Gamma-Ray Bursts: Characteristics and Prospects

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Gamma-Ray Bursts: Characteristics and Prospects

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Abstract. Gamma-ray bursts (GRBs) are the most powerful explosions in the universe. They have remained the object of intense research ever since their discovery was declassified in the early 1970s. Several space-borne missions have been dedicated to their study, including the Compton Gamma-Ray Burst Observatory (CGRO) in the 1990s and the current *Swift* and *Fermi* satellites. However, despite several decades of focused research, the precise mechanisms behind these enigmatic explosions have not been fully established. In the first part of this paper, we review what is currently known about GRBs. This includes: GRB light-curves and spectra; the different progenitor models, i.e., the "collapsar" and "merger" models; and the afterglow characteristics, including external shocks and the surrounding medium. In the second part of the paper, we present our work, which focuses on utilizing GRBs as cosmological probes. GRBs are ideal cosmological tools, because they have been observed to great distances (redshifts up to $z = 9.4$) and their radiation is unencumbered by any intervening dust. Although GRBs are not standard candles, the discovery of several energy and luminosity correlations, like the Amati relation which correlates the intrinsic spectral peak energy, $E_{p,i}$ to the equivalent isotropic energy, E_{iso}, has ushered in a new era in which GRBs are used to investigate cosmological issues like the star formation rate and the value of the matter-density parameter, Ω_M.

1. Introduction

Gamma-ray bursts (GRBs) are the most powerful explosions in the universe. Their total isotropic energy is in the range of 10^{48}–10^{55} erg [1–6]. A bimodal distribution for GRB durations was detected in the BASTSE data [7], which led to the classification of GRBs into short bursts ($T_{90} < 2$ s) and long bursts ($T_{90} > 2$ s), where T_{90} refers to the time needed for 90% of the fluence to be accumulated [8]. During the 1980s and early part of the 1990s, there was a debate concerning whether GRBs had cosmological or galactic origins. The isotropic spatial distribution of GRBs obtained by BATSE strongly implied a non-galactic origin. The issue was settled in 1997 when the first afterglow observation by the *BeppoSAX* satellite succeeded in pinning down the redshift of GRB970228 [9, 10].

In this paper, we provide a brief review of the main characteristics of GRBs, followed by a discussion of the prospects of using GRBs as cosmological tools. We also briefly present some of our recent results in this area.

2. Prompt and Afterglow Emissions

The prompt emission of GRBs consists of high-energy gamma-ray photons as well as hard X-ray photons. The spectrum is non-thermal, and the energy flux has a peak at around a few hundred keV. Although the spectrum varies from one burst to another, it can be fit very well by the Band function, which consists of two power laws joined smoothly at a break energy [11].

The temporal structure of the prompt emission is highly variable. First, the duration of GRBs spans a wide range: from less than 0.1 s to more than 1000 s. Second, within a certain burst, the light curve usually shows dramatic variations in the flux (sometimes by as much as 100%) on very short timescales. In fact, the variability timescale, Δt, is typically a factor of 10^4 shorter than the GRB's duration, T_{90}.

Unlike the prompt emission which is attributed to internal dissipation, the afterglow emission is attributed to external dissipation. As the outflow from some catastrophic event interacts with the surrounding medium, it dissipates energy through external shocks. The afterglow emission ranges from X-rays all the way down to radio waves [12−14].

3. Progenitor Models

Observations indicate that some (but not all) long bursts are associated with supernovae, hence with the violent death of stars. According to the "collapsar" model (the most popular current model for long bursts) when a very massive (M >~ 30 M_{sun}), low-metallicity, rapidly spinning star collapses at the end of its life, the "hypernova" produces a black hole at the core and produces an explosion. The infalling material forms a dense accretion disk that ejects two relativistic jets along the axis of rotation [15, 16].

The "collapsar" model, however, does not explain the formation of short bursts, which typically occur in regions with limited star formation. Several models have been proposed to explain the formation of short GRBs. The most successful models involve the merger of two compact objects, like two neutron stars. As the two compact objects spiral slowly toward one another, they release gravitational energy until the tidal forces rip the progenitors apart and the system collapses into a black hole. The infalling material creates an accretion disk which emits a burst of energy, similar to what is produced in the "collapsar" model but with shorter durations [17, 18].

4. Cosmological Prospects

GRBs hold great potential as cosmological tools for two reasons. First, they have been observed to very high redshifts, up to $z = 9.4$ so far and with hopes of reaching $z = 20$ with future satellites [19]. Second, their gamma radiation is unencumbered by any intervening dust. Although GRBs are not standard candles, the discovery of several energy and luminosity correlations (see below) has permitted their use as cosmological probes.

