Synchrotron modeling of the gamma-ray to optical afterglow of GRB 130427A and expected neutrino flux

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Abstract. GRB 130427A, at redshift 0.34, is one of the brightest and most energetic long duration gamma-ray bursts (GRBs) ever detected. A 95 GeV photon, the highest energy ever detected from a GRB, has also been reported by the Large Area Telescope (LAT) on board the Fermi Gamma ray Space Telescope. Simultaneous observations in the gamma ray, X-ray and ultraviolet/optical ranges, make this GRB one of the most well studied in history. We have modeled temporal the temporal evolution of flux in different frequencies and the broadband spectral energy distribution at different time intervals by using optically thin synchrotron radiation from a relativistic blast wave expanding in a constant density interstellar medium and in a wind-type medium with density gradient. We find that the afterglow of GRB 130427A is better described in case of a wind-type medium. We also calculate the expected neutrino flux from this GRB, if protons are accelerated to ultrahigh energies in the blast wave and interact with afterglow photons. Neutrino telescopes which are currently operating and those being planned for the future should be able to either detect this flux or, at least, constrain ultrahigh energy cosmic ray acceleration in GRBs.

1. Introduction

The Gamma Ray Burst detected on 27th April 2013 (GRB 130427A) is one of the most energetic explosions, with redshift z=0.34. The burst took place only a quarter of the way across the universe and it is one of the brightest gamma ray bursts (GRBs) ever recorded. GRB 130427A has the highest fluence recorded and has the longest gamma ray emission in the 100 MeV energy range for a duration of 20 hours [1] . It was such a hyper energetic burst that we could record a 95-GeV photon at 244 seconds and a 32-GeV photon after 34366 seconds [1]. NASA's Fermi Gamma ray Space Telescope with the Gamma ray Burst Monitor (GBM) and the Large Area Telescope (LAT) and the Swift Gamma Ray Burst explorer, the multi wavelength space observatory with all its three instruments, the Burst Alert Telescope (BAT),the X-ray Telescope (XRT) and the Ultraviolet/Optical Telescope (UVOT), have observed GRB 130427A and its afterglows in the gamma ray, X-ray, ultraviolet, and optical energy ranges. The emission was also detected at radio, infrared and visible wavelengths with ground based telescopes. The X-ray afterglow is recorded by the Swift at photon energies 0.3-10 keV and by the NuSTAR at 3-80 keV, for more than a week [2]. The RAPTOR telescopes have also observed the direct optical and infrared afterglows for a few hours [3].

Most of the models of GRBs and the afterglows are based on the synchrotron emission from the relativistic electrons accelerated within the forward shock [4, 5]. The ejecta of the GRBs interact with the interstellar medium and produces afterglow radiation. This radiation can be described by the synchrotron emission of electrons in the blast wave. With time the intrinsic properties of the blast wave like Lorentz boost factor Γ, the internal radius R, in turn the energy density and magnetic field changes. The synchrotron spectrum of electron is affected by the minimum Lorentz boost factor $\gamma_{e,min}$ and cooling Lorentz boost factor $\gamma_{e,c}$ of electron, where it starts to produce Synchrotron radiation. These Lorentz factors of electron depends on the intrinsic parameters of the blast wave. So we expect a temporal evolution of the radiation flux which can be attained by modeling of the blast wave. In case of , $\gamma_{e,c} < \gamma_{e,min}$, all the electrons cool to be in fast cooling regime. Whereas for $\gamma_{e,c} > \gamma_{e,min}$, the Synchrotron spectrum is in slow cooling regime. We have modeled the broadband spectral energy distribution (SED) at different time intervals and the temporal evolution of the flux for different frequencies, by using optically thin synchrotron radiation from a relativistic blast wave expanding in a constant density interstellar medium (ISM) and in a wind-type medium in which the density decreases as $1/R^2$, where R is the radial distance from the center of the GRB. The data for the spectral energy distribution and light curves of GRB 130427A are better explained with wind environment compared to the ISM environment. GRB spectra are of significant importance in the study of the source environment and the formation of the jet.

2. Synchrotron spectrum model and light curves of GRB 130427A

To get the overall instantaneous synchrotron spectrum of electrons we need to model the blast wave evolution. The synchrotron frequencies, ν_m, ν_c and ν_s correspond to the minimum energy, cooling energy and the saturation energy of the electrons respectively. ν_a is the self absorption frequency.

