ASSESSING THE STARBURST CONTRIBUTION TO THE $\gamma$-RAY & NEUTRINO BACKGROUNDS

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ABSTRACT

If cosmic ray protons interact with gas at roughly the mean density of the interstellar medium in starburst galaxies, then pion decay in starbursts is likely to contribute significantly to the diffuse extra-galactic background in both $\gamma$-rays and high energy neutrinos. We describe the assumptions that lead to this conclusion and clarify the difference between our estimates and those of Stecker (2006). Detection of a single starburst by GLAST would confirm the significant contribution of starburst galaxies to the extra-galactic neutrino and $\gamma$-ray backgrounds.

Subject headings: galaxies:starburst — gamma rays:theory, observations — cosmology:diffuse radiation — ISM:cosmic rays — radiation mechanisms:non-thermal

1. INTRODUCTION & PROTON CALORIMETRY

Inelastic proton-proton collisions between cosmic rays and ambient nuclei produce charged and neutral pions, which subsequently decay into electrons, positrons, neutrinos, and $\gamma$-rays. Neutral pion decay accounts for most of the $\gamma$-ray emission from the Milky Way at GeV energies (e.g., Strong et al. 2004). The contribution of pion decay to high energy emission from other galaxies — and thus also to the extra-galactic neutrino and $\gamma$-ray backgrounds — remains uncertain, however, because of the current lack of strong observational constraints. For example, aside from the LMC (Sreekumar et al. 1992), EGRET did not detect $\gamma$-ray emission from star formation in any other galaxy. In two recent papers (Loeb & Waxman 2006; Thompson, Quataert, & Waxman 2006; hereafter LW and TQW, respectively), we have estimated that starburst galaxies contribute significantly to the extra-galactic neutrino and $\gamma$-ray backgrounds, with most of the contribution arising from starburst galaxies at $z \sim 1$. TQW also provide detailed predictions for the $\gamma$-ray fluxes from nearby starbursts, several of which should be detectable with GLAST.

Using what seem to be similar arguments, however, Stecker (2006) presents an upper limit on the starburst contribution to the neutrino and $\gamma$-ray backgrounds that is a factor of $\approx 5$ below the predictions of LW and TQW. Here we clarify the difference between these predictions (see 4).

The timescale for cosmic ray protons to lose energy via $p$-$p$ collisions with gas of number density $n$ cm$^{-3}$ is $\tau_{pp} \approx 7 \times 10^7 / n$ yr. The importance of pion losses depends on the ratio of $\tau_{pp}$ to the cosmic-ray proton escape timescale, $\tau_{esc}$. The escape timescale for cosmic rays is quite uncertain, but in starbursts it is probably set by advection in a galactic superwind, rather than diffusion, as in the Galaxy. If correct, the escape timescale from a starburst with a wind of velocity $V \approx 300$ km s$^{-1}$ and a gas scale height of $h \approx 100$ pc is of order $\tau_{esc} \approx h/V \approx 3 \times 10^5$ yr. This implies that cosmic rays interact with gas of mean density $n \gtrsim 100$ cm$^{-3}$, then $\tau_{pp} \lesssim \tau_{esc}$ and we expect that essentially all cosmic ray protons are converted into charged and neutral pions and their secondaries before escaping. In this limit, the galaxy is said to be a “cosmic ray proton calorimeter.” If escape is instead due to diffusion rather than advection, then the density threshold required for a galaxy to be a proton calorimeter is likely to be significantly lower.

In the Milky Way, few GeV cosmic-ray protons only lose $\approx 10\%$ of their energy to pion production before escaping the galaxy. For this reason, LW and TQW focused on the high energy emission from luminous starbursts. These galaxies have much higher gas densities and likely dominate the contribution of star-forming galaxies to the total $\gamma$-ray and neutrino backgrounds. For reference, we note that the local starbursts NGC 253 and M 82 have $n \gtrsim 400$ cm$^{-3}$, and the nuclei of Arp 220 have gas densities of order $10^3$ cm$^{-3}$, well in excess of that required by the above arguments for $\tau_{pp} < \tau_{esc}$.

