Cosmic Explosions: The Beasts and Their Lair

by

Edo Berger

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Thesis by
Edo Berger

In Partial Fulfillment of the Requirements
for the Degree of
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Acknowledgements

Embarking on the fascinating study of gamma-ray bursts I could have found no better group of guides and companions than my past and present colleagues at the ”Caltech-NRAO GRB group”. I am indebted to them and many other colleagues at Caltech and elsewhere for their unconditional pursuit of scientific knowledge, and for making the last five years exciting and rewarding. I would like to think that some of this knowledge and excitement is captured in this thesis.

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by

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Abstract

The diversity of stellar death is revealed in the energy, velocity and geometry of the explosion debris ("ejecta"). Using multi-wavelength observations of gamma-ray burst (GRB) afterglows I show that GRBs, arising from the death of massive stars, are marked by relativistic, collimated ejecta ("jets") with a wide range of opening angles. I further show that the jet opening angles are strongly correlated with the isotropic-equivalent kinetic energies, such that the true relativistic energy of GRBs is nearly standard, with a value of few times 10^{51} erg. A geometry-independent analysis which relies on the simple non-relativistic dynamics of GRBs at late time confirms these inferences. Still, the energy in the highest velocity ejecta, which give rise to the prompt γ-ray emission, is highly variable. These results suggest that various cosmic explosions are powered by a common energy source, an "engine" (possibly an accreting stellar-mass black hole), with their diverse appearances determined solely by the variable high velocity output. On the other hand, using radio observations I show that local type Ibc core-collapse supernovae generally lack relativistic ejecta and are therefore not powered by engines. Instead, the highest velocity debris in these sources, typically with a velocity lower than $100,000$ km/sec, are produced in the (effectively) spherical ejection of the stellar envelope. The relative rates of engine- and collapse-powered explosions suggest that the former account for only a small fraction of the stellar death rate. Motivated by the connection of GRBs to massive stars, and by their ability to overcome the biases inherent in current galaxy surveys, I investigate the relation between GRB hosts and the underlying population of star-forming galaxies. Using the first radio and submillimeter observations of GRB hosts, I show that some are extreme starburst galaxies with the bursts directly associated with the regions of most intense star formation. I suggest, by comparison to other well-studied samples, that GRBs preferentially occur in sub-luminous, low mass galaxies, undergoing the early stages of a starburst process. If confirmed with future observations, this trend will place GRBs in the forefront of star formation and galaxy evolution studies.

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To see a world in a grain of sand
And a heaven in a wild flower,
Hold infinity in the palm of your hand
And eternity in an hour

— William Blake (*Auguries of Innocence*)

What we call results are beginnings.

— Ralph Waldo Emerson

CHAPTER 1

Introduction and Overview

SECTION 1.1

History: The Discovery of Gamma-Ray Bursts and Their Afterglows

Gamma-ray bursts are short, intense and non-thermal bursts of photons with $\sim$ MeV energies, which outshine the entire γ-ray sky (Klebesadel et al. 1973). GRBs were discovered serendipitously by the *Vela* satellites, launched in the late 1960s to monitor compliance with the Nuclear Test Ban Treaty, during a search for γ-ray emission from supernovae (Colgate 1968). The basic properties of these events were outlined within several years of their discovery (e.g., Cline et al. 1973; Wheaton et al. 1973; Strong et al. 1974; Imhof et al. 1974; Norris et al. 1984): (i) an apparently random distribution on the sky, (ii) durations ranging from less than 1 second to hundreds of seconds, (iii) a broken power-law energy spectrum with a maximum at a few hundred keV, (iv) a complex time structure resolvable on a timescale of at least several tens of milliseconds, (v) a relation between spectral hardness and intensity, and a softening of the spectrum as the burst evolves, and (vi) episodes of quiescence during which no emission above the background is detected. The GRB of April 27, 1972 (i.e., GRB 720427), detected on board *Apollo 16* (Metzger et al. 1974), provides an illustrative example: the burst lasted 25 s, exhibited pulse substructure on a timescale of 300 ms, a quiescent episode lasting several seconds, a possible precursor a few seconds prior to the main event, and a smooth power-law energy spectrum ranging from 2 keV to 5 MeV with a turnover at about 200 keV.