The instantaneous synchrotron spectrum follows a power law with index p for an electron energy E is, $N(E) = N_0 E^{-p}$. The observed photon flux in the slow cooling regime, as given in [5] is:

$$F_\nu = F_{\nu,max} \begin{cases} (\frac{\nu}{\nu_a})^2 (\frac{\nu_a}{\nu_m})^{\frac{1}{3}};\ \nu < \nu_a, \\ (\frac{\nu}{\nu_m})^{\frac{1}{3}};\ \nu_a < \nu < \nu_m, \\ (\frac{\nu}{\nu_m})^{\frac{-(p-1)}{2}};\ \nu_m < \nu < \nu_c, \\ (\frac{\nu_c}{\nu_m})^{\frac{-(p-1)}{2}} (\frac{\nu}{\nu_c})^{\frac{-p}{2}};\ \nu_c < \nu_s. \end{cases} \tag{1}$$

The equations for the synchrotron frequencies in wind environment are given as [6, 7]:

$$\nu_m = 9.5 \times 10^{13} \epsilon_{b,0.1}^{1/2} \epsilon_{e,0.1}^{2} E_{55}^{1/2} (1+z)^{1/2} t_d^{-3/2}\ Hz, \tag{2}$$

$$\nu_c = 2.1 \times 10^{15} \epsilon_{b,0.1}^{-3/2} E_{55}^{1/2} (1+z)^{-3/2} t_d^{1/2} A_*^{-2}\ Hz, \tag{3}$$

$$\nu_a = 8.3 \times 10^{9} \epsilon_{b,0.1}^{1/5} \epsilon_{e,0.1}^{-1} E_{55}^{-2/5} (1+z)^{-2/5} t_d^{-3/5} A_*^{6/5}\ Hz, \tag{4}$$

$$\nu_s = 8.22 \times 10^{22} A_*^{-1/4} E_{55}^{1/4} (1+z)^{-3/4} t_d^{-1/4} \phi_1^{-1}\ Hz, \tag{5}$$

and $F_{\nu,max}$, the observed peak flux, is given as:

$$F_{\nu,max} = 3.53 \times 10^{-24} \epsilon_{b,0.1}^{1/2} E_{55}^{1/2} (1+z)^{-1/2} t_d^{-1/2} d_{l,28}^{-2}\ erg/cm^2/s/Hz. \tag{6}$$

Here E_{55} is the initial kinetic energy of the blast wave in units of 10^{55} ergs, ϵ_e is the electron equipartition fraction or the fraction of energy going to the relativistic electrons, $\epsilon_{e,0.1} = \epsilon_e/0.1$, ϵ_b is the fraction of energy going to the magnetic energy, $\epsilon_{b,0.1} = \epsilon_b/0.1$, $d_{l,28}$ is the luminosity distance in units of 10^{28} cm unit, t_d is the time after the prompt emission in days, ϕ is the number of gyroradii needed for the electron acceleration in the magnetic field and $\phi_1 = \phi/10$, $A_* \equiv \dot{M}_{-5}/v_8$ corresponding to a mass-loss rate of $\dot{M}_w = 10^{-5}\dot{M}_{-5}M_\odot yr^{-1}$ in wind by the progenitor star with velocity $v_w = 10^8 v_8$ cm/s.

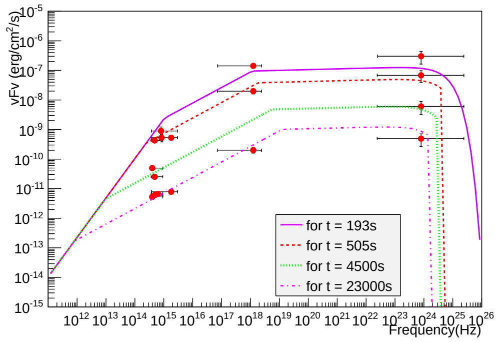

Figure 1. Spectral energy distribution in wind medium. Here the red points are the observed data with errors.

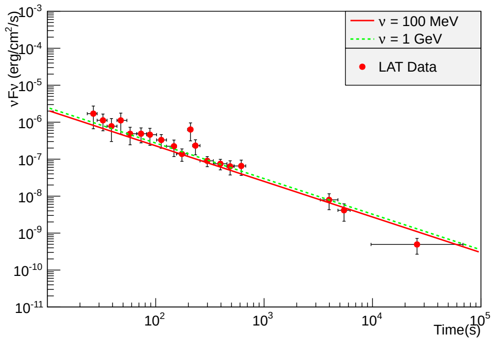

Figure 2. Light curve for LAT data in wind medium.

