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The spectacular stellar explosion - GRB 130427A: synchrotron modeling in the wind and the ISM

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GRB 130427A, is the spectacular gamma ray explosion ever detected. It is believed to be originated from the core collapse of a massive star. It also achieved the record of being one of the most fluent and the longest duration GRB in GeV gamma rays lasting for about 20hrs. The redshift of this GRB has been detected as z=0.34. The Fermi-LAT Gamma-ray Space Telescope has detected a 95-GeV energy photon from GRB 130427A. The after glow radiation of this GRB was recorded by *Swift* XRT, BAT and UVOT. The Spectral Energy Distribution (SED) and Light curves of the prompt emission and afterglow help us to study the GRBs in detail. We have explained the afterglow SEDs and Light curve detected by LAT, XRT-BAT and UVOT/optical observations for GRB 130427A, by fitting it with the synchrotron emission model from the accelerated electrons for the adiabatic blastwave in both the interstellar medium (ISM) and wind environments. We see a better explanation of the observed data with synchrotron model in wind environment compared to ISM for this GRB.

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1. Introduction

It is an exciting fact that a large number of explosions take place in our mysterious universe and the most energetic explosions ever detected are Gamma Ray Bursts. These GRBs can last from fractions of seconds to hours and are accompanied by long lasting afterglows in all electromagnetic wavelengths. In GRBs, the prompt emissions reflect interactions within the system itself and the afterglows starts when the shock fronts of the jets reach the ISM. GRB 130427A is a spectacular explosion happened on 27th April 2013 marking one of the extremely high energetic event ever detected. The red shift of this GRB 130427A has been detected as z = 0.34 which is only about 3.6 billion light years away [1] from us and is one of the nearest GRB observed. GRB 130427A is recorded as one of the most fluent and luminous burst. GRB 130427A was first spotted by Fermi Gamma-ray Burst Monitor (GBM) on board the Fermi Gamma Ray space telescope. The Large Area Telescope (LAT) on board Fermi has detected 95 GeV photon which is the maximum energy ever detected from a GRB [1]. The X-ray and optical afterglows were so bright that it was observed for many days. X-Ray afterglows were detected by Swift at 0.3-10KeV and NuSTAR at 3-80 KeV of photon energies for more than a week [2]. The optical afterglows were also detected by UVOT telescopes of swift and other robotic and optical telescopes like Liverpool Telescope, MITSuME 50cm telescope of Akeno Observatory, Faulkes Telescope, Okayamma Telescopes and Murikabushi 1m telescope of Ishigakijima Astronomical Observatory [3]. Due to these facts GRB 130427A has been the center of attraction for astronomy as well as high energy astrophysics.

2. Synchrotron Modeling of GRB 130427A.

The GRB models are usually described based on the synchrotron emission of the relativistically accelerated electrons [4, 5]. In GRBs, after the explosion relativistic shells containing matter collide to form internal shocks. Synchrotron loss of these relativistic matter produce prompt emission. As the shock waves continue to expand outward they interact with ISM and the wind environment. The electrons in the external shocks get Fermi accelerated and produce photons by synchrotron cooling in the magnetic field resulting in afterglows [4].

The GRB 130427A has got a hyper energetic prompt emission and extremely bright afterglows in the X-ray, optical and infra-red wavebands. Here we have modeled the SEDs and light curves for this GRB in both the wind environment and the ISM. The data used to plot the synchrotron spectrum model are given in Table 1 to 5 [3].

Time (s)	Flux [erg/cm^2/s]	Flux error [erg/cm^2/s]
193	3.01E-07	1.38E-07
505	6.81E-08	2.95E-08
4500	6.03E-09	2.84E-9
23000	4.93E-10	2.24E-10

Table 1: LAT data in the energy band (0.1-100 GeV)

Time (s)	Flux [erg/cm^2/s]	Flux error [erg/cm^2/s]
193	1.42E-7	2.42E-8
505	1.99E-8	3.89E-9
23000	2.01E-10	4.15E-11

Table 2: XRT-BAT data in the energy band (0.3-10keV)

Time [s]	Flux [erg/cm^2/s]	Filter
505.0	5.3e-10 ± 4.8e-11	$w1$
	4.4e-10 ± 1.66e-10	u
	8.94e-10 ± 3.32e-10	b
23000	7.04e-12 ± 1.68e-13	$w1$

Table 3: UVOT data in the wavelength range (170-650nm).

