Diffuse Extragalactic Gamma Rays and Gamma Ray Bursts

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Abstract

If gamma ray bursts produce a total energy of $10^{54}$ ergs and this energy is concentrated in the high energy tail of the spectrum $E > 1$ TeV, then they may account for the observed diffuse extragalactic gamma ray emission for energies $> 100$ MeV. Such an energy could be released if the GRB’s are produced by the burning of the total mass of a neutron star in a phase transition which violates baryon number.

I. INTRODUCTION

The diffuse extragalactic gamma ray flux has cosmological consequences since it gives information on processes produced at cosmological distances. This flux has been recently measured by EGRET [1] in the energy region from 30 MeV to 100 GeV. The spectrum is obtained by subtracting the modelled galactic background. The derived spectrum is consistent with a single power law $\alpha = 2.1 \pm 0.03$ and with an intensity of $1.45 \pm 0.05 \times 10^{-5}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ above 100 MeV.
There exist a large number of models to explain the origin of the extragalactic diffuse gamma ray emission based on discrete sources and on diffuse origin (see for instance [3] for a review). The most favoured model is based on gamma ray production on unresolved active galactic nuclei [4]. This hypothesis is favoured by the discovery of EGRET that some AGN’s are strong γ ray emitters [5]. The average spectral index of the observed blazars agrees with the observed one for the diffuse emission [2].

In this note we comment on the possibility of a common origin of gamma ray bursts (GRB) and the extragalactic diffuse γ-ray background. If GRB’s have a high energy spectrum extending up to several tens of TeV or higher and if the energy is dominated by the high energy tail, then it may be possible that the diffuse spectrum is produced by GRB’s. High energy γ rays will pair produce on the infrared (IRB) and cosmic microwave backgrounds (CMBR) and due to magnetic fields the electron positron pair will be delayed, producing a continuous diffuse flux.

In order to see how this is possible let’s consider the energy requirements. The extragalactic diffuse gamma ray flux between 100 MeV and 100 GeV is well represented by a power law of index $\alpha = 2.1 \pm 0.03$ [1–3]. This implies a total emissivity of $\dot{Q} = 4\pi \Phi(> 100 \text{ MeV}) \, d^{-1} \sim 4 \times 10^{46} \text{ ergs/Mpc}^3\text{yr}$, where we have used $d = 1 \text{ Gpc}$ and $\Phi(> E_{\text{min}})$ is the integral energy flux measured by EGRET.

On the other hand the energy injected by GRB’s per unit volume and unit time is given by $\dot{Q}_B = E_T R \sim 3 \times 10^{44} \text{ ergs/Mpc}^3\text{yr}$, where we have used the commonly accepted values $E_T \sim 10^{52} \text{ ergs}$, the total energy produced by a GRB and $R \sim 3 \times 10^{-8} \text{ Mpc}^{-3} \text{yr}^{-1}$, the rate of GRB’s. We see that GRB’s do not have sufficient power to produce the observed extragalactic flux. However, if a GRB’s has significant emission at very high energy $E > 1 \text{ TeV}$, and if the energy flux is dominated by this high energy part of the spectrum then we may have sufficient energy to produce the observed extragalactic diffuse emission. This view may be supported by the recently claim by the HEGRA group [6] of a correlation observed between the GRB 920925c and an excess observed on the same time and in the same position at energies greater than 16 TeV. A naive extrapolation with constant slope of GRB fluxes
to this energy would rend a flux completely unobservable for HEGRA. If this association is confirmed this would imply that the total energy emitted by a GRB’s is in fact much higher than currently estimated. We can see from above that the total energy required to accomplish this is of the order of $E \sim 10^{54}$ ergs. This is an enormous amount of energy, of the same order of magnitude as the total energy of a solar mass. Most of current GRB models could not account for this energy, but see below.

