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Chapter 1

GAMMA-RAY BURSTS: ORIGIN, TYPES, AND PROSPECTS

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ABSTRACT

Gamma-ray bursts (GRBs) are the most powerful explosions in the universe. They were discovered serendipitously in the late 1960s, and despite decades of intense research, the precise mechanism behind their formation remains enigmatic. GRBs are divided traditionally into two types based on duration: long bursts with $T_{90} > 2$ seconds, and short bursts with $T_{90} < 2$ seconds, where T_{90} is the time needed for 90% of the fluence to accumulate. According to the "collapsar" model, long GRBs originate from the death and collapse of a massive star into a black hole. On the other hand, short GRBs are believed to originate from the merging of two neutron stars. Several energy and luminosity correlations currently exist for gamma-ray bursts (GRBs). For instance, the Amati relation is a correlation between the intrinsic peak energy, $E_{p,i}$, in the νF_ν spectrum of a burst and its equivalent isotropic energy, E_{iso}, and the Yonetoku relation is a correlation between $E_{p,i}$ and the isotropic peak luminosity, L_{iso}. Assuming that these correlations are robust, they may then be used as cosmological probes. In this chapter, we first provide a brief review of the GRB progenitor models, the GRB classification schemes, and the GRB correlations that currently exist. We then explore other scenarios that might prove fruitful in explaining the origin, the types, and the cosmological utility of GRBs.

Keywords: Gamma-Ray Bursts; progenitor models; types; cosmological prospects

1. INTRODUCTION

Gamma ray bursts (GRBs) are the most powerful explosions in the Universe and are promising cosmological probes of the early Universe [1]. They were serendipitously discovered by the Vela satellites in the 1960s [2]. The luminosity of the brightest GRBs rivals that of the entire Universe at all wavelengths although they last only for a few seconds [3]. The following decades witnessed only slow progress since gamma-ray instruments of the time exhibited poor positioning capabilities, and thus allowed only wide-field insensitive telescope follow-ups. Since their discovery, great efforts have been deployed to have a better understanding of their origin and the precise mechanism behind their formation. The bursts radiate between 10^{48} and 10^{55} erg and are isotropically distributed on the sky. These facts led most astronomers to conclude that GRGs are located at cosmological distances beyond the local group of galaxies. A confirmation of the cosmic distance scale of GRBs was first obtained by the BeppoSAX satellite in 1997. Bursts are usually followed by an afterglow that appears at longer wavelengths. X-ray and optical afterglow emissions were first observed in 1997, and led to the determination of the first GRB redshift ($z = 0.695$) [4-5]. Subsequently, the study of GRB afterglows provided a wealth of information about these enigmatic explosions [6-10]. Traditionally, GRBs have been classified into long bursts (LGRBs) with $T_{90} > 2$sec, and short bursts (SGRBs) with $T_{90} < 2$sec, where T_{90} is the duration needed to accumulate 90% of the burst fluence [11]. Long duration GRBs (LGRBs) are typically observed in the star-forming regions of the host galaxies [11-15]. An important parameter characterizing the bursts is their duration. It lasts from few milliseconds to several minutes and depends upon the mechanism involved, the nature of the progenitor, and the environment. Recently, GRBs exhibiting very short durations ($T_{90} < 0.1$) have been discovered [16]. The distribution of different GRB classes, based on duration alone, exhibits a broad profile with significant overlap, and hence makes the classification scheme inconclusive. There is compelling evidence that some long duration GRBs are associated with supernovae events [17-21], since long duration GRBs are typically observed in the star-forming regions of their host galaxies [20-23]. Beaming effects are usually associated with LGRBs, and observations suggest a significant variation in the jet angle ranging from 2 to 20 degrees [22].

The most favored model of SGRBs is the merger of compact objects such as neutron stars and black holes. The jets associated with these events are less collimated than LGRBs [23], and sometimes they are not collimated at all [24].