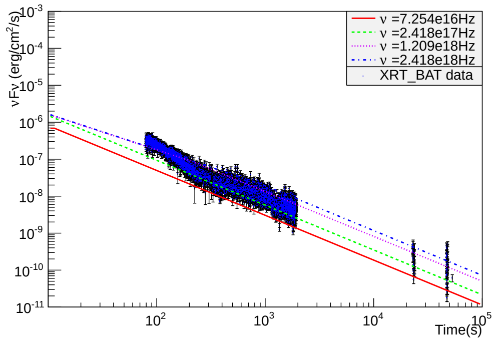

Figure 3. Light curve for XRT-BAT data in wind medium.

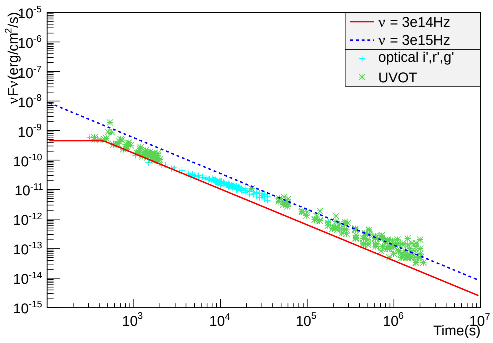

Figure 4. Light curve for UVOT/optical data in wind medium.

Figure 1 shows observed LAT, XRT-BAT and UVOT/optical data from GRB 130427A at different times and corresponding synchrotron model fluxes at those times. The data points are average fluxes in time intervals around the reported times. Here the model parameters are, $\epsilon_{b,0.1} = 0.025$, $\epsilon_{e,0.1} = 0.095$, $E_{55} = 0.5$, $p = 1.95$, $A_* = 0.1$, $z = 0.34$, $d_{l,28} = 0.56$ and $\phi_1 = 0.1$. In Fig. 2, Fig. 3 and Fig. 4, the energy fluxes are plotted as a function of time starting from the trigger of GRB 130427A and fitted with the model parameters for different frequencies using LAT, XRT-BAT and UVOT/optical data, respectively.

We do the same synchrotron modeling of GRB 130427A afterglow data for interstellar medium. In ISM, the different frequencies and the observed peak flux are:

$$\nu_m = 1.644 \times 10^{14} \epsilon_{b,0.1}^{1/2} \epsilon_{e,0.1}^{2} E_{55}^{1/2} (1+z)^{1/2} t_d^{-3/2} \ Hz, \tag{7}$$

$$\nu_c = 1.931 \times 10^{13} \epsilon_{b,0.1}^{-3/2} E_{55}^{-1/2} (1+z)^{-1/2} t_d^{-1/2} n^{-1} \ Hz, \tag{8}$$

$$\nu_a = 5.53 \times 10^9 \epsilon_{b,0.1}^{1/5} \epsilon_{e,0.1}^{-1} E_{55}^{1/5} (1+z)^{-1} n^{3/5} \ Hz, \tag{9}$$

$$\nu_s = 5.334 \times 10^{22} n^{-1/8} E_{55}^{1/8} (1+z)^{-5/8} t_d^{-3/8} \phi_1^{-1} \ Hz, \tag{10}$$

$$F_{\nu,max} = 7.95 \times 10^{-23} (1+z)^{-1} n_0^{1/2} d_{l,28}^{-2} E_{55} \epsilon_b^{1/2} \ erg/cm^2/s/Hz. \tag{11}$$

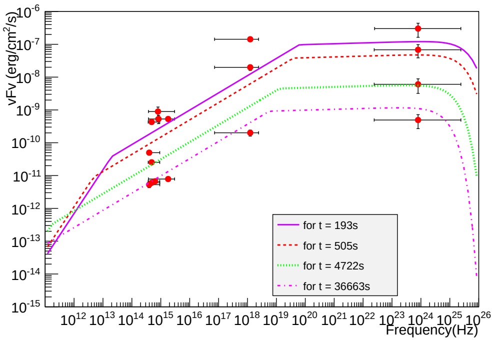

Figure 5. Spectral energy distribution in ISM.

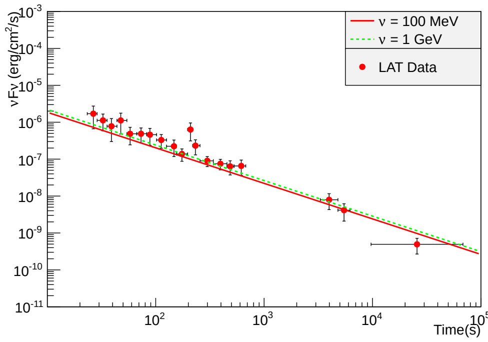

Figure 6. Light curve for LAT data in ISM.

