Scattered radiation from gamma ray bursts in the GeV energy range

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Abstract: The scattering of GeV gamma rays from GRB (and similar energetic sources) by the molecular cloud is studied. It is shown that at such high energies the Delbrück scattering, the elastic scattering of a photon in the Coulomb field of a nucleus via a virtual electron pair which is a QED process, has a significant contribution. Since the Delbrück scattering cross section has a strong dependence on atomic number, in principle the scattered radiation at such high energies can probe the presence of heavy elements in GRB atmosphere. The possibility of detection of such an effect has been discussed.

Keywords: GRB, scattered radiation**,** Delbrück scattering**.**

1 Introduction

Radiation from Gamma Ray Burst (GRB) scattered off interstellar dust grains/molecular cloud can give rise to time variable X-ray halos around the GRB [1]. Such diffuse X-ray halos have been observed around several GRBs [2]. The scattered radiation in X-ray range may be useful in estimating the distance of variable sources [3] or the collimation angle of GRB jet [4].

The maximum energy of emitted radiation from GRBs is, however, not limited to keV (X-ray) range but can go up to several GeV or even higher. For instance the EGRET instrument onboard the *CGRO and* the GRID instrument onboard AGILE detected in few GRBs an emission above 100 MeV [5] whereas the Large Area Telescope (LAT) on board the *Fermi* telescope has detected several GRBs in the 100 MeV to few GeV energy range [6]. Hence it is imperative to examine scattering of such GRB/pulsar emitted high energy gamma ray photons by the ambient medium, and in the present work we would study scattered radiation from GRBs in the GeV energy range.

2 Scattering

The typical angle of scattering of γ-rays of energy ε by a scatterer of size a is given by

$$\vartheta(\epsilon) \sim 2.4 \times 10^{-7} \left(\frac{a}{1\ nm}\right)^{-1} \left(\frac{\epsilon}{1\ GeV}\right)^{-1} \qquad (1)$$

GRBs are expected to occur in the regions having dense gaseous clouds of their host galaxies and moreover GRBs are likely to form from evolution of massive stars. It is thus natural to expect that such dense cloud in the vicinity of a GRB will contain high Z molecules. Consequently GRB emitted γ-rays should be scattered by such high Z molecules. The ionic radius of Fe is of the order of 0.1 nm, which implies that the scattered radiation in the γ-ray band will be in very forward direction.

At GeV γ-ray band a photon can be scattered both elastically and inelastically. Among the inelastic processes pair production and Compton scattering will be the dominant processes at this energy range whereas above 0.1 GeV the elastic scattering is solely determined by Delbrück scattering process.

2.1 Compton versus Delbrück scattering

In Delbrück scattering, which demonstrates a non-linear effect of quantum electrodynamics (QED), an incident photon is assumed to get converted into a pair of electron and positron in the Coulomb field of the scattering nucleus, and this pair interacts with the nucleus via virtual photons and then recombines to form the final photon having the same energy. The cross section of the Delbrück scattering process has been measured in several high precision experiments [7].

Delbrück scattering is a second order QED phenomenon and its cross section goes as $r_o^2 (Z\alpha)^4$, α being the fine structure constant and r_o is the classical electron radius. The differential cross section for Delbrück scattering at high energy and small angle [8] can be estimated for $m^2 / E << \Delta << m$ (m is rest mass of an electron, Δ ($= 2E\, Sin\,\theta/2$) is the momentum transferred to the nucleus) using a simplified relation

$$\frac{d\sigma^D}{d\Omega} = \frac{1}{2}(Z\alpha)^4 r_o^{\,2}\left[a(E) + b(E)\ln(Sin\theta/2) + c(E)\{\ln(Sin\theta/2)\}^2\right] \qquad (2)$$

where $a(E) = \left(\frac{E}{\pi m}\right)^2 \left(0.1187 - 0.737\ln 2E + 1.21(\ln 2E)^2\right)$

$$b(E) = \left(\frac{E}{\pi m}\right)^2 \left(2.42\ln 2E - 0.737\right)$$

and $c(E) = 1.21\left(\frac{E}{\pi m}\right)^2$ (3)

For relatively larger scattering angles satisfying $m << \Delta << E$, the asymptotic form of cross section takes the form of Coulomb scattering cross section and can be expressed as

$$\frac{d\sigma^D}{d\Omega} = \frac{1}{4\pi^2}(Z\alpha)^4 r_o^{\,2}\, \frac{m^2}{E^2 Sin^4\theta/2}\left(\left|g(Z)\right|^2 + \left|h(Z)\right|^2\right) \qquad (4)$$

where

$$g(Z) = (1/3(Z\alpha)^2)[1 - 2\pi Z\alpha(1 - 2(Z\alpha)^2)/Sinh(2\pi Z\alpha)]$$

and $h(Z) = [1 - Z\alpha\,\mathrm{Im}\,\psi'(1 - iZ\alpha)]$ (5)

On the other hand the differential cross section for Compton scattering, at small angles such that Cosθ ~ 1, can be approximated as

$$\frac{d\sigma^C}{d\Omega} = \frac{1}{2} r_o^{\,2}\left(1 + Cos^2\theta\right) S(\theta, E, Z) \qquad (6)$$

where S is the so called incoherent scattering function (ISF) and is a function of θ, E and Z.