In the first section of this chapter, we introduce the collapsor model in which a massive star collapses to form a black hole. In the second section, we discuss the possible origin of SGRBs. In the third section, we investigate the origin of jets associated with LGRBs, their types, and the mechanism of formation. After that, we consider other aspects of GRB physics, including the afterglow spectra and origin, the relation of GRBs and the star formation rate. Finally, we will look at the potential use of GRBs as cosmological probes.

2. THE COLLAPSOR MODEL

Long duration GRBs are thought to be the final fate of massive stars [25]. A black hole is usually formed after the core collapse. In certain cases, a magnetar is formed as an intermediate state which eventually collapses to a black hole [26]. The central engine is formed from a compact core of few solar masses with the Schwarzschild radius $r_s \sim 10^4 (M_{BH} / 3M_\odot) m$, where M_{BH} is the mass of the black hole and $M_\odot$ is the solar mass. The black hole accretes the in-falling gas rather efficiently. An important part of the gravitational energy, $\sim 10^{54}$ erg, is radiated as thermal neutrinos, whereas a smaller part is radiated as gravitational waves [27]. A small fraction, however, $\sim 10^{51}$ erg, is converted to a GRB fireball which becomes eventually the origin of a highly relativistic bipolar jet and is responsible for the observed gamma rays [28, 29].

According to this model, the minimum angular momentum needed is basically the value associated with the last stable orbit around a black hole which, for a non-rotating black hole is given by [30]

$$J = 2(3)^{1/2} GM / c = 4.6 \times 10^{16} [M_{BH} / 3M_\odot] cm^2 / s \quad (1)$$

where G is the universal gravitational constant, c is the speed of light in vacuum, M_{BH} is the mass of the black hole, and $M_\odot$ is the solar mass. For a rotating black hole it is given by [31]

$$J = 2GM / (3)^{1/2} c = 1.5 \times 10^{16} [M_{BH} / 3M_\odot] cm^2 / s \quad (2)$$

The GRB fireball model assumes that a large amount of energy is released within a short time scale. The luminosity of the out-flowing material in this case is given by $L \sim E_{iso}/t$, where E_{iso} is the equivalent isotropic energy, and t is the duration of the LGRG [32]. The fireball consists of gamma rays, electron-positron pairs, and some baryons. The relativistic jet is formed when the optically thick plasma expands to overcome the gravitational pressure [33]. The jet is characterized by a bulk Lorentz factor which increases initially as $\Gamma(r) \sim r / r_o$, where $r_o \sim 10^5$ m, is the inner radius of the accretion disc. The Lorentz factor becomes constant at a value $\Gamma \sim \eta$, where η is the baryon loading of the fireball and is defined as the ratio between the total energy and the mass flow. The fireball attains a radius of $r_o \eta$ at this Lorentz factor [34-35]. A prompt γ-ray emission from GRBs occurs when a significant fraction of the fireball energy is converted back to radiation energy. This emission is currently explained in terms of the internal shock model where collisions between shells of plasma produce shocks, and thus converting a fraction of the kinetic energy to particles that radiate via synchrotron mechanism. The internal shock collisions are semi-relativistic and occur due to a difference in the Lorentz factor between the shells [32]. The colliding shell model was successful in producing the observed pulse structure of the GRB spectra [36-37]. The magnetic field is thought to be amplified by a fraction of the shock energy [38-39], whereas electrons are accelerated via the Fermi mechanism to relativistic energies by another fraction of the shock energy. A characteristic peak, ε_{sp}, attributed to synchrotron radiation usually appears at a few hundred keV in the γ- ray spectrum. The observed spectra above ε_{sp} can be explained as due to synchrotron radiation resulting from the power-law distributed electron Lorentz factor [32]. However, the synchrotron shock model described above has difficulties in explaining the observed γ- ray spectrum below ε_{sp} for a large fraction of bursts [40-42]. In the fast cooling synchrotron model, electrons lose most of their energy to the observed radiation via the synchrotron/Compton mechanism. In this model, a spectrum of the form $n(\varepsilon) \sim \varepsilon^{-3/2}$ below ε_{sp} is expected to be found. This is in contrast to the $n(\varepsilon) \sim \varepsilon^{-1}$ typically observed for LGRBs. A harder variation, $n(\varepsilon) \sim \varepsilon^{-2/3}$, synchrotron spectrum for electrons in a random magnetic field is often referred to as the "synchrotron death line" [40], and is violated by a considerable fraction of LGRBs.