While most bursts share these basic properties, it is important to bear in mind that the GRB phenomenon is extremely diverse with durations, peak fluxes and fluences ranging over several order of magnitude, spectral peaks ranging from several keV (the so-called X-ray flashes or XRFs) to an MeV, and light curves ranging from highly variable to a smooth single peak. To date, only one simple classification scheme has been evident, with a class of long-duration ($t > 2$ sec), soft-spectrum GRBs, which account for about two-thirds of the known event rate, and a class of short-duration, hard-spectrum GRBs (Norris et al. 1984; Kouveliotou et al. 1993). This thesis is focused solely on the origin and diversity of the long bursts; the origin of the short bursts is perhaps the greatest unsolved mystery of GRB astronomy.

Following the discovery of GRBs, theoretical interpretations of the phenomenon spanned the gamut from stellar flares (Stecker & Frost 1973) to comets crashing into neutron stars (Harwit & Salpeter 1973) and "nuclear goblins" exploding upon ejection from their parent stars[1] (Zwicky 1974). The now-accepted association with the death of stars was first advanced by Bisnovatyi-Kogan et al. (1975) in the context of γ-ray emission produced by neutrino interactions during the stellar collapse process. By

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[1] Curiously, Zwicky (1974) points out that nuclear goblins – putative parcels of nuclear matter stable only under extreme pressure (Zwicky 1958) – exploding with an energy of about 10^{40} erg would be accompanied by optical flashes of about 10^{th} magnitude lasting about 100 seconds. Bright optical flashes were subsequently detected from a few GRBs (e.g., Akerlof et al. 1999), but the physical mechanisms and absolute luminosities of these flashes are entirely different than those envisioned by Zwicky.

1994 there were 135 published models for the origin of GRBs (Nemiroff 1994).

The proliferation of GRB models was a direct consequence of the unknown distance and energy scales. This resulted from the inability to collimate γ-rays and precisely associate GRBs with specific astronomical objects. Subsequently, source triangulation using several widely-separated spacecraft, the so-called inter-planetary network (IPN; e.g., Cline & Desai 1976; Barat et al. 1981), provided arcminute positional accuracy, but usually with a considerable time delay. An alternative, single-spacecraft approach was suggested by Gorenstein et al. (1976), using a wide-field, coded aperture mask hard X-ray instrument with a potential arcminute localization accuracy. The desired accuracy was driven by the need to localize GRBs to specific galaxies if they originated in the local universe, or specific bright stars if they originated in the Galaxy. Improvements in both designs ultimately provided the first localizations with sufficient accuracy and rapidity for the discovery of counterparts at other wavelengths.

Along with improvements in γ-ray positional accuracy, searches for counterparts in the radio and optical bands were also undertaken, as those could potentially provide arcsecond positions (e.g., O'Mongain & Weekes 1974; Grindlay et al. 1974; Baird et al. 1975, 1976; Cortiglioni et al. 1981; Schaefer 1986; Greiner et al. 1987; Hudec et al. 1987; Schaefer et al. 1989; Frail & Kulkarni 1995; McNamara et al. 1995). To some extent, these observations were motivated by theoretical predictions (see §1.3). However, based on our current knowledge it is clear that these searches did not reach sufficient depth rapidly enough.

The failure to implicate specific astronomical objects as the progenitors of GRBs turned attention to statistical methods, particularly the angular distribution of GRBs on the sky, and their number distribution as a function of peak flux, $\log N/\log S$. The former can vary between strong anisotropy, if GRBs originate within the disk of the Galaxy, to isotropy, if GRBs arise in an extended Galactic halo or are cosmological in origin (Usov & Chibisov 1975). The $\log N/\log S$ distribution follows the Euclidean power law slope $S^{-3/2}$ if the sources are uniformly distributed, but has a shallower slope at faint fluxes if the distribution is bounded in space (Prilutskii & Usov 1975). The alternative $V/V_{\rm max}$ test[2] (Schmidt et al. 1988) provides the same information, but it is not affected by the experimental sensitivity threshold.

