

Upper Limits to Fluxes of Neutrinos and Gamma-Rays from Starburst Galaxies

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Abstract.

Loeb and Waxman have argued that high energy neutrinos from the decay of pions produced in interactions of cosmic rays with interstellar gas in starburst galaxies would be produced with a large enough flux to be observable. Here we obtain an upper limit to the diffuse neutrino flux from starburst galaxies which is a factor of ~ 5 lower than the flux which they predict. Compared with predicted fluxes from other extragalactic high energy neutrino sources, starburst neutrinos with \sim PeV energies would have a flux considerably below that predicted for AGN models. We also estimate an upper limit for the diffuse GeV γ -ray flux from starburst galaxies to be $\mathcal{O}(10^{-2})$ of the observed γ -ray background, much less than the component from unresolved blazars.

1. Introduction

Interactions of cosmic-ray nuclei with interstellar gas nuclei in our galaxy produce π^0 's which decay to produce most of the galactic γ -rays above 0.1 GeV [1]; the decay of the π^+ 's produced yields galactic cosmic-ray neutrinos [2].

The distribution of high energy γ -rays in our Galaxy is related to the distribution of molecular clouds and very young hot high-mass stars in OB associations which are short-lived and explode into supernovae [3, 4]. This association between supernovae which are likely to produce cosmic rays and dense regions of molecular gas led to the scenario where interactions between the gas and cosmic rays produces the galactic γ -rays *via* the decay of the π^0 . A natural implication then would be that starburst galaxies, which are undergoing a phase of extremely active star formation would be likely sources of high energy γ -rays [5, 6].

Loeb and Waxman (LW) [7] have suggested that such hadronic processes in starburst galaxies can produce, *in toto*, a large enough background of diffuse high energy neutrinos to be observable with a very large neutrino detector such as *Icecube* [8]. LW then argue that radio observations of starburst galaxies imply a *lower limit* on the cumulative extragalactic neutrino flux from starburst galaxies which is within the sensitivity range of *Icecube*. We derive here an *upper limit* to the cumulative high energy neutrino flux from starburst galaxies which is significantly lower than the LW "lower limit". The diffuse flux of GeV γ -rays from the same processes is found to be $\mathcal{O}(10^{-2})$ of the observed γ -ray background, much less than the component from unresolved blazars and more than an order of magnitude below a recent estimate [9].

2. Radio Emission and the Neutrino Flux from Starburst Galaxies

LW start with the observed synchrotron emission from starburst galaxies which is produced by relativistic electrons in these sources [10]. They then make the assumptions that (1) the presence of relativistic electrons in these sources implies the presence of relativistic protons, (2) the protons lose essentially all of their energy to pion production, and (3), a lower limit to the energy loss rate of the protons can then be obtained from the synchrotron radio flux by assuming that all of the electrons (and positrons) which are radiating are from pion decay.

Assumption (1) is a reasonable one which is supported by observations of cosmic rays in our own Milky Way galaxy. Assumption (3), *viz.*, the “lower limit” assumption depends on assumption (2). However, assumptions (2) and (3) can be questioned because (a) the synchrotron radiating electrons may be largely accelerated primaries rather than secondaries related to pion production and decay, as is the case in our own Galaxy, and (b) the conditions in starburst galaxies are significantly different from those in our own galaxy. In particular, starburst galaxies exhibit strong “superwinds” [11]. Such winds have significant dynamical effects and may disrupt magnetic fields and drive protons out of these galaxies before they can lose all of their energy by interacting with interstellar gas nuclei to produce pions [12]. In contrast, assumption (2) of LW assumes full trapping of relativistic nuclei in the disks of starburst galaxies to the point where they only lose energy in hadronic interactions with gas atoms. This is in stark contrast to the situation in our own Galaxy (see footnote 1) and is also contradicted by recent observations of high redshift galaxies [13].