Many attempts have been devised to explain the discrepancy in the observed Compton mechanism. Among these explanations are the Compton scattering of optical photons to keV energies [43], low-pitch angle scattering or jet radiation [44, 45], synchrotron self-absorption in the keV range [46], mixing of keV photons with axion-like particles [47], time-dependent acceleration [48], and photospheric thermal emission [32].

3. SHORT DURATION GAMMA RAY BURSTS

The Swift satellite has provided valuable information regarding the origin of short duration GRBs. Accurate localization of the bursts led to the discovery that a fraction of these bursts are located in elliptical galaxies, i.e., associated with older stellar populations, and were found to be on average less energetic and at a lower redshift than LGRBs [49-53]. These observations confirm the old idea that SGRBs originate from the merger of compact objects such as neutron stars and black holes [54, 55]. Nevertheless, so far there is no conclusive proof for this model.

4. GAMMA-RAY BURST JETS

GRBs jets have been the subject of intense research in the Fermi era. The Fermi satellite observations of GRBs over a broad energy range revived interest in the model of Poynting-flux dominant GRB jets [56, 57]. Modeling Fermi data supports magnetic models that provide a natural explanation of the GRB jets. In these models, particles are accelerated in the reconnection region of the magnetic field lines and produce the observed radiation. Two categories of magnetic models can be inferred from the data. The first category is characterized by a complete absence of baryons in the jet, or they are dynamically negligible, at least in the initial phase [58, 59]. The second category is characterized by a significant baryon load which is dynamically sub-dominant relative to the magnetic stresses [60-63]. These two models can merged in a hybrid model dubbed ICMART [64] in which an initial Poynting flux dominates the outflow with only few baryons that lead to internal shocks when the magnetic energy subsides at larger radii.

Some researchers have suggested that GRB outflows are collimated [65]. The evidence of this collimation is inferred from an achromatic break seen in many afterglow light curves, and is known as "jet breaks". The light curve steepens following the jet break. This observation is due to two effects [66, 67]. The first is the so-called "edge" effect [68-70]. For a relativistically moving jet with a Lorentz factor Γ, photons emitted at any point of the jet are beamed within a $1/\Gamma$ cone as seen in the lab frame. The second effect of a finite jet angle on the light curve is produced by sideway expansion [66, 67]. Numerical simulations show that the sideway expansion of a relativistic jet remains unimportant until Γ drops below 2 [71-73].

The GRB jets are expected to exhibit a structure arising from the variation of the luminosity per unit angle and the Lorentz factor with angle across the jet. This variation follows either a power-law function [74, 75] or a Gaussian distribution [76-78]. Other types of jet structure are the two-component jet model in which the GRB outflow is composed of a narrow jet, characterized by a higher isotopic luminosity $\Gamma_{\gamma,iso}$ and Γ factor, which is usually surrounded by a wider jet with lower a $\Gamma_{\gamma,iso}$ and Γ component.

The GRB jet can also exhibit a "patchy" appearance, resulting from emissions produced by many patches or "mini-jets" within a broad cone [79, 80]. Mechanisms responsible for theses patchy jets include non-uniform shells within the internal shock scenario [79], localized Lorentz boosted emission regions associated with relativistic outflows in magnetic reconnections, or turbulence in a magnetically-dominated jet [81-83].

Another interesting effect, dubbed, "orphan afterglows" involves the detection of afterglow events of a relativistic jet with a finite opening angle, but without the detection of the prompt γ- ray emission itself [84-86]. In this case, an observer lying outside the jet cone might not see γ- rays because of the strong relativistic beaming of photons in the direction of the jet and away from the observer's line of sight.