Time [s]	Flux [mJy]	Filter
505.0	74.2 ± 0.14	r'
4500.0	6.97 ± 0.03	i'
4500.0	5.35 ± 0.03	r'

Table 4: Optical/Faulkes Telescope North

Time [s]	Flux [mJy]	Filter
23000.0	1.29 ± 0.03	i'
23000.0	1.17 ± 0.02	r'

Table 5: Optical/MITSuME 50cm telescope of Akeno Observatory

2.1 SED and light curves for GRB 130427A in wind-environment.

The instantaneous spectrum of low energy photons from a GRB can be modeled by the synchrotron emission of a single power law distribution of electrons. However the photon spectrum will have breaks at different frequencies due to absorption and cooling effects of electrons. These break frequencies are ν_m, the photon frequency corresponding to the minimum Lorentz factor $\gamma_{e,min}$ of electron, ν_c, the photon frequency corresponding to the cooling Lorentz factor of electrons $\gamma_{e,c}$, ν_a, the photon frequency due to self absorption and ν_s presenting maximum energy of the electron. [1]T_{90} for the GRB 130427A is nearly 162s. We chose the available afterglow data after this time so, the low energy spectra is in the slow cooling regime ($\gamma_{e,c} > \gamma_{e,min}$).

The instantaneous synchrotron spectrum F_ν, from a power law distribution of electrons in the slow cooling regime can be expressed as given in [4]. However in our modeling we have also included the self absorption effect and the exponential cut-off at higher energy in the spectrum.

$$F_\nu = F_{\nu,max}\begin{cases} (\frac{\nu}{\nu_a})^2(\frac{\nu_a}{\nu_m})^{\frac{1}{3}}; & \nu < \nu_a; \\ (\frac{\nu}{\nu_m})^{\frac{1}{3}}; & \nu_a < \nu < \nu_m, \\ (\frac{\nu}{\nu_m})^{\frac{-(p-1)}{2}}; & \nu_m < \nu < \nu_c, \\ (\frac{\nu_c}{\nu_m})^{\frac{-(p-1)}{2}}(\frac{\nu}{\nu_c})^{\frac{-p}{2}} exp(-\nu/\nu_s); & \nu_c < \nu_s \end{cases} \tag{2.1}$$

The break frequencies for the wind environment in equation 2.1 can be written following [6, 7] as,

$$\nu_m = 9.5 \times 10^{13} \varepsilon_{b,0.1}^{1/2} \varepsilon_{e,0.1}^{2} E_{55}^{1/2} (1+z)^{1/2} t_d^{-3/2} \quad \text{Hz}, \tag{2.2}$$

$$\nu_c = 2.1 \times 10^{15} \varepsilon_{b,0.1}^{-3/2} E_{55}^{1/2} (1+z)^{-3/2} t_d^{1/2} A_*^{-2} \quad \text{Hz}, \tag{2.3}$$

$$\nu_a = 8.3 \times 10^{9} \varepsilon_{b,0.1}^{1/5} \varepsilon_{e,0.1}^{-1} E_{55}^{-2/5} (1+z)^{-2/5} t_d^{-3/5} A_*^{6/5} \quad \text{Hz}, \tag{2.4}$$

$$\nu_s = 8.22 \times 10^{22} A_*^{-1/4} E_{55}^{1/4} (1+z)^{-3/4} t_d^{-1/4} \phi_1^{-1} \quad \text{Hz}, \tag{2.5}$$

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

$$F_{\nu,max} = 3.53 \times 10^{-24} \varepsilon_{b,0.1}^{1/2} E_{55}^{1/2} (1+z)^{-1/2} t_d^{-1/2} d_{l,28}^{-2} \quad \text{erg/cm}^2\text{/s/Hz}. \tag{2.6}$$

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[1] T_{90} of a GRB measures the duration of the time interval during which 90% of the total observed counts have been detected, with the interval starting by the time at which 5% of the total counts have been observed and ending with the time at which 95% of the total counts have been detected.