Early attempts to utilize GRB correlations to constrain cosmological models faced several hurdles [19, 20]. First, there was the issue of the paucity of GRBs with measured redshifts. Second, there was the problem of the wide scatter in the correlations. Finally, there was the issue of the circularity problem, which refers to the fact that in order to calibrate the energy and luminosity correlations, one must assume a cosmological model, which defeats the goal of determining cosmological parameters from GRB characteristics. However, as the quality and the abundance of the data improved, there has been a revived interest in GRB cosmology [21].

In a recent study [22], we used a sample of 126 *Swift* bursts to put limits on the cosmological density parameters (Ω_M and Ω_Λ) by employing two GRB correlations: the Amati relation and the Dainotti relation. The Amati relation is a correlation between the intrinsic spectral peak energy, $E_{p,i}$, and the equivalent isotropic energy, E_{iso}, which can be written as

$$E_{p,i}\,(\mathrm{keV}) = K \times [E_{iso} / 10^{52}\ \mathrm{erg}]^m, \tag{1}$$

where K and m are fitting parameters. The Dainotti relation is a correlation between the X-ray afterglow luminosity, L_X, and the break time, T_a, which is observed in the X-ray flux. We calibrated the Dainotti relation and expressed it as

$$[T_a / (1 + z)] = 10^{25.2} L_X^{-0.46}. \tag{2}$$

Our analysis involves employing a maximum likelihood method to carry out a "reverse job" in which we search for the cosmological parameters that provide the best fit, which occurs when the likelihood function $-\ln(L)$ is minimized [22]. The fit is not given by specific values but rather by contours that correspond to the same values of $-\ln(L)$, which is achieved by numerically varying Ω_M and Ω_Λ between 0 and 1. We stress that in order for this approach to work, it is important to have high-quality data with little scatter, otherwise the values of Ω_M and Ω_Λ do not converge.

We sum up our results as follows:

- Our analysis indicates that the results obtained using the Amati relation favor a universe dominated by dark energy, whereas those obtained using the Dainotti relation favor a universe dominated by matter.
- The results we obtain are qualitatively in agreement with those obtained using other methods (like Supernovae Ia and the Cosmic Microwave Background).
- For our technique to work well, it is important to obtain large data sets with low scatter.
- We were able to numerically reduce the scatter in the Dainotti relation before utilizing it to place limits on Ω_M and Ω_Λ.

In the future, we hope to pursue this line of analysis by studying other GRB correlations, like the Ghirlanda relation and the Yonetoku relation, and by using larger data sets with the aim of obtaining more stringent limits on the values of the cosmological parameters.

5. Conclusion

Gamma-ray bursts are the most distant and powerful explosions in the universe. They display a wide variety in terms of their light curves and spectra. Although several progenitor models have been proposed to explain the formation of long and short bursts, the precise mechanism behind these enigmatic explosions has yet to be established. In recent years, there has been a revived interest in GRB cosmology, in which correlations between GRB parameters (energies, luminosities, spectra break time, etc.) are utilized to investigate and discriminate between cosmological models. Our study indicates that such an approach is indeed fruitful because it manages to put limits on cosmological parameters.

References

[1] Nakar E 2007 *Phys. Rep.* **442** 166
[2] Zhang B 2011 *Comptes Rendus Physique* **12** 206
[3] Gehrels N and Razzaque S 2013 *Frontiers of Physics* **8** 661
[4] Berger E 2014 *ARA&A* **52** 43
[5] Kumar P and Zhang B 2015 *Phys. Rep.* **561** 1
[6] Mészáros P 2006 *Reports on Progress in Physics* **69** 2259
[7] Meegan C A *et al* 1992 *Nature* **355** 143
[8] Kouveliotou C *et al* 1993 *ApJ* **413** L101
[9] Costa E 1997 *Nature* **387** 783
[10] Van Paradijs J *et al* 1997 *Nature* **386** 686
[11] Band D et al. 1993 *ApJ* **413** 281
[12] Dermer C D 2007 *ApJ* **664** 384

[13] Frail D A *et al* 2000 *ApJ* **534** 559
[14] Frontera F *et al* 2000 *ApJS* **127** 59
[15] MacFadyen A I and Woosley S E 1999 *ApJ* **524** 262
[16] Woosley S E 1993 *ApJ* **405** 273
[17] Vietri M and Stella L 1998 *ApJL* **507** L45
[18] MacFadyen A I 2006 *AIP Conference Proceedings* **836** 48
[19] Azzam W J and Alothman M J 2006a *Adv. Space Research* **38** 1303
[20] Azzam W J and Alothman M J 2006b *Nuovo Cimento B* **121** 1431
[21] Dainotti M G, Del Vecchio R and Tarnopolski M 2016 *Preprint* arXiv:1612.00618v1
[22] Zitouni H, Guessoum N and Azzam W J 2016 *Astrophys. & Space Science J.* **361** 383