5. GAMMA-RAY BURST AFTERGLOWS

The Swift satellite, with its X-ray and UV-optical telescopes, has provided a unique opportunity to localize GRBs. Once a burst is detected, these on-board telescopes slew to the GRB position within few seconds to observe the target as it transits from the γ- ray phase to the lower frequency afterglow phase. Thus, Swift has provided a wealth of information regarding the nature and evolution of the burst [87, 88]. It was found that a variety of physical processes affect the early X- ray afterglow lightcurve [89]. The Swift X-ray telescope has found that for about 50% of the GRBs, the X-ray flux decays rapidly after the burst ($F_x \propto t^{-3}$), followed by a plateau during which the X-ray afterglow decreases at a much slower rate ($F_x \propto t^{-1/2}$) than expected by the standard forward-shock model [90]. It was suggested that the γ- ray prompt radiation and the afterglows are produced by two different mechanisms [90] or one produced by different outflows. Swift data also indicate a sharp increase in the X-ray flux (flares) minutes to hours after the end of the GRB [91-93]. The rapid risetime for the X-ray flux suggests that a central engine in these explosions is active for a time period much longer than the burst duration [94, 95].

6. γ - RAY PROMPT EMISSION

The nature and mechanism of the prompt γ - ray radiation that triggers detectors on board GRB satellites remains a puzzle. Many models have been investigated to answer this question. Among these models is the internal shock model, the external shock model, or something entirely different. In addition, are γ - ray photons produced via synchrotron processes or inverse-Compton processes, or by some other in identified mechanism? Answering these questions will certainly provide a clue as to the source of these bursts.

Some of these questions can be investigated by analyzing data in the range ~ 10 keV to > 300 GeV provided by the multipurpose Fermi satellite. These data were the source of many discoveries regarding the spectra and evolution of the bursts [96, 97]. Data provided by this satellite indicate that in most cases the high-energy photons (> 10^2 MeV) were detected with a delay of a few seconds with respect to the lower energy emission ($\leq$ 1 MeV), and lasts for a time period much larger ($\sim 10^3$ s) than the low energy emission (1 minute for most GRBs). In addition, the broad-band prompt γ - ray spectra consist, in most cases, of one peak and a power-law function with different indices at low and high energies and with a smooth transition from one to the other. Many authors have found strong evidence suggesting that the observed high-energy photons (>10^2 MeV) are due to the external forward shock via the synchrotron process [98, 99]. However, the origin of the prompt γ - ray emission at low and high energies remains elusive. Among the proposed models to explain the γ - ray emission in these energy domains are synchrotron and inverse-Compton radiation processes with internal or external shocks, or at locations where the magnetic field in the Poynting jet is dissipated [100-106].

7. GAMMA-RAY BURSTS AND STAR FORMATION RATES

The Swift satellite data has provided a rich number of measured GRB redshifts that permit an accurate statistical analysis of the distribution of LGRBs. These GRBs are most probably powered by the core collapse of massive stars [107-109]. This idea is strongly supported by observations of associations between LGRBs and supernovae [110, 111]. The collapsor model suggests that the cosmic GRB rate should, in principle, trace the cosmic star formation rate [112, 113]. However, observations seem to indicate that the rate of LGRBs does not strictly follow the star formation rate (SFR), but instead increases with cosmic redshift faster than the SFR, specially at high-z [114-116]. The observed enhancement of the GRB rate has led many research groups to postulate several possible mechanisms that produce such enhancement [117-119]. The prevailing idea that has gained support recently is the possibility that the enhancement has an evolutionary origin that may be parameterized as $(1+z)^{\delta}$ [117]. This approach encompasses the effect of cosmic metallicity evolution [120], an evolution in the stellar mass function [121], as well as possible selection effects. However, Jun-Jie Wei et al. advance the idea that the enhancement of the GRB redshift distribution compared to the SFR is not completely answered [122]. They have proposed eliminating the discrepancy between the GRB rate and the SFR by assuming a modest evolution, parametrized as $(1+z)^{0.5}$ - an effect that perhaps implies a cosmic evolution in metallicity. They found a relatively higher metallicity cut off, $z = 0.68z_{\odot}$ than reported by previous studies, and suggested that LGRBs occur preferentially in metal poor environments with $z = 0.1 - 0.3z_{\odot}$.