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

The SED and light curves of Wind model

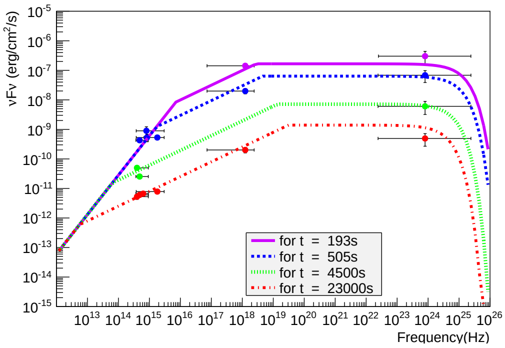

Figure 1: Spectral Energy Distribution in Wind medium

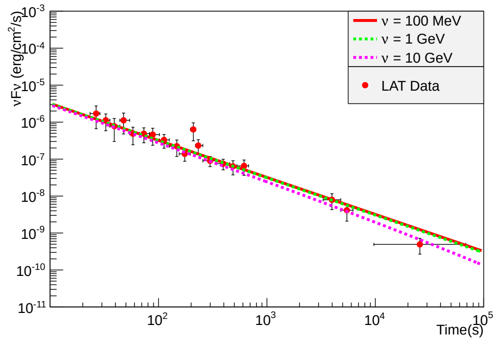

Figure 2: Light curve for LAT data in wind

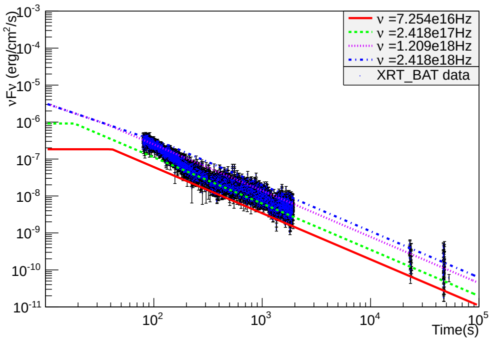

Figure 3: Light curve for XRT-BAT data in Wind medium

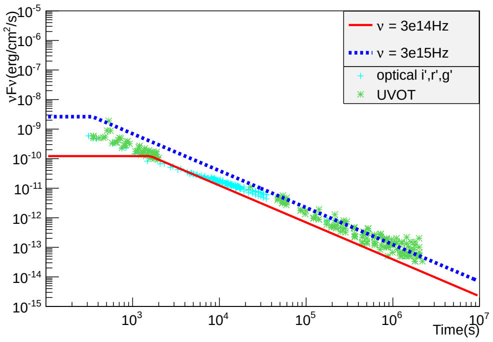

Figure 4: Light curve for optical/uv data in wind

The SED in the slow cooling regime for the GRB 130427A in the wind medium is plotted in Fig.1 , it shows the spectrum for the observed LAT, XRT-BAT and UVOT/optical data of GRB 130427A for different time intervals. It also shows the fitting with synchrotron emission spectra for the adiabatic blast waves in the wind environment. The fitted model parameters we obtained are, $\varepsilon_b = 0.0001$, $\varepsilon_e = 0.0085$, $E_{55} = 1.1$, $p = 2.0$, $A* = 1.0$, $z = 0.34$, $d_{L,28} = d_L/10^{28} = 0.56$ and $\phi_1 = \phi/10 = 0.01$

We have also modeled the temporal evolution of the flux in different frequencies. To model the light curves we have done the flux versus time plot of available data [3] at different energy levels and fitted it with the equation 1, as the break frequencies given in the equation are dependent on time. We have used the model parameters obtained from the SED to fit the data. In Fig. 2 the energy fluxes as a function of time from the trigger for observed LAT data are shown. Similarly Fig. 3 and Fig. 4 shows XRT-BAT, UVOT/optical light curves respectively.

2.2 SED and light curves for GRB 130427A in ISM.

The synchrotron modeling of GRB 130427A afterglow is also done for the constant density ISM. Equations derived for all the synchrotron frequencies, also explained in [6] in the ISM environment are given as,

$$\nu_m = 1.644\times10^{14}\varepsilon_{b,0.1}^{1/2}\varepsilon_{e,0.1}^{2}E_{55}^{1/2}(1+z)^{1/2}t_d^{-3/2}\quad \mathrm{Hz}, \tag{2.7}$$

$$\nu_c = 1.931\times10^{13}\varepsilon_{b,0.1}^{-3/2}E_{55}^{-1/2}(1+z)^{-1/2}t_d^{-1/2}n_0^{-1}\quad \mathrm{Hz}, \tag{2.8}$$

$$\nu_a = 5.53\times10^{9}\varepsilon_{b,0.1}^{1/5}\varepsilon_{e,0.1}^{-1}E_{55}^{1/5}(1+z)^{-1}n_0^{3/5}\quad \mathrm{Hz}, \tag{2.9}$$

$$\nu_s = 5.334\times10^{22}n_0^{-1/8}E_{55}^{1/8}(1+z)^{-5/8}t_d^{-3/8}\phi_1^{-1}\quad \mathrm{Hz}, \tag{2.10}$$

$$F_{\nu,max} = 7.95\times10^{-23}(1+z)^{-1}n_0^{1/2}d_{l,28}^{-2}E_{55}\varepsilon_b^{1/2}\quad \mathrm{erg/cm^2/s/Hz}. \tag{2.11}$$

Here, $n_0 = 1/cm^3$ is the particle density in the ISM.