As it is well known, a high energy photon does not propagate for a long distance due to its interaction with the CMBR and the IRB. The problem of propagation of photons in the intergalactic medium has been extensively studied [7,8]. We follow closely the conclusions of Aharonian and Coppi [8]. Any high energy photon injected at cosmological distances will pair produce in the CMBR. For a 1 TeV photon the mean free path is small, typically less than a few hundred Mpc. Subsequent cascading will produce many photons with energies well below the TeV. The important point to notice is that the spectrum of the produced photons is independent of the original injection spectrum. The general features of the spectrum are as follows [8]: For $E < E_b$ the reprocessed spectrum goes like $E^{-1.5}$ and for $E_b < E < E_{\text{cut}}$ the spectrum goes like $E^{-\alpha}$, where $\alpha \sim 2$. $E_{\text{cut}}$ is the cut off energy due to interaction with the CMBR and IRB, and $E_b \sim 1$ GeV ($E_{\text{cut}}/1$ TeV)$^2$. Most of the energy is concentrated in the second region, where we are interested.

From this we see that the observed extragalactic diffuse gamma ray flux in the region from 100 MeV to 100 GeV is consistent with being produced by the cascading at cosmological distances of an unknown and otherwise arbitrary flux. Using $E_b \sim 100$ MeV, we obtain $E_{\text{cut}} \sim 300$ GeV. Note that if we assume that the injection took place at $z \sim 1$ then $E_{\text{cut}} \sim 300$ GeV is in agreement with the prediction by MacMinn and Primack [3] based on galaxy formation. This result is also consistent with the upper limit on the IRB from the detection of Mkn 501 by the HEGRA collaboration [10]. Previous models would have for $z \sim 1$, $E_{\text{cut}}$ values as low as 10 GeV (see figure 2 on ref. [8]).

The other effect of cascading in the IRB is the delay on the arrival time. This effect has been already extensively studied [11]. In the presence of an extragalactic magnetic field
the pair produced by the original photon is bent and the increased distance will delay the cascade photons with respect to the original burst. Due to fluctuations on the propagation, there will be a spread on time of the electromagnetic cascade. The spread time is of the same order of magnitude as the delay time itself and both are given by $[11]$:

$$\Delta t \sim 6.5 \times 10^5 \frac{d}{\text{Gpc}} \left(\frac{E_\gamma}{100 \text{ MeV}}\right)^{-2} \left(\frac{B}{10^{-18} \text{ G}}\right)^2 \text{ years},$$

(1)

where we are normalizing to the minimum energy, $E \sim 100 \text{ MeV}$. On the other hand the spread time must be less than the age of the universe, if we want to observe today the spreaded flux. This gives the condition:

$$B < 10^{-16} \text{ G}.$$  

(2)

Any magnetic field higher than this would invalidate the model since, in its presence, photons of very low energy would not have had enough time to reach us.

Assuming then that the above holds, the spreaded (observed) flux will be given by:

$$\frac{dN^{\text{obs}}}{dE} = \frac{d}{4\pi} E_T R K E^{-\alpha} = 4 \times 10^{-7} \left(\frac{E_T}{10^{54} \text{ erg}}\right) \left(\frac{R \text{ Mpc}^3 \text{ yr}}{3 \times 10^{-8}}\right) \left(\frac{d}{1\text{ Gpc}}\right) E^{-\alpha} \frac{\text{ ph.}}{\text{ cm}^2 \text{ s sr GeV}},$$

(3)

where $K$ is a constant which depends on the minimum energy, $d$ is the average distance of a GRB and $E_T$ is the total energy liberated by the GRB. For typical values of the parameters the predicted flux agrees well with the observed spectrum both in normalization and slope.

