC10	2.1×10^{-11}	N/A	$0.02\ \sigma$	$0.05\ \sigma$	$\gg 10$ yr

which is slightly below the sensitivity limit of GLAST. As seen in Table 2, after a 10 year sky survey, the detection is at the 4.2σ level (comparable to the current LMC significance). If we use the highest available estimates for the M33 gas content and supernova rate, the flux would rise to $0.2 \times 10^{-8}\ \mathrm{photons\ cm^{-2}\ s^{-1}}$, which would allow for a 5σ detection after a sky survey of 4.39 years. Alternatively, even if eq. (6) is accurate, M33 will be detectable at the 5σ level within 10 years if the GLAST effective area and field of view achieve their "goal" levels (as opposed to the "required" levels we have used).

The next best candidates for detection (highest combination of Σ and f) in the local group are NGC6822 and IC10. However, using the data shown in Table 1 for these galaxies, eq. (3) predicts fluxes which are comparable within our uncertainty limits and equal to about $0.002 \times 10^{-8}\ \mathrm{cm^{-2}\ s^{-1}}$. Such tiny fluxes would require exposure GLAST times of decades, and thus appear to lie beyond reach for the foreseeable future.

5 Discussion

In anticipation of future high-energy γ-ray observatories such as GLAST, we have estimated the γ-ray flux due to diffuse emission for Local Group galaxies. To do this, we have used a simple leaky box model of cosmic ray propagation, and taken supernova blasts to be the engines of cosmic ray acceleration. Our model makes different assumptions than more detailed treatment of Fichtel, Özel, Stone, and Sreekumar (1991), but both give similar results, and are in reasonable agreement with LMC γ-ray observations.

Applying our model to other Local Group galaxies, we predict that M31 has a γ-ray flux above 100 MeV of about $1.0 \times 10^{-8}\ \mathrm{photons\ \ cm^{-2}\,s^{-1}}$, with an uncertainty of about a factor of 3. Fortunately, despite this large error budget, we can conclude that M31 should be observable by GLAST, and we therefore strongly urge that M31 be looked for in GLAST maps. A detection will provide important and unique information about cosmic rays in a galaxy similar to our own. In addition, we find that the SMC should have a flux of about $1.4 \times 10^{-8}\ \mathrm{photons\ \ cm^{-2}\,s^{-1}}$, readily detectable by GLAST. The comparison among the LMC, SMC, and M31 γ-ray luminosities will provide new information about cosmic ray densities and confinement, and supernova rates, in these systems and in the Milky Way.

The high-energy γ-ray flux from other Local Group galaxies is much smaller. Other than M31 and the Magellanic clouds, the only system that is potentially observable is M33, with a flux of about $0.1 \times 10^{-8}\ \mathrm{photons\ \ cm^{-2}\,s^{-1}}$. If GLAST can stretch to reach its sensitivity goals, this too will be observable. All other Local Group galaxies have emission that is at least 2 orders of magnitude smaller.

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