The SED and light curves of ISM model

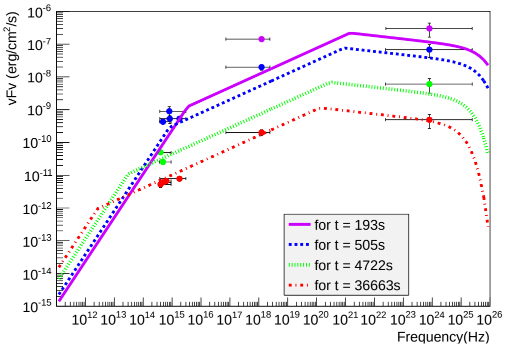

Figure 5: Spectral Energy Distribution in ISM

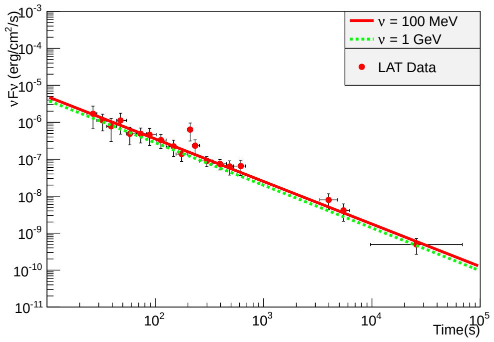

Figure 6: Light curve for LAT data in ISM

Fig. 5 shows the flux versus frequency spectrum at different time intervals 193s, 505s, 4500s and 23000s from early time to later time of the burst. It is observed that the spectrum in case of ISM is not fitting well as it does in the wind environment. The model parameters that we obtained for the ISM model are $\varepsilon_{b,0.1} = 4\times10^{-4}$, $\varepsilon_e = 0.028$, $E_{55} = 0.6$, $z = 0.34$, $d_{l,28} = 0.56$, $p = 2.2$, $n_0 = 0.01$ and $\phi_1 = 0.1$. Fig. 6, 7 and 8 are the light curves fitted with model parameters obtained from SEDs at different frequencies for LAT, XRT-BAT and UVOT/optical data respectively.

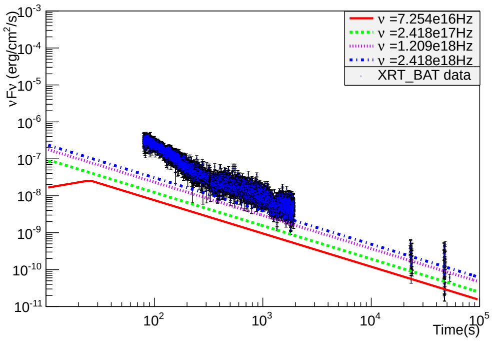

Figure 7: Light curve for XRT-BAT data in ISM

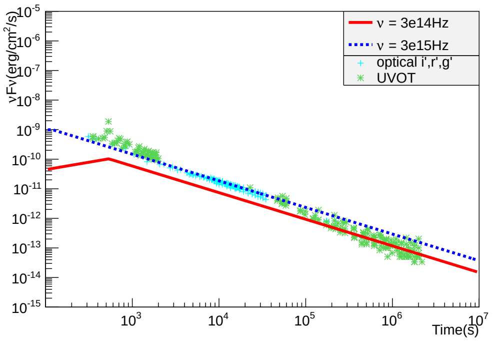

Figure 8: Light curve For UVOT/optical data in ISM

3. Discussion and conclusion

GRBs are extremely energetic explosions in the sky. GRB 130427A is one of the most energetic, bright and nearby GRB ever detected. The source of radiations from GRBs can be described in terms of synchrotron emission from accelerated electrons. In this article we have done the synchrotron modeling of broadband SED at different time intervals and the temporal evolution of flux in different frequencies for GRB 130427A. The modeling is done for both cases of ISM and wind environment. This GRB didn't fit well with the ISM environment and is well described in wind media with reasonable parameters, which is expected for GRB progenitor stars as they are thought to be massive and produce strong wind.

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