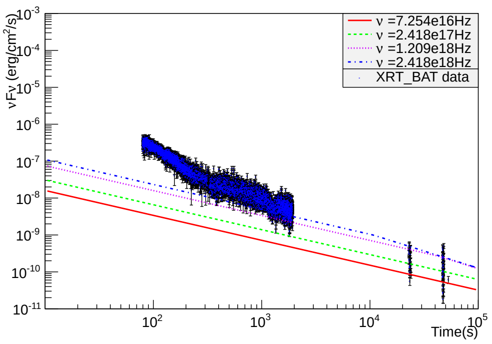

Figure 7. Light curve for XRT-BAT data in ISM.

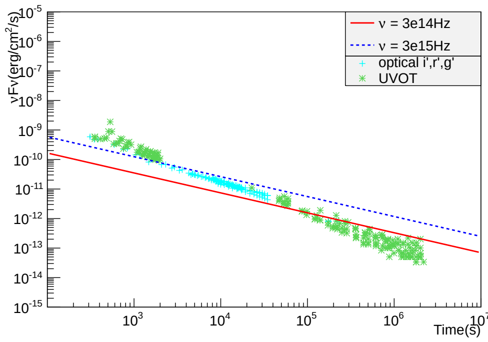

Figure 8. Light curve for UVOT/optical data in ISM.

Fig. 5 shows the spectral energy distribution for the GRB 130427A in ISM. The fitting of data for ISM is not as good as we obtained for wind environment. The model parameters used for the spectrum fit are: $\epsilon_{b,0.1} = 4 \times 10^{-4}$, $\epsilon_{e,0.1} = 0.028$, $E_{55} = 0.5$, $z = 0.34$ and $d_{l,28} = 0.56$, $p = 1.95$, $n = 1$ and $\phi_1 = 0.1$. Fig. 6, Fig. 7 and Fig. 8 are the light curves for LAT, XRT-BAT and UVOT/optical data, respectively.

3. Neutrino flux calculation for GRB 130427A

Neutrinos are the only high energy particles which can directly convey astronomical information from far and from the most high energy processes in the universe. Long-duration GRBs like GRB 130427A are the candidate sources of Ultra High Energy Cosmic Rays (UHECRs). The interaction of these cosmic rays with synchrotron radiated photons can produce neutrinos [6, 8]. The calculation of the flux for these neutrinos is done here using the parameters obtained from the synchrotron emission model fit for GRB 130427A.

In GRBs, interaction of shock accelerated relativistic protons with low energy photons can produce ultra high energy muons, pions, neutrons and kaons. The interactions are as follows [6, 9, 10]:

$$p\gamma \rightarrow X\pi^+\pi^-, XK^+K^- \tag{12}$$

where, X can be protons.

$$p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+ \tag{13}$$

Here we calculated the neutrino flux from pion and muon decay, where pions are produced via Δ^+ resonance from $p\gamma$ interaction in the GRB 130427A blast wave.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu \ . \tag{14}$$

To calculate the neutrino flux, the photon spectrum obtained from the synchrotron spectrum can be expressed in terms of proper density of the synchrotron photon $n'_\gamma(E')$ [5, 6]. Here $E' = \frac{h\nu}{\Gamma}(1+z)$ is the photon energy in the co-moving frame, where ν is defined in the equation(1), Γ is the bulk Lorentz factor and R is the radius of the blast wave. For the slow cooling:

$$n'_\gamma(E') = \frac{2d_L^2(1+z)F_{\nu,max}}{R^2 c\Gamma E'(m)} \times \begin{cases} (\frac{E'}{E'_a})^2(\frac{E'_a}{E'_m})^{\frac{1}{3}}\frac{E'_m}{E'};\ E' < E'_a, \\ (\frac{E'}{E'_m})^{\frac{-2}{3}};\ E'_a < E' < E'_m, \\ (\frac{E'}{E'_m})^{\frac{-(p-1)}{2}};\ E'_m < E' < E'c \\ (\frac{E'_c}{E'_m})^{\frac{-(p-1)}{2}}(\frac{E'}{E'_c})^{-p/2}\frac{E'_m}{E'}e^{\frac{-E'}{E'_s}};\ E'_c < E' < E'_s. \end{cases} \tag{15}$$

Here we consider the slow cooling afterglow synchrotron spectrum and the $p\gamma$ opacity scales with proton energy in the slow cooling regime as [11] :

$$\tau_{p\gamma}(E_p) = \tau_{p\gamma}(E_{pl}) \times \begin{cases} (\frac{E_{ph}}{E_{pl}})^{\frac{k}{2}-\frac{1}{2}}(\frac{E_p}{E'_{Ph}})^{\frac{k}{2}};\ E_p < E_{ph}, \\ (\frac{E_p}{E_{pl}})^{\frac{k}{2}-\frac{1}{2}};\ E_{ph} < E_p < E_{pl}, \\ 1;\ E_p > E_{pl}. \end{cases} \tag{16}$$

Where E_{pl} is the minimum energy corresponds to the break energy $h\nu_m$ in the afterglow synchrotron spectrum, E_{ph} is the energy corresponding to the break energy $h\nu_c$ and E_{ps} is the highest energy the protons. For details, see Ref. [6].

