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An Investigation of the origin the bimodal distribution of optical afterglow luminosities of gamma-ray bursts

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Gamma-ray bursts (GRBs) are the most violent explosions in the universe. Much of what we know about these highly energetic, short-duration bursts of gamma-rays comes from their afterglows, which are long-lasting broadband signatures following the initial bursts. Scientists have long speculated over the x-ray afterglow light curves of GRBs, which contain a mysterious shallow decay component. Recently, Ryo Yamazaki introduced a new theoretical model for the shallow decay component called "prior emission." According to his model, there is actually x-ray emission *prior* to the prompt GRB. Our goal is to determine if the prior emission model is consistent with the external shock model. To do this, we will analyze prompt optical data and compare it to predictions derived from the theoretical models. Determining whether or not prior emission is consistent with the external shock model is crucial to better understanding the origin of the prior emission and the physics of GRB progenitors.

An Investigation of the Origin the Bimodal Distribution of Optical Afterglow Luminosities of Gamma-Ray Bursts

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Abstract

The determination of which properties of gamma-ray bursts and the surrounding interstellar medium contribute to the observed bimodal distribution of optical afterglow luminosities will provide insight into the physical processes that give rise to the two families of optical afterglows.

Introduction

Background:

> Gamma-ray bursts (GRBs): the brightest sources of electromagnetic radiation since the Big Bang; also the most violent explosions in the universe

> Most GRBs (Type II) are linked to supernovae; other GRBs (Type I) may be related to mergers between compact objects such as neutron stars and black holes

> GRB afterglow: occurs when the material from the explosion collides with circumburst material (such as the interstellar medium, also known as ISM); can be observed in all bands up to X-ray and lasts much longer than the initial explosion

> Light curve: plot of flux vs. time in a particular frequency; most common way to study GRB afterglows

The Question:

Analyses of the light curves of Type II GRB optical afterglows (detected approximately 10-12 hours after the prompt emission) have led three independent research groups (Liang & Zhang, Kann et. al, Nardini et. al) to determine that there are two tight groups of optical afterglow luminosities. It appears that, despite the many different physical properties of individual GRBs, the optical afterglow luminosities cluster around two values. This was an unexpected and puzzling result.

The physical origin of this bimodal distribution of optical afterglow luminosities has yet to be fully explained. Is it a property of the actual GRBs that creates this effect, or is it a property of the ISM? The objective of my research project this summer was to address this question.

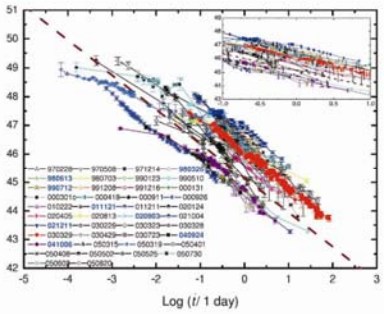
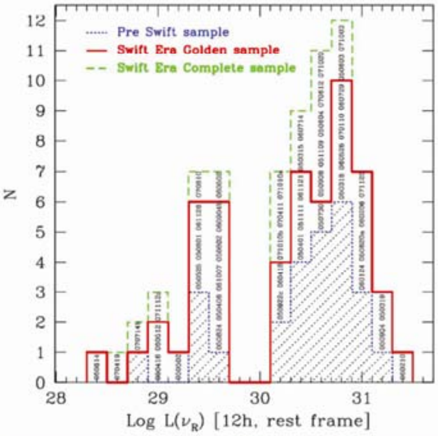


Figure 1 (left): Taken from Liang and Zhang (2006), this plot of the light curves of 42 GRBs illustrates the observed bimodality of afterglow luminosities in the optical band. The dashed line separates the more populous optically luminous group from the optically dim group. [1]

Figure 2 (lower left): Taken from Nardini et al. (2008), this histogram of optical luminosities of various samples of GRBS clearly illustrates the observed bimodal distruibution at t = 12 hrs. [2]



The Variable Parameters

For the scope of this summer project I focused on five parameters upon which the luminosity light curve of a GRB afterglow depends:

p (spectral index)

E_K (isotropic kinetic energy of the fireball)

n (ISM density)