Since the fraction of the proton energy supplied to secondary electrons, positrons, and neutrinos is determined by the microphysics of the Standard Model, the $\gamma$-ray and neutrino fluxes from starbursts depend primarily on astrophysical properties of star forming galaxies via

1. the fraction of a SN’s canonical $10^{51}$ ergs of energy supplied to cosmic ray protons, $\eta$,
2. the spectral index $p$ of the injected cosmic ray proton distribution,
3. the evolution of the comoving star formation rate density of the universe, $\rho_\star(z)$ ($M_{\odot}$ yr$^{-1}$ Mpc$^{-3}$),
4. and the fraction of all star formation that occurs in the proton calorimeter limit as a function of cosmic time, $f(z)$.

For any $\eta$ and $p$, the $\gamma$-ray and neutrino emission from a given proton calorimeter can be readily calculated, while the cumulative extra-galactic backgrounds also depend on the star formation history of the universe via $\rho_\star(z)$ and $f(z)$.

As TQW and LW show, in the proton calorimeter limit the total $\gamma$-ray and neutrino luminosities for an individual starburst can be related to $L_{\text{TIR}}$, the galaxy’s total IR luminosity, by

$$L_\gamma \approx (2/3) L_{\text{mm}} \approx 1.5 \times 10^{-4} \eta_{0.05} L_{\text{TIR}},$$

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where $\eta_{0.05} = \eta/0.05$ (i.e., $5 \times 10^{59} \eta_{0.05}$ ergs per supernova is supplied to cosmic ray protons). $\eta$ is constrained by the requirement that the radio emission from secondary electrons/positrons in starbursts be consistent with the observed FIR-radio correlation (see, e.g., Yun et al. 2001). For proton calorimeters, $\eta \geq 0.05$ is only possible if ionization, bremsstrahlung, and/or inverse-Compton losses dominate synchrotron losses for secondary electrons and positrons in starbursts (see TQW; Thompson et al. 2006).

2. THE STARBURST BACKGROUND

Because of the predicted one-to-one correspondence between the neutrino, $\gamma$-ray, and radio emission of starbursts and their IR emission, the diffuse background in $\gamma$-rays or neutrinos can be normalized to the TIR background, $F_{\text{TIR}}$. Figure 1 shows a number of models for $\rho_\star(z)$ drawn from the literature, based on observations of star-forming galaxies at different redshifts. The integrated background from star formation is then simply

$$ F_{\text{TIR}} = \frac{c}{4\pi H_0} \int_0^\infty \frac{\bar{\rho}_\star(z)c^2}{(1+z)^2 E(z)} \, dz. \quad (2) $$

where $E(z) = \left[\Omega_m(1+z)^3 + \Omega_\Lambda\right]^{1/2}$ and $\epsilon$ is an IMF-dependent constant. Results for $F_{\text{TIR}}$ for the various models shown in Figure 1 are given in the caption and range from $F_{\text{TIR}} \approx 0.8$ to $F_{\text{TIR}} \approx 1.15$, where $F_{\text{TIR}} = F_{\text{TIR}}/20 \text{nW m}^{-2} \text{sr}^{-1}$. Note that our calculation here does not include the order unity contribution to the optical/NIR background at $z \approx 0$ from the old stellar population (e.g., Nagamine et al. 2006; Dole et al. 2006).

Figure 2 shows the cumulative contribution to $F_{\text{TIR}}$ as a function of redshift:

$$ \zeta(z) = \int_0^z \frac{\bar{\rho}_\star(z')dz'}{(1+z')^2 E(z')} \left\{ \int_0^\infty \frac{\bar{\rho}_\star(z)dz}{(1+z)^2 E(z)} \right\}. \quad (3) $$

The dotted lines indicate $z = 1$ and $\zeta = 0.4$ and 0.5, and have been added for reference. Note that all of the models consistent with the observed star formation history of the universe have $\sim 1/2$ of the TIR background produced at $z \gtrsim 1$.