8. GRBs as Cosmological Probes

Gamma-ray bursts are powerful tools in probing cosmological models, since they can be detected to large redshifts (z > 9) and are unencumbered by dust [123–128]. Furthermore, several robust correlations between the radiated energy and the peak energy in the νF_ν spectrum have been utilized to pin down certain cosmological parameters, like the density parameter Ω_M [129–132].

If the redshift and the spectrum of a GRB are known, then two important parameters can be computed: the equivalent isotropic energy, E_{iso}, and the intrinsic peak energy, $E_{p,i}$, in the νF_ν spectrum. E_{iso} can be computed by integrating the spectrum in the $1 - 10^4$ keV range, and $E_{p,i}$ is simply given by $E_{p,obs} \times (1 + z)$, where $E_{p,obs}$ is the observed peak energy in the νF_ν spectrum.

In 2002, Amati et al. [131, 132] found a strong correlation between E_{iso} and $E_{p,i}$. The correlation can be written as:

$$\log(E_{iso}) = A + B \log(E_{p,i} / \langle E_{p,i} \rangle) \quad (3)$$

where $\langle E_{p,i} \rangle$ is the mean intrinsic peak energy for the entire sample, and A and B are fitting parameters that are obtained through least-square fits [131].

In a similar way, one may investigate other correlations, like the Yonetoku relation which is a correlation between the peak isotropic luminosity, L_{iso}, and $E_{p,i}$. The relation may be written as:

$$\log(L_{iso}) = A + B \log(E_{p,i} / \langle E_{p,i} \rangle), \quad (4)$$

where again A and B are fitting parameters that are obtained through least-square fits.

Several studies [124, 125] have looked at the robustness of these relations and whether they are redshift independent. These studies have confirmed the robustness of these relations and that they are not due to selection effects.

The L_{iso} obtained from the Yonetoku relation can be compared to L_Ω which is obtained from the luminosity distance, d_L, for an assumed cosmological model, as follows:

$$L_\Omega = 4\pi\varepsilon P \, d_L^2 \quad (5)$$

where ε is the mean photon energy and P is the peak photon flux. The luminosity distance can be calculated for different values of the cosmological parameters and the resulting L_Ω is then compared to L_{iso}. The best values for the cosmological parameters are the ones that bring L_{Ω} closest to L_{iso}.

Such cosmological investigations started in earnest in 2004 with the discovery of the Ghirlanda relation which was tighter than the Amati relation and was thus more suited for cosmological investigations [136]. The results of these studies were promising and were successfully used to put limits on Ω_M and Ω_Λ [137]. This, in turn, led to the derivation of a GRB Hubble diagram which ended up being a powerful cosmological tool [138–141]. Despite the success of the Ghirlanda relation, in the long run, the Amati relation proved more fruitful since it did not require knowledge of the jet opening angle. By using a sample of 156 bursts, Amati et al. [132] succeeded in obtaining reliable values for Ω_M.

From what has been mentioned so far, it is clear that GRBs hold great promise as cosmological probes. As more GRB data become available, the GRB correlations will become tighter and more effective in pinning down cosmological parameters.

CONCLUSION

Gamma-ray bursts are the most powerful explosions in the Universe. They come in two basic types: long and short. Several progenitor models have been proposed, but none have been fully confirmed. The Swift and Fermi satellites have provided a wealth of data, especially in regard to afterglow studies. Gamma-ray bursts also hold great promise as cosmological probes since they can be detected to large redshifts and are not encumbered by dust.

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