In our calculation, we have put a condition on opacity: $\tau_{p\gamma} \leq 3$. In order to calculate the neutrino flux, the proton flux $J_P(E_p)$ and the intermediate pion flux $J_\pi(E_\pi)$ need to be calculated first and finally the neutrino flux is calculated. For details, see Ref. [6, 11].

Expected neutrino fluxes from GRB 130427A at different time intervals (same as we considered in modeling) in a wind environment and in ISM are plotted in figures 9 and 10 respectively. The wind environment and ISM model parameters were used for the calculation of the respective neutrino fluxes.

4. Conclusions

In this work, we have done synchrotron modeling of GRB 130427A in a wind environment and in ISM. We studied the spectral energy distribution of the GRB at different time intervals and the temporal evolution of the flux for different frequencies, using data in gamma-ray, X-ray and optical ranges. This was done considering a slow cooling regime for the electrons, both in a wind environment and constant density ISM. The wind environment model described in this work seems to fit the data of GRB 130427A better than the ISM model, if applied with reasonable parameters. The GRB 130427A is expected to be a powerful source of ultra high

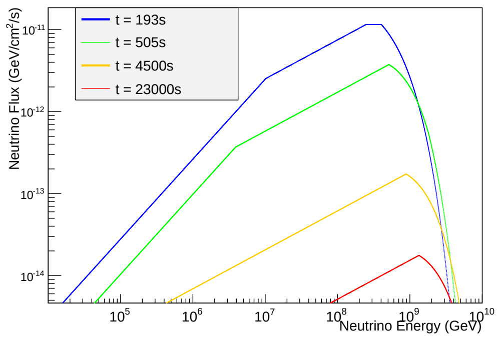

Figure 9. Neutrino flux for wind

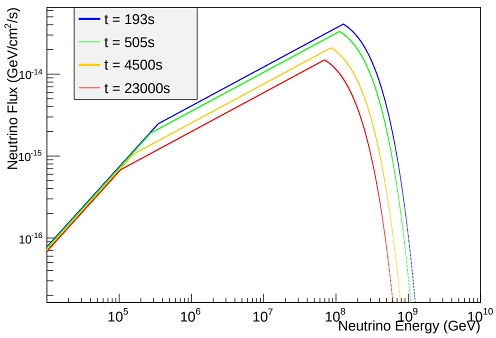

Figure 10. Neutrino flux for ISM

energy cosmic rays (UHECRs) and the interaction of these UHCRs with the burst's afterglow could produce neutrinos. We have calculated the expected neutrino flux from the GRB taking the model parameters at different time intervals used in the modeling (reference section 2), in both ISM and a wind environment.

The detailed study of this extremely energetic GRB and the calculation of the associated neutrino flux from it will give more insight in to the possible sources and the environments of the GRBs. Hopefully, the neutrino telescope currently in operation and those being planned for the future will be able to detect the neutrino flux calculated in this work, or a non-detection will help in putting an upper limit on UHECRs acceleration and neutrino production in GRBs.

5. References

[1] Ackermann M et al. 2013 *Science* **343** 42
[2] Kouveliotou C et al. 2013 *Astrophys.J.Lett* **779** 1
[3] Vestrand W T 2014 *Science* **343** 38
[4] Meszaros P and Rees M J 1997 *Astrophys.J.* **476** 23
[5] Piran T 2005 *Rev. Mod. Phys.* **76** 1143
[6] Razzaque S 2013, *Phys. Rev.* D **88** 103003
[7] Granot J, Piran T, Sari R 2010 *Astrophys.J.* **527** 236
[8] Waxman E and Bahcall J N 1997 *Phys. Rev. Lett.* **78** 2292
[9] Guetta D, Hooper D, Alvarez-Muniz J, Halzen F, and Reuveni E 2004 *Astropart.Phys.* **20** 429
[10] Gupta N and Zhang B 2007 *Astropart.Phys.* **27** 386
[11] Razzaque S, Yang L 2015 *Phys.Rev.* D **91** 043003