The total $\gamma$-ray and neutrino backgrounds can now be simply estimated from the TIR background. Equation (1) for the $\gamma$-ray and neutrino emission from a given proton calorimeter implies that

$$ F_\gamma \approx (2/3) F_{\text{nu}} \approx 1.4 \times 10^{-6} \eta_{0.05} f_{0.75} F_{\text{TIR}} \text{nW cm}^{-2} \text{sr}^{-1}. \quad (4) $$

where $f_{0.75} = f_{\text{cal}}/0.75$ and

$$ f_{\text{cal}} = \int_0^\infty \frac{\rho_\star(z)f(z)dz}{(1+z)^2 E(z)} \left/ \int_0^\infty \frac{\rho_\star(z)dz}{(1+z)^2 E(z)} \right\}. \quad (5) $$

is the fraction of the TIR background produced by starburst galaxies that are in the proton calorimeter limit (i.e., $\tau_{pp} < \tau_{\text{esc}}$; 11 and $f(z)$ is that fraction at every $z$. For a flat $\gamma$-ray spectrum ($p \approx 2$), equation (4) implies a specific intensity at GeV energies of

$$ \nu I_{\nu, \gamma}(\text{GeV}) \approx (2/3)\nu I_{\nu, \text{vis}} \approx 10^{-7} \eta_{0.05} f_{0.75} F_{\text{TIR}} \text{GeV cm}^{-2} \text{sr}^{-1}. \quad (6) $$
Given the strong constraint on $\eta$ implied by the FIR-radio correlation and the reasonable convergence of models and data on the TIR background ($F_{\text{TIR}}^{\text{20}} \approx 1$; Fig. 1), the estimated $\gamma$-ray and neutrino backgrounds depend primarily on the fraction of star formation that occurs in the proton calorimeter limit: $f(z)$ and $f_{\text{cal}}$. Locally, we estimate $f(z \approx 0) \sim 0.1$ from the fraction of the local FIR and radio luminosity density produced by starbursts (e.g., Yun et al. 2001). However, at high redshift, a much larger fraction of star formation occurs in high surface density systems that are likely to be proton calorimeters. For example, the strong evolution of the IR luminosity function with redshift implies that $f(z) \sim f_{\text{cal}}$ increases dramatically from $z \approx 0$ to $z \approx 1$ (e.g., Dole et al. 2006). If we take $f(z \gtrsim 1) \sim 1$ and $\rho(z)$ as in any of the models of Figure 1, we find that $f_{\text{cal}} \approx 1$, with a significant contribution to the $\gamma$-ray and neutrino backgrounds coming from $z \approx 1 - 2$. In fact, we find that

$$F_{\gamma} \propto \nu L_{\nu} (\text{GeV}) \times f(z \approx 1 - 2).$$

More specifically, taking $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and assuming a function $f(z) = \min(0.5, z + 0.1)$ that smoothly interpolates from a small local starburst fraction ($f(z \approx 0) \approx 0.1$) to an order unity starburst fraction at high redshift, we find that $f_{\text{cal}} \approx 0.8$ for the models shown in Figure 1 (see caption). As an example of another alternative, assuming $f(z) = \min[0.11(1 + z)^2, 0.8]$, in which the starburst fraction increases roughly in proportion to $\rho(z)$ and saturates at $f(z = 1) = 0.8$, $f_{\text{cal}} \approx 0.6$ for the same models.

For numerical calculations for the $\gamma$-ray background specific to a given $f(z)$, $\rho(z)$, and proton injection spectra, $p$, see Figure 1 of TQW.

