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Cosmic-Ray Origin and History Probed by GLAST: Gamma-Rays from Star-Forming Galaxies

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Abstract: Gamma rays have long been recognized as a uniquely powerful probe of the existence, origin, and nature of cosmic rays beyond the solar system. The unprecedented sensitivity and resolution of GLAST should for the first time confirm the presence of cosmic rays in Local Group galaxies today, and in all galaxies throughout the history of cosmic star formation. We show that GLAST should detect, with high confidence, three Local Group galaxies: the Large and Small Magellanic Clouds, and M31. Observations of their gamma-ray intensities will measure the cosmic-ray flux within these galaxies, and tests whether supernovae are their dominant accelerators. Essentially all other galaxies in the universe will be too dim for GLAST to detect individually, but their collective emission will significantly contribute to the diffuse extragalactic gamma-ray background (EGRB) seen by GLAST. This cosmic-ray component of the EGRB will have a unique characteristic spectrum peaked around 0.5 GeV. GLAST measurements of the intensity and spectral shape of this emission will probe cosmic ray history and should reflect the cosmic star-formation history in a well-defined and testable way.

Introduction

It has long been appreciated that diffuse gamma rays and cosmic rays are intimately connected. The γ-ray sky above 100 MeV [1] is dominated by Galactic emission from cosmic ray interactions with the ISM, and has been modeled in detail (e.g., [2]). Extragalactic cosmic rays have proven much more elusive. In fact, the only extragalactic object detected in diffuse emission is the LMC [3].

Cosmic Ray Origin: Gamma-Rays from Resolved Local Group Galaxies

Here, we summarize a systematic study [4] of the γ-ray emission from Local Group galaxies and its detectability. Our predictions for the Local Group will be testable by the forthcoming *Gamma-ray Large Area Space Telescope* (GLAST).

Our main task is to 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 impose a scaling of the CR source (injection) rate density q_p with $R_{\rm SN}$, the mean SN rate in a galaxy: $q_{\rm CR} \propto R_{\rm SN}$.

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 find $\Phi = \ell_{\rm esc}\, q_{\rm cr}$, 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 Φ in a galaxy G, we need to have some understanding of the CR confinement in that galaxy. 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. (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: $\Phi_{\rm CR} \propto R_{\rm SN}$. The γ-ray luminosity from the galaxy is then proportional to the product of this flux with the total number of targets, i.e., the interstellar gas mass $M_{\rm gas}$: $L_\gamma \propto \Phi_{\rm CR} M_{\rm gas} \propto R_{\rm SN} M_{\rm gas}$. We then simply apply the inverse square law to arrive at the γ-ray flux of photons > 100 MeV from each galaxy.

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.

We see that GLAST should firmly confirm the EGRET LMC signal, and should confidently detect the SMC and M31. Thus we will be able to compare the cosmic-ray environments of these galaxies with each other and with our own, for the first time gaining insight into the cosmic ray energetics, propagation, and interactions in a resolved extragalactic system. Beyond these source M33 lies at the edge of detecatbility, and all other Local Group sources are hopelessly faint.

Cosmic Ray History: Gamma-Rays from the Star-Forming Universe

Table 1 shows that GLAST will detect at best a handful of local galaxies undergoing star formation and hence cosmic-ray production. The rest of the star-forming universe will also give rise to supernovae which accelerate cosmic rays and generate diffuse gamma-rays. Because GLAST will not resolve these galaxies individually, their collective photon emission will appear in the diffuse extragalactic gamma-ray background (hereafter EGRB). In this section we will summarize the [5] calculation of the star-forming contribution to the EGRB, and the extension of this work by [6].

The calculatation of the EGRB contribution from all cosmic star-forming and specifically supernova-forming galaxies naturally divides into two pieces: the cosmic-ray and gamma-ray production per galaxy, and then the cosmological sum over the emission from all galaxies.