In Fig. 1 the Delbrück scattering and Compton scattering differential cross section are plotted at photon energy 0.1 GeV and for Z = 26. It is clear from the figure that at very small angle (up to few tens of milli-degree which is our region of interest) the Delbrück scattering dominates over the Compton scattering.

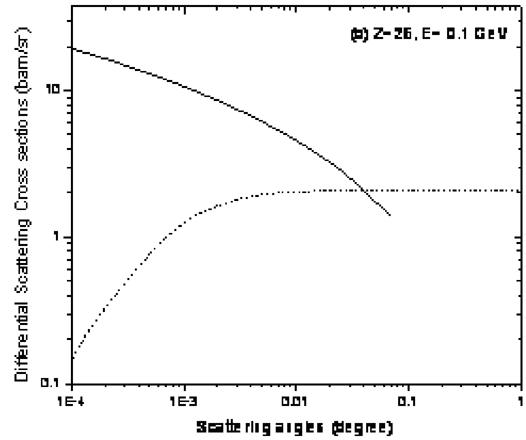

Figure 1: The dashed and solid curves represent Compton and Delbrück cross section respectively at photon energy of 0.1 GeV and Z= 26.

3 Scattered gamma radiations:

We consider a simple model in which the GRB is at the center of a spherical dust of uniform density n and radius R. The detector is assumed to be located on the axis of symmetry. A fraction of the emitted gamma rays will be attenuated through pair production. However, it is found that due to attenuation of GeV gamma rays via pair production while traversing through a sphere of molecular cloud of radius 10 pc with n=1 cm^{-3}, the gamma ray decreases by less than 2% of the total flux.

We choose our time in such a way that the γ-rays, after elastically scattered by an angle θ, will reach the detector D after time t whereas those γ-rays which do not participate in the scattering process will be detected at t = 0. The locus of scattering centers making a constant delay will be a paraboloid with its focus at the GRB site. If the host galaxy is at a red shift z then [9]

$$r = ct / \{(1+z)(1 - Cos\theta)\} \qquad (7)$$

The scattered and hence delayed γ-ray flux F_γ reaching the detector after time t will be

$$F_\gamma = S_\gamma n \int_{\theta_1}^{\theta_o} \frac{d\sigma}{d\Omega}\frac{dr}{dt}\, d\Omega \qquad (8)$$

where S_γ is the γ-ray burst fluence in the energy band ε_1 to ε_2.

For a given γ-ray energy ε and atomic number Z there exists an angle θ_o beyond which the Delbrück scattering cross section is smaller than Compton cross section. For given E and Z if θ_o is such that it satisfies the condition $m^2 / E << \Delta << m$, then, the Delbrück scattered γ-ray flux F_γ^D is obtained by inserting $d\sigma^D / d\Omega$ from Eq.(2) in Eq.(8) which is given by

$$F_\gamma^D = A\ (\alpha Z)^4\ [a \ln\frac{(1-Cos\theta_o)}{(1-Cos\theta_1)} + .$$

$$\frac{b}{4}\left(\ln\frac{(1-Cos\theta_o)}{(1-Cos\theta_1)}\right)^2 + \frac{c}{12}\left(\ln\frac{(1-Cos\theta_o)}{(1-Cos\theta_1)}\right)^3] \qquad (9)$$

Where

$$A = (S_\gamma n\pi\, r_o^2 c)/(1+z) \qquad (10)$$

Expressing in terms of elapsed time t the Delbrück scattered γ-ray flux F_γ^D will be then

$$F_\gamma^D = A\ (\alpha Z)^4 \left[a\ln\frac{t_1}{t} + \frac{b}{4}\left(\ln\frac{t_1}{t}\right)^2 + \frac{c}{12}\left(\ln\frac{t_1}{t}\right)^3 \right] \qquad (11)$$

Taking R=10 pc and z =1 for a GRB site enveloped by a molecular cloud having average atomic number Z = 26, we compute the scattered radiation due to Delbrück scattering of 0.1 GeV gamma-ray. For these choices of parameters, we find the maximum angle θ_o to be about 0.071 degree. In Fig. 2 the flux of scattered radiation has benn plotted in the units of 1/A. The scattered flux due to Compton scattering is also given the figure 2 for comparison.