3. COMPARISON WITH STECKER (2006)

In a recent paper, Stecker (2006) (S06v1, v2, v3) estimates a significantly smaller $\gamma$-ray and neutrino background from starburst galaxies than found in TQW and LW, respectively. In his original version of the paper (S06v1), Stecker normalized the total neutrino background to the local FIR luminosity density from starburst galaxies in Yun et al. (2001) (based on IRAS), thereby neglecting the contribution to the background from redshifts above $z \approx 0$. This error led to a factor of $\approx 10$ underestimate of the total neutrino background relative to LW.

S06v2 corrects this error and addresses both the $\gamma$-ray and neutrino backgrounds expected from starburst galaxies. Stecker finds a value for the neutrino and $\gamma$-ray backgrounds approximately equal to the value quoted in S06v1, $\sim 5$ times lower than LW and TQW. There are two primary differences that lead to this discrepancy:

1. Stecker advocates that 22% of the extra-galactic background is produced by star formation above $z > 1.2$ (see his Table 1, S06v3). Figures 1 and 2 show, however, that essentially all models for the star formation history of the universe that are consistent with the observed evolution of the star formation rate density with redshift ($\rho(z)$) yield roughly equal contributions to $F_{\text{TIR}}^{\text{20}}$ below and above $z \approx 1$.

2. We argue that order unity of all star formation at $z \approx 1$ occurs in starbursts likely to be proton calorimeters, whereas Stecker quotes 13% in the range $0.2 \leq z \leq 1.2$ and 60% for $z > 1.2$ (see his Table 1, S06v3). This step function model for $f(z)$ likely significantly underestimates the contribution of $z \approx 1$ galaxies to the $\gamma$-ray and neutrino backgrounds.

Thus, the inconsistency between our predicted $\gamma$-ray and neutrino backgrounds and Stecker’s upper limit is a simple consequence of his model for the star formation history of the universe and the redshift evolution of the starburst population. For the reasons explained above, we believe that our assumptions are in better agreement with observations of star-forming galaxies at $z \gtrsim 1$.

4. CONCLUSION

The magnitude of the observed diffuse $\gamma$-ray background is quite uncertain, primarily as a result of foreground subtraction. Whereas Sreekumar et al. (1998) (compare with Strong et al. 2004) find a specific intensity of $1.4 \times 10^{-6}$ GeV sr$^{-1}$ cm$^{-2}$ s$^{-1}$ at GeV energies, Keshet et al. (2004) derive an upper limit of $\nu_{\gamma_{\text{vir}}} < 5 \times 10^{-7}$ GeV sr$^{-1}$ cm$^{-2}$ s$^{-1}$. Future observations by GLAST should alleviate some of the uncertainty in the background determination. A comparison of the upper limit by Keshet et al. (2004) and equation (6) indicates that starburst galaxies may indeed contribute significantly to the diffuse $\gamma$-ray background.

Even in stacking searches, EGRET did not detect a single starburst galaxy (Cillis et al. 2005). In TQW (their Figure 1) we show that the EGRET non-detections are required by predictions that are correctly calibrated to the FIR or radio emission from galaxies. Hence, the EGRET non-detections do not provide a significant constraint on the contribution of starburst galaxies to the $\gamma$-ray or neutrino backgrounds. GLAST will, however, be much more sensitive. Using equation (1) and numerical calculations for different $p$, TQW show that GLAST should be able to detect several nearby starbursts (NGC 253, M82, IC 342; see TQW Table 1) if they are indeed proton calorimeters.

The dominant uncertainty in assessing the starburst contribution to the $\gamma$-ray and neutrino backgrounds lies in whether a significant fraction of cosmic-ray protons in fact interact with gas of average density or whether the cosmic rays escape despite the galactic wind without coupling to the high density ISM (the star formation history of the universe is comparatively well understood). Detection of a single starburst galaxy by GLAST would strongly support the estimates of LW and TQW and thus the importance of starburst galaxies for the extra-galactic neutrino and $\gamma$-ray backgrounds. Such a detection would also provide an important constraint on the physics of the ISM in starburst galaxies.

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