First, one must specify the mean γ-ray emissivity $q_\gamma(E,z)$ per comoving cosmic volume over all cosmic history $t(z)$, where E is the photon energy in the source rest frame. Consistent with our calculations of the γ-ray production from Local Group galaxies, we will assume (1) that supernovae are the sources of cosmic rays; (2) that that the escape parameter $\ell_{\rm esc}$ retains the present locally-measured value; and (3) that a galaxy's cosmic rays permeate its interstellar medium which forms the target population. Thus, if a galaxy has a star formation rate ψ and a gas mass $M_{\rm gas}$, then the photon *luminosity* L_γ for a single galaxy scales as $L_\gamma \propto \psi M_{\rm gas} = \psi \mu M_{\rm baryon}$, where the last expression defines and uses the gas mass fraction μ. If the (possibly time-dependent) number density of galaxies is $n_{\rm gal}$, then the mean emissivity is $q_\gamma(E) = \langle L_\gamma n_{\rm gal} \rangle = \langle \mu M_{\rm baryon} \psi n_{\rm gal} \rangle$.

Different galaxies will of course have different histories of star formation and hence supernova production and cosmic-ray acceleration. However, we are intersted in the cosmic *mean*, and we note that the mean star formation rate per comoving cosmic volume is precisely the cosmic star formation rate (hereafter CSFR) $\dot\rho_\star = \langle \psi n_{\rm gal} \rangle$, whose normalization and redshift history is a subject of intense study [7, 8]. Furthermore, the cosmic star formation rate also represents the gas consumption rate; thus $\dot\rho_\star$ also fixes the evolution of the gas fraction $\mu(z)$ (given some assumption about gas infall our outflow, and about the initial mass function).

Combining these results, we see that the cosmic star formation rate gives the redshift *shape*–i.e., the cosmic history–of the cosmi-ray induced photon production in star-forming galaxies. Namely, we have $q_\gamma(z) \propto \mu(z)\dot\rho_\star(z)$. To obtain the *normaliza-*

Table 1: Predicted Gamma-Ray Flux and GLAST Requirements for Selected Local Group Galaxies

	Flux > 100 MeV (photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$)		GLAST Significance		GLAST On-Target
Galaxy	Prediction	EGRET Value/Limit	2 years	10 years	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

tion of the emissivity, we scale to the present-day properties of the Milky Way. Specficially, we use the present star formation rate ψ_0 and gas fraction μ; for details see [4]. We also use the present γ-ray energy spectrum as measured by EGRET [1]. This is well-fit by a broken power law, with a break at $\epsilon = 0.77$ GeV.

Given an emissivity, we now sum up the contributions from all cosmic-ray-accelerating galaxies to the γ-ray sky. Namely, the total diffuse EGRB intensity (photon surface brightness) I follows in a straightforward way from the well-known expression for photon propagation in an expanding universe:

$$I_\epsilon = \frac{c}{H_0} \int q_\gamma[(1+z)\epsilon, z]\,(1+z)\,\left|\frac{dt}{dz}\right|\,e^{-\tau}\,dz \tag{1}$$

where ϵ is the observed photon energy, and the Hubble length c/H_0 sets the lengthscale for the line of sight. The extiction factor accounts for γ-ray absorption and scattering at the souce and along the line of sight; the optical depth τ is small for $\epsilon < 10$ TeV and we will neglect it in what follows, though determinations of τ from TeV observations can also provide important information on the cosmic star formation processes that lead to the intergalactic photon background [9].

Figure 1 plots the results of our calculation and compares these with observational constraints and with the expected emission from other sources. The lowest solid curve is the signal from cosmic-rays in star-forming galaxies, as computed by [4] using the cosmic star formation rate of [10]. The highest curve at all but the lowest energies shows the contribution from unresolved blazars [11], and the remaining solid curve shows and upper limit to the emission due to the unresolved counterparts of the EGRET unidentified sources [12]. Data points are from EGRET and represent two subtractions of the Galactic foregrounds: upper points are from [13] and represent an upper limit to the EGRB, while lower points are from [14] and are a more conservative estimate. The systematics of the Galactic subtraction are thus clearly large, as shown by the dotted error envelope around the lower data points.