The availability of degree-scale localizations, primarily from the IPN (e.g., Klebesadel et al. 1982; Hartmann & Epstein 1989), made it apparent that GRBs were not concentrated along the Galactic plane, and moreover were not associated with the Virgo cluster, nearby galaxies, or rich Abell clusters (van den Bergh 1983). The $\log N/\log S$ distribution was severely affected by the sensitivity threshold (Cline & Desai 1976), but the sample of bursts from the Venera 13-14 and Phobos missions did exhibit $\langle V/V_{\rm max}\rangle \approx 0.4$, suggesting a deviation from uniformity (Mitrofanov et al. 1991). In a seminal paper, Paczynski (1986) used these preliminary results, along with the implied similar energy release to supernovae and an expected peak energy in the MeV range, to argue for a cosmological origin.

Significant progress, however, was made with the launch of the *Burst and Transient Source Experiment* (BATSE) on-board the *Compton Gamma-Ray Observatory.* The unprecedented sensitivity of BATSE combined with degree-scale localizations provided the first clear indication for a bounded distribution, $\log N/\log S \propto S^{-0.8}$ and $\langle V/V_{\rm max}\rangle \approx 0.35$, and an isotropic sky distribution (Meegan et al. 1992). These results were not consistent with known Galactic source populations and thus favored a cosmological origin (Paczynski 1991a,b). However, interest in Galactic models with an extended halo population ($d \gtrsim 20$ kpc; Li & Dermer 1992) remained strong, particularly in the context of the then newly discovered high-velocity neutron stars (e.g., Frail et al. 1994; Lyne & Lorimer 1994). The dispute between a Galactic and cosmological origin culminated in the "great debate" of 1995 (Lamb 1995; Paczynski 1995).

The long-awaited determination of the distance scale was finally made in 1997. On February 28

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[2] Formally, $V_{\rm max}$ is the maximum volume to which an object can be detected in an experiment with a limiting count rate, $c_{\rm lim}$, and $V/V_{\rm max}$ is simply defined as $(c_{\rm obj}/c_{\rm lim})^{-3/2}$, where $c_{\rm obj}$ is the count rate of a particular object. For a uniform space distribution, $\langle V/V_{\rm max}\rangle = 0.5$.