It is seen from Fig.2 that, for the adapted parameters, the Delbrück scattered flux is about 1000 times more than the Compton scattered flux for $\theta<\theta_{o.}$

Note that when the chosen values of E and Z are such that the angle θ_o falls within the range $m << \Delta << E$, the Delbrück scattered γ -ray flux for angles $\theta < \theta_o$ is obtained by putting Eq.(4) in Eq. (8).

4 Discussion

The typical value of the GRB fluence S_γ in the energy range 100-600 MeV is order of 10^{-6} erg cm^{-2}. So, for n = 10^3 cm^{-3} , S_γ =10^{-6} erg cm^{-2}, z = 1, we get from Eq.(10), $A \approx 3.7\times10^{-18}$. Consequently the scattered flux would be $F_\gamma^D \approx 3.7\times10^{-12}$ erg cm^{-2} s^{-1} at the very beginning of the afterglow. The Fermi LAT instrument is expected to detect up to a flux of order 10^{-9} erg cm^{-2} s^{-1}. So, normally, the chances of observing Delbrück scattered γ-ray echo from a GRB using Fermi LAT is not much unless an exceptionally bright GRB is observed. But it is expected that future gamma ray telescopes should be able to detect such scattered radiation.

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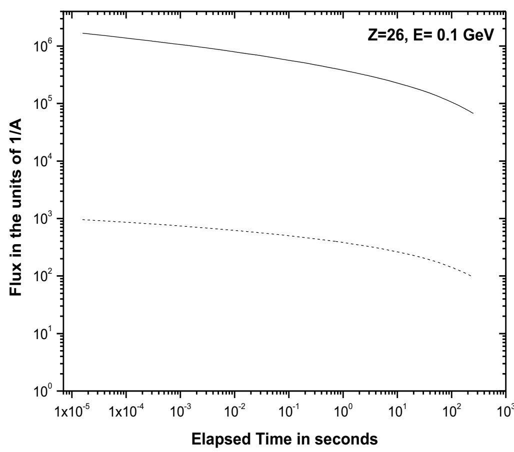

Figure 2: The very early flux of a GRB at z =1 in the units of 1/A where A is defined in eqn. (10). Here θ_o=0.071 degree. The solid line and the dashed line correspond to the γ-ray echo of the molecular dust via Delbrück and Compton scatterings respectively. The fluxes are shown up to a time 253 s corresponding up to scattering angle of 0.028 degree.

5 Conclusion

The present findings suggest that scattered radiation from the vicinity of GRBs by molecular cloud in the GeV range is essentially due to Delbrück scattering and hence contain signature of non-linear effect of QED. To our knowledge this is first application of Delbrück scattering in astrophysical scenario.

In this work we mainly concentrate on the GRB emitted gamma radiation scattered by molecular cloud. However, the present computation is applicable to several other categories of gamma ray sources such as pulsars, AGN. In particular scattered gamma radiation from pulsar will be quite interesting as the pulsars are nearby sources which will be reported shortly elsewhere.

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References

[1] J. W. Overbeck, ApJ, 1965, 141, 864; S. Klose, APJ, 1998, 507, 300
[2] C. W. Mauche & P. Gorenstein P. ApJ 1986, 302, 371; P. Predehl & J. H. M. M. Schmitt A&A 1995, 293, 889; S. Vaughan , R. Willingale, P. T. O'Brien et al. ApJ 2004, 603, L5, R. Romano et al. GCN Circ. 2005, 3685
[3] J. Tr¨umper J. & V. Sch¨onfelder, A&A 1973, 25, 445; B. J. Draine & N. A. Bond., ApJ 2004, 617, 987
[4] S. Yu. Sazonov and R. A. Sunaev, A &A, 2003, 399, 505
[5] B. L. Dingus, Ap& S S, 1995, 231, 187; A. Giuliani et al., Astron. & Astrophys., 2008, 491, L25
[6] Fermi Lat, Fermi-GBM Collaboration, APJ Letts, 2010, 717, L127
[7] M. Schumacher, Rad. Phys. and Chem., 1999, 56, 101-111, B. Kunwar, A. Bhadra, S. K. Sengupta, J. P. J. Carney, and R. H. Pratt, Phys. Rev.A 2005, 71, 032724.
[8] H. Cheng, and T.T. Wu, Phys. Rev. D 1972, 5, 3077; A. Milstein, and V. M. Strakhovenko, Phys. Lett. A, 1983, 95, 135
[9] R. D. Blandford, & M. J. Rees, Astrophys. Lett., 1972, 10, 77