Another way to see this is the following. The observed diffuse spectrum is given by the sum of all the delayed fluxes produced by GRB’s in a given time. i.e.:

$$\frac{dN^{\text{obs}}}{dE} = \frac{1}{4\pi} N_{\text{GRB}} \frac{\tau}{\Delta t} \frac{dN^{eq}}{dE},$$

(4)

where $N_{\text{GRB}}$ is the number of GRB’s which occur in a time $\Delta t$, $\tau$ is the mean duration of a GRB and $\Delta t$ the delay (spread) time. $dN^{eq}/dE$ is the flux of photons produced by the cascading of the original flux of a single GRB. The factor $\tau/\Delta t$ takes into account the dilution of the flux due to the spread on time. The important point to notice is that the observed
flux is in fact independent of $\Delta t$ since we are integrating over a total of $N_{\text{GRB}} \sim \Delta t/T$ bursts, where $T \sim 1$ per day is the observed rate of GRB’s. This estimate is equivalent to the previous one, eq. (3).

Is it possible to have GRB’s producing $10^{54}$ ergs? For most models this is a difficult task [12–14]. However, this can be achieved in scenarios where neutron stars, due to gravitational instability, undergo a phase transition [15]. The result is that a burning front is produced which could convert into radiation the whole neutron star. For such models we expect a total energy of order $E \sim 5 \times 10^{54} (M_{\text{tot}}/3M_{\odot})$ ergs, where $M_{\text{tot}}$ is the total neutron mass. In addition this model explains easily the baryon load problem since the burning front is very efficient in transforming baryons into leptons.

The compactness problem can be resolved in the usual way assuming a relativistic shock. The source will be optically thin if it is moving towards us with a lorentz factor [12] $\gamma > 10^{18/(4+2\alpha)} (E_T/10^{54} \text{ ergs}) \sim 300$. Where we are assuming that the spectral index, $\alpha \sim 1.5$, in order for the flux to be dominated by the high energy tail. This does not modify substantially the constrain on the $\gamma$ factor.

In this respect it is interesting to note that, using common values for the total energy and GRB rate, $E_T = 10^{52}$ ergs and $R = 3 \times 10^{-8}$ Mpc$^{-3}$ yr$^{-1}$, HEGRA would not be expected to observe any GRB’s at TeV energies [16], as the predicted rate for observation of high energy events associated to GRB by HEGRA is 1 every 100 years [16]. Therefore the observation of 1 event over a period of 1 year (the analyzed time), suggests either a flux or a burst rate 100 times larger, in complete accordance with our proposed results. Moreover, if we assume that the event GRB 920925c took place at around 100 Mpc (and this is necessary in order for HEGRA to detect it), the flux observed by HEGRA is in agreement with an extrapolation of typical GRB fluxes at low energy, with a flat spectrum, $\alpha \sim 1.5$. This implies again that most of the energy goes into the higher energy part of the spectrum. On the other hand, extrapolation of the fluxes measured by EGRET to TeV energies with a steeper slope do not give any measurable flux at HEGRA.

This result is further supported by possible detection of other GRB by EAS-TOP [17] and
by an array at the University of Dublin [18]. In both cases a detection would be impossible with the currently accepted values of total energy and rate of GRB [16].

There are a number of predictions which make the model testable. If GRB’s produce the diffuse gamma ray flux then AGN’s should produce a negligible amount of power in gamma rays, which should be tested in a near future. Also, the model of GRB’s formation predicts a large flux of high energy (∼100 GeV neutrinos), essentially $10^{52}$ ergs go to these neutrinos [15]. This flux could be observed, in principle, in large detectors such as AMANDA [19]. In fact the number of interacting neutrinos in the fiducial volume would be large, of order of 100 [19], enabling a detection with a high statistical significance. Finally, if significant power is produced at TeV energies by GRB’s we should observe more correlated events of GRB’s with air shower arrays at ground.

Acknowledgements

The author thanks C.O. Escobar, F. Halzen, M.C. Gonzalez Garcia, and E. Zas for useful discussions. I thank the IFT for its kind hospitality where this work was done. This work was supported by FAPESP.

Note When completing this work we were aware of similar work by T. Totani, astro-ph/9810206, astro-ph/9810207. He came to similar conclusions as ours using different arguments. In particular he relates the UHECR production to GRB’s and arrives to a similar energy requirements. The differences are due mainly to a different GRB rate and the unknown distance scale.
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