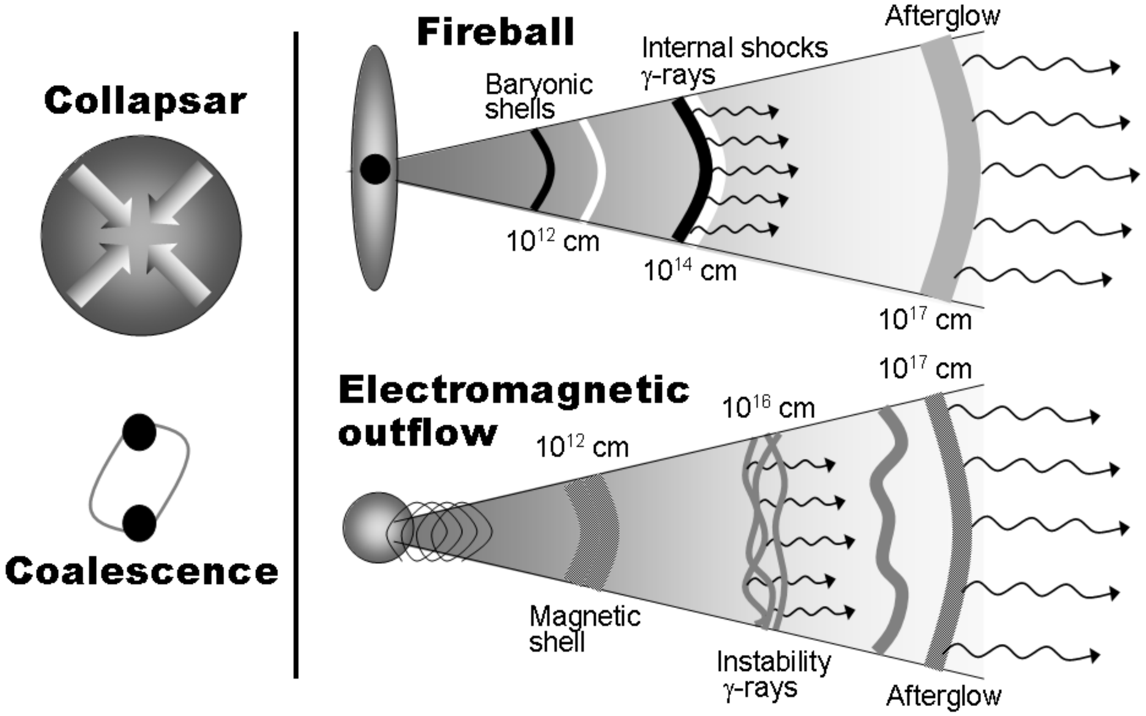

Figure 1.1: The energy scale of GRBs has focused attention on two progenitors models: coalescence of compact objects (NS-NS, BH-NS, BH-WD; e.g., Eichler et al. 1989) and "collapsars", accreting stellar mass black hole remnants, which power relativistic jets (Woosley 1993). Detections of supernova signatures in several long-duration GRBs supports the collapsar model, while coalescence events are thought to be the progenitors of the short-duration GRBs. Models for the energy transport focus primarily on fireballs (§1.2), in which the radiative energy is converted into kinetic energy of a low baryon load ($\sim 10^{-5}$ $M_\odot$) and is then re-converted to radiation via internal shocks (γ-ray burst) and an external shock with the circumburst medium (afterglow). Magnetic-dominated outflows are also possible, with a dissipation into γ-rays arising from magnetic instabilities.

of that year, the newly launched Dutch-Italian *Beppo-SAX* satellite (Boella et al. 1997) localized the prompt emission and fading X-ray afterglow (Costa et al. 1997) from GRB 970228 to a circle of 3-arcminute radius and relayed this information to ground observers a few hours after the burst. Optical observations revealed a fading afterglow (van Paradijs et al. 1997) associated with a faint source, shown with *Hubble Space Telescope* (HST) imaging to be extended and similar to a high redshift galaxy (Sahu et al. 1997). A direct confirmation of the cosmological origin was made with the next burst, GRB 970508, for which an absorption spectrum indicated a minimum distance of $z = 0.835$ (Metzger et al. 1997). By the time of writing of this thesis 35 GRB redshifts have been measured, ranging from 0.1 to 4.5, with a median redshift of $z \approx 1.1$.

One notable exception is GRB 980425 associated with the type Ic SN 1998bw at a distance of only 40 Mpc (Galama et al. 1998a; Pian et al. 2000). Due to its small distance, the γ-ray energy release of this burst was orders of magnitude below that of cosmological GRBs, while the associated SN 1998bw exhibited peculiarly high expansion velocities and kinetic energy compared to other type Ibc supernovae (Iwamoto et al. 1998; Kulkarni et al. 1998; Höflich et al. 1999; Li & Chevalier 1999; Nakamura et al. 2001). The origin of this GRB/SN is still hotly debated and has recently received great impetus with the detection of SN 2003dh, a close analogue to SN 1998bw, in association with the cosmological GRB 030329 (Hjorth et al. 2003; Stanek et al. 2003).

SECTION 1.2

Implications of a Cosmological Origin: Relativistic Fireballs

Gamma-ray bursts are one of the most energetic phenomena in the Universe, with isotropic-equivalent energy releases in some cases exceeding 10^{54} erg. Taken in conjunction with their short durations and high-energy spectra, GRBs require the violent creation of high energy photons in a compact region, a so-called fireball (Cavallo & Rees 1978). In general terms, fireballs are opaque due to the creation copious numbers of electron-positron pairs, and thus expand and cool until the energy spectrum is degraded below the pair-production threshold and the fireball becomes transparent. In the context of pure radiation fireballs, the fluid expands under its own pressure and so the bulk Lorentz factor, $\Gamma = [1-(v/c)^2]^{-1/2}$, increases to relativistic velocities as the outflow becomes optically thin (Goodman 1986; Paczynski 1986). However, the emergent radiation is a thermalized blackbody spectrum, in direct contradiction with the observed spectra of GRBs.