These caveats call into serious question the argument that the radio data can provide a lower limit on the cumulative diffuse flux of neutrinos from starburst galaxies. But here we consider that assumptions (1)-(3) can be used for obtaining an analytic *upper limit* for such a flux. We also will accept the other estimates which lead to the ratio of injected power of protons to electrons at a fixed particle energy, $\eta_{p/e} \simeq 6$ and a neutrino luminosity which is then related to the local radio luminosity density by

$$E_\nu^2 \Phi_\nu(E_\nu = 1 \text{ GeV}) \simeq (ct_H/4\pi)\zeta[4f(dL_f/dV)]_{f=1.4\text{GHz}} \quad (1)$$

where t_H is the age of the universe and $\zeta = 3$ is an evolution factor which takes account of the fact that starburst galaxies were more numerous in the past [7]. LW take the local energy production rate per unit volume at a frequency $f = 1.4$ GHz to be $\simeq 10^{28.5} \text{ W Mpc}^{-3}$. Let us reexamine this value for $f(dL_f/dV)]_{f=1.4\text{GHz}}$.

The local 1.4 GHz energy production rate has been derived by LW by making use of the correlation between GHz and far infrared (FIR) emission in galaxies given by Yun, Reddy and Condon (YRC) [10]. YRC use the data on *IRAS* galaxies to derive the local infrared luminosity density at $60 \mu\text{m}$ to be $2.6 \times 10^7 L_\odot \text{ Mpc}^{-3}$. This *total* power density is then used by LW to obtain the 1.4 GHz power density *via* the relation given by YRC. The key difference between the result derived here and that obtained by LW is in choosing how to interpret the paper of YRC. YRC state that less than 10% of the local FIR luminosity density is contributed by luminous IR galaxies with $L_{\text{FIR}} > 10^{11} L_\odot$; this is the component which includes the starburst galaxies. (Figure 11 of YRC yields an estimate of $\sim 6\%$.) We therefore take the local contribution from starburst galaxies alone at $60\mu\text{m}$ to be $< 2.6 \times 10^6 L_\odot \text{ Mpc}^{-3}$. Consequently, the component of the local radio luminosity density from starburst galaxies is $\Phi_{1.4\text{GHz}} < 10^{27.5} \text{ W Mpc}^{-31}$

There is a higher relative fraction of the energy input from the higher relative number of starburst galaxies at higher redshifts. The fraction of the FIR background, $\kappa(\Delta z)$ contributed by galaxies in different redshift ranges, Δz , is obtained from Ref. [14]. We multiply $\kappa(\Delta z)$ by the

¹ One might ask “Why not consider “normal” galaxies with lower FIR luminosities and add them in to estimate a higher neutrino flux?” However, in normal galaxies like ours, cosmic rays lose only a small fraction of their energy *via* hadronic interactions, contrary to assumption (2). Also galactic PeV cosmic rays have a much steeper spectrum than the E^{-2} assumed by LW.

fraction of the FIR background contributed by starburst galaxies in different redshift ranges, $\xi(\Delta z)$, to estimate the mean fraction of the total FIR background contributed by starburst galaxies. Estimates for κ and ξ are shown in Table 1. Using the results from Table 1, we estimate that 23% of the observed FIR background integrated over redshift is from starburst galaxies.

Table 1: Relative contributions to the ν Starburst Galaxy Flux (see text).

| Redshift Range (Δz) | $\kappa(\Delta z)$ [14] | $\xi(\Delta z)$ | Reference for ξ |
|-------------------------------|-------------------------|-----------------|---------------------|
| 0 to 0.2 | 10% | $< 10\%$ | [10] |
| 0.2 to 1.2 | 68% | $\sim 13\%$ | [14] |
| > 1.2 | 22% | $\sim 60\%$ | [15] |

3. Observability of High Energy Neutrinos from Starburst Galaxies

The upper limit on the radio flux from starburst galaxies obtained above can be used to obtain an upper limit on the neutrino flux from starburst galaxies by using equation (1) of LW. One then finds that the neutrino background energy flux from starburst galaxies $< 2 \times 10^{-8}$ GeV $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. Such a flux would be undetectable above the atmospheric background neutrino flux, even if equation (1) is assumed to be valid when extrapolated to 300 TeV and even granting all of the assumptions made by LW.²