To show how cosmic-ray history is encoded in diffuse γ-rays, we have computed [6] the photon spectrum resulting from different cosmic star formation (and thus cosmic-ray) evolution. Results appear in Figure 2. Cosmic star-formation histories are parameterized by a characteristic redshift $z_{\max}$: for $z < z_{\max}$ we take $\dot{\rho}_\star \propto u^3 e^{-3u}$, where $u = (1+z)/(1+z_{\max})$, which rises to a peak at $z_{\max}$, beyond which we take $\dot{\rho}_\star$ constant. The very low redshift case $z_{\max} = 0.01$ is not realistic but instead serves to illustrate the shape of the source spectrum when essentially unmodified by cosmological effects.

Discussion

Figure 1 illustrates several important conclusions. (1) The cosmic-ray signal in the EGRB has (when plotted flattened by ϵ^2) a characteritic peak around 0.5 GeV. This feature arises due to the break in the source (i.e., Galactic) spectrum at 0.77 GeV in the rest frame, here smeared out and redshifted due to cosmology. (2) Neither of the other sources plotted show any spectral peak, so a feature of this kind represents a *spectral signature* of cosmic-ray activity in star-forming galaxies. (3) Both blazars and star-forming galaxies (and presumably EGRED unidentified sources) will see new

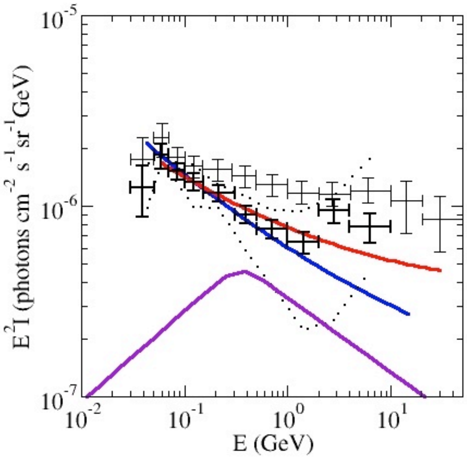

Figure 1: The diffuse γ-ray background: gauranteed contributions and observational constraints. Note the flattening by a factor ϵ^2. See text for discussion and references.

sources resolved by GLAST, which will reduce each source's *unresolved* contribution to the diffuse EGRB. However, as we have seen above, only a handful of star-forming galaxies will be resolved by GLAST, whereas it is likely [11, 12] that many of the other source classes will be resolved, and thus the competing signatures in the EGRB should drop. Consequently, the cosmic-ray signal in the EGRB should be *more prominent* in the GLAST spectrum.

If as we expect GLAST detects the cosmic-ray peak in the EGRB, one can then go further and ask what quantitative information we can infera about cosmic-ray and massive star history. Figure 2 shows that both the amplitude and position of the peak are senstive to the details of the history. While the amplitude is sensitve to a number of model-dependent factors beyond the nature of $\dot{\rho}_\star$, the peak position offers an inviting and fairly robust target, whose offse from the source value 0.77 GeV measures the mean redshift at which star- and cosmic-ray production occurs.

In light of these results, we eagerly await the launch of GLAST later this year, and the real hope of an unprecedented new glimpse of the nature of cosmic-rays over the span of cosmic time.

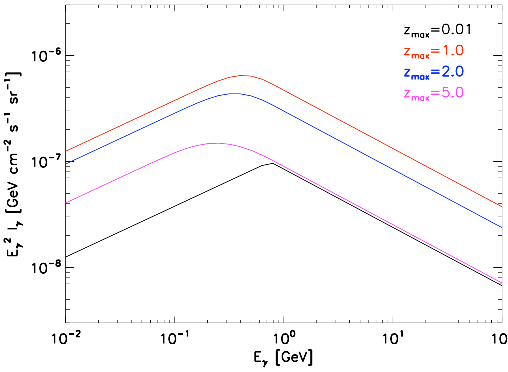

Figure 2: EGRB predictions for different star-formation and thus cosmic-ray formation histories [6]. See discussion in text.

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