This discrepancy, dubbed the "compactness problem," is at the heart of our current understanding of GRBs. The optical depth arising from the production of electron-positron pairs is

$$\tau_{\gamma\gamma} = \frac{f_{\rm pp}\sigma_T F d^2}{m_e c^2 R^2} \approx 10^{13}, \tag{1.1}$$

where $R = c\delta t \approx 3 \times 10^8$ cm is determined by the millisecond variability timescale observed in many GRBs, $f_{\rm pp}$ is the fraction of photons capable of creating pairs, and $F \sim 10^{-7}$ erg cm^{-2} and $d \sim 10^{28}$ cm are the fluence and distance of the burst, respectively. Clearly, the radiation will be thermalized.

The resolution of the compactness problem lies in the relativistic expansion of the fireball. For an outflow velocity Γ, the radiation is emitted from a radius $\Gamma^2 c\delta t$, while the photon energies in the rest-frame are lower by a factor of Γ. Thus, the optical depth is reduced by a factor of $\Gamma^{4+2\alpha}$ (where $\alpha \sim 1$ is the γ-ray spectral index), and for $\Gamma \gtrsim 100$ it is less than unity, giving rise to a non-thermal spectrum.

In the simplest scenario, and the one generally accepted at the present, the relativistic motion is intimately related to the dynamics of the fireball and the production of γ-ray radiation[3]. This was first understood in the context of the "baryon loading problem". Astrophysical fireballs are expected to entrain baryons, which will precipitate the conversion of the radiative energy into kinetic energy and will furthermore increase the optical depth of the fireball due to the associated electrons (Cavallo & Rees 1978; Goodman 1986; Shemi & Piran 1990). The relevant parameter in this context is the initial ratio of radiative energy to the rest mass energy of the entrained baryons,

$$\eta \equiv \frac{E_0}{Mc^2}. \tag{1.2}$$

The final Lorentz factor of the baryon-loaded outflow and the fraction of initial energy emitted as γ-rays both depend on the value of η, and are lower for increasingly large baryon loads (i.e., lower values of η). Thus, even for a load of $\sim 10^{-9}$ M$_\odot$ the delay in reaching optical thinness and the conversion of radiation to bulk motion result in a weak burst; for $M \sim 10^{-5}$ M$_\odot$, a GRB will not be produced at all, but the baryons will attain $\Gamma \approx \eta \gtrsim 100$.

To produce a GRB, therefore, the kinetic energy of the baryons has to be re-converted to radiation. This is achieved via deceleration of the ultra-relativistic outflow and dissipation of the kinetic energy in shocks, either externally by sweeping up interstellar matter (Meszaros & Rees 1992) or internally through instabilities in the outflow (Narayan et al. 1992; Rees & Meszaros 1994; Paczynski & Xu 1994); see Figure 1.1. A high value of Γ, and hence η, will give rise to γ-ray radiation. This naturally solves the compactness problem as well.

Thus, the unavoidable contamination of the fireball by baryons provides a mechanism for delaying

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[3] Bulk relativistic motion of the source itself has also been considered (Krolik & Pier 1991), but this scenario is energetically unfavorable.