Table 2: Neutrino Energy Fluxes (GeV $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$)

| ν Source | $E^2\Phi(10\text{TeV})$ | $E^2\Phi(100\text{TeV})$ | $E^2\Phi(1\text{PeV})$ | Reference |
|---------------------|-------------------------|--------------------------|------------------------|------------|
| Atm: AMANDA-II | 2×10^{-6} | 7×10^{-8} | $< 3 \times 10^{-9}$ | [16] |
| Atm (Vertical) | 7×10^{-7} | $\sim 2 \times 10^{-9}$ | — | [17] |
| AMANDA-II Diff.Lim. | 9×10^{-8} | 9×10^{-8} | 9×10^{-8} | [18] |
| Starburst Galaxies | $< 2 \times 10^{-8}$ | $< 2 \times 10^{-8}$ | $< 2 \times 10^{-8}$ | This paper |
| AGN Cores | 5×10^{-10} | 10^{-8} | 10^{-7} | [19] |
| AGN | 3×10^{-9} | 3×10^{-8} | 2×10^{-7} | [20] |
| GRB | 5×10^{-10} | 3×10^{-9} | 3×10^{-9} | [21] |
| Icecube Sensitivity | — | 4×10^{-9} | 4×10^{-9} | [22] |

Table 2 shows a comparison of the upper limit on the flux from starburst galaxies given here with the atmospheric neutrino flux and with approximate model predictions of neutrino fluxes γ -ray bursts (GRB) and active galactic nuclei (AGN) along with detector array sensitivities. It can be seen from this table that at 100 TeV none of the extragalactic sources proposed will dominate over the atmospheric foreground. The present upper limit on the diffuse neutrino energy flux below 1 PeV from AMANDA-II is $\sim 8.8 \times 10^{-8}$ GeV $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ in the 10 TeV to 1 PeV energy range [18]. The full *Icecube* detector array is expected to push down to a sensitivity of $\sim 10^{-9}$ GeV $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ in the energy range $100 \text{ TeV} < E_\nu < 100 \text{ PeV}$ after several years of observation. Under the extreme assumption that the primary cosmic ray spectra in all starburst galaxies are as hard as E^{-2} up to energies $\mathcal{O}(10 \text{ PeV})$, PeV neutrinos from starburst galaxies

² Even if we make a second extreme assumption that 100% of the IR galaxies at redshifts greater than 1.2 are starburst galaxies, we would still predict a neutrino flux $< 3 \times 10^{-8}$ GeV $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. If we use the fast evolution model of Ref. [25], we would obtain a similar upper limit.

may be detectable just above the projected sensitivity of *Icecube*. However, as can be seen from Table 2, above 1 PeV the AGN models predict fluxes which will be significantly larger than the the atmospheric foreground (expected to be $< 3 \times 10^{-9}$) $\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ at 1 PeV), as well as the fluxes from γ -ray bursts (GRB) and starburst galaxies.

4. Observability of Diffuse γ -rays from Starburst Galaxies

In a follow-up paper to LW, Thompson *et al.* [9] have estimated the contribution of π^0 -decay γ -rays from starburst galaxies to the observed γ -ray background in the GeV energy range. Using an E^{-2} primary spectrum they get estimates of $E^2\Phi(E)$ fluxes for both γ -rays and neutrinos of $3 \times 10^{-7} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$.

Our estimated starburst galaxy γ -ray flux for the same E^{-2} primary spectrum assumed in Ref. [9] is $\sim 2 \times 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ for γ -ray energies less than $\sim 10 \text{ GeV}$. This is $\mathcal{O}(10^{-2})$ of the observed flux of $\sim 1.4 \times 10^{-6} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ determined by the *EGRET* group [23] and is therefore unobservable. Above $\sim 10 \text{ GeV}$ the background spectrum will steepen owing to absorption from pair production interactions with the extragalactic ultraviolet background radiation [24]. Stecker and Salamon have shown that the bulk of the observed background can be produced by unresolved blazars [24]. Note, almost all of the observed extragalactic GeV γ -ray sources are blazars; no starburst galaxies have been observed.

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