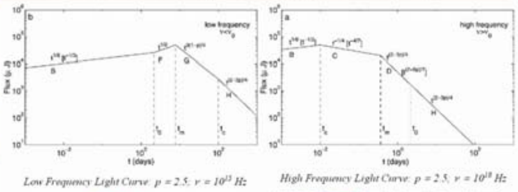
ε_e (fraction of internal shock energy partititoned to non-thermal electrons)

ε_B (fraction of internal shock energy partitioned to magnetic fields)

Method

The objective of this research project required that I create a computational code that allowed me to calculate the flux and luminosity of a GRB afterglow at any frequency and at any time after the initial explosion. I can input any values for the five variable parameters and my afterglow luminosity code will output the corresponding luminosity light curve. As shown in Figures 3(a) through 4(b), I was able to reproduce the light curves from Sari et al. 1998, a landmark GRB afterglow paper. Once I had developed the afterglow luminosity code, I utilized the Monte Carlo method to simulate various distributions of the five variable parameters. By trial and error, I experimented with different combinations of the distributions to see which best reproduced the observed bimodal distribution of optical afterglow luminosities.

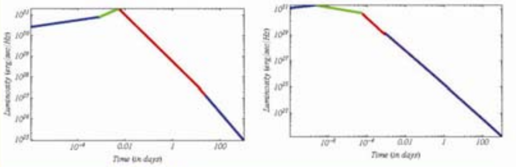
Figures 3(a), 3(b) (top): Taken from Sari et al. 1998, these show the low frequency and high frequency light curves, with the temporal indices for the fully radiative case in brackets (vs. the unbracketed fully adiabatic case). [3]



Low Frequency Light Curve: p = 2.5; ν = 10¹³ Hz

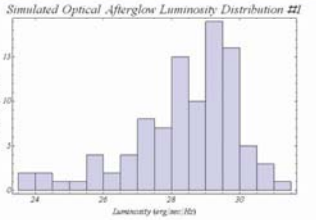
High Frequency Light Curve: p = 2.5; ν = 10¹⁸ Hz

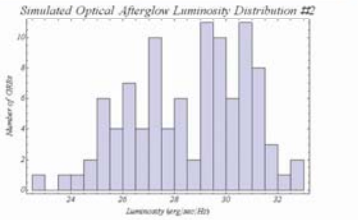
Figures 4(a), 4(b) (bottom): Example low frequency and high frequency light curves outputted by my afterglow luminosity program based on the following parameter values: n = 1 cm^{-3}; $E_K = 10^{52}$ ergs; $\varepsilon_e = 0.1$; $\varepsilon_B = 0.01$.



Results

Although I did not have time to experiment with a large number of combinations of distributions of the parameters, below are some examples of simulations using a uniform distribution of p between 2.0 and 3.0 and constrained Gaussian distributions of the $\log_{10}$ values of ε_e and ε_B. The three simulations shown below were created by varying the types of distributions of E_K and n. In Simulations #1 and #2, the n distribution is given a Gaussian distribution of the $\log_{10}$ values of n. In Simulation #3, the E_K distribution is the same broken power law from Simulation #1. Judging from the testing thusfar, changing the E_K distribution seems to have a larger impact on the simulations than does changing the distributions of the other four parameters.





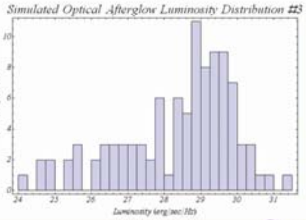


Figure 5a (upper left): Simulation with broken power law distribution for E_K.

Figure 5b (above): Simulation with double-humped Gaussian distribution for E_K.

Figure 5c (lower left): Simulation with broken power law distribution for E_K and double-humped Gaussian distribution for n.

Conclusion

Out of the current set of results, Simulations #2 and #3 are the closest reproductions of Figure 2. However, the break between the lower and upper luminosity groups is not as defined as it should be, or in the right place. The peaks in both groups may also be systematically lower than in Figure 2, especially in the case of Simulation #3. In addition, the simulation generates outlying low luminosities that are not shown in Figure 2 because of an observational selection effect: low luminosity bursts (particularly at higher redshifts) are much less likely to be detected. As work on this project continues, this selection effect needs to be taken into account. In addition, more experimentation with distributions of the parameters (particularly E_K and n) is needed.

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