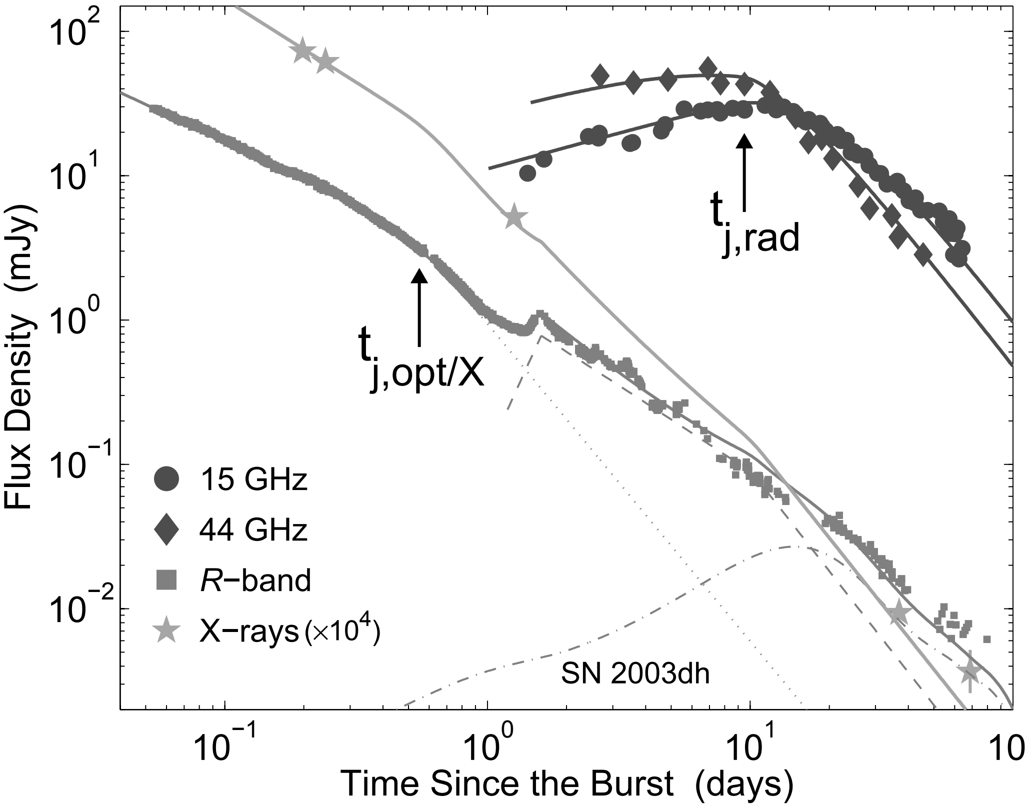

Figure 1.2: Radio to X-ray emission from the afterglow of GRB 030329 (Chapter 6). The solid lines represent models of synchrotron emission from a jet expanding in a medium of uniform density. The excellent match between the model and observations represents the success of the afterglow model in describing the observed properties and evolution of GRB afterglow.

the production of γ-rays until $\tau_{\gamma\gamma} \lesssim 1$ and at the same time provides a mechanism for the production of γ-rays. Efficiency arguments and the observed variability of GRB light curves implicate internal shocks rather than an external shock (but see e.g., Dermer & Mitman 1999). While the original baryon loading problem has actually provided a solution to the compactness problem, its current incarnation still persists, namely, how to ensure the right amount of baryons without producing a non-relativistic outflow with $\eta \sim 1$.

It is important to note that the outflow can alternatively be electro-magnetically dominated (e.g., Usov 1992); see Figure 1.1. In such models, the energy is extracted from the rotation of a strongly magnetized compact object or a black hole surrounded by an accretion disk. The relativistic magnetic outflow eventually develops instabilities which accelerate electrons and positrons and gives rise to γ-rays. Such models may have certain advantages over a baryonic fireball and internal shocks (Lyutikov & Blandford 2003), but at the present it is difficult to observationally discriminate between the two models.

SECTION 1.3

Afterglows: Out of the Darkness and into the Light

The generic picture of GRB production invokes three steps: a compact "engine" which gives rise to a radiation fireball contaminated with a small fraction of baryons, the conversion of this energy to bulk motion of the baryons, and its re-conversion to non-thermal γ-rays. The identity of the engine is lost in the process, although some of its properties may be indirectly inferred from the prompt emission. Since the re-conversion of the kinetic energy to radiation is not fully efficient, a natural consequence of