Cosmic Explosions: The Beasts and Their Lair

Thesis by
Edo Berger

In Partial Fulfillment of the Requirements
for the Degree of
Doctor of Philosophy

California Institute of Technology
Pasadena, California

2004

(Defended May 18, 2004)

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.

My thesis advisor, Professor Shri Kulkarni, has been an incredible and unrelenting source of knowledge, inspiration, motivation, emulation, on rare occasions frustration, scientific and political discussion (often charged and controversial), and friendly and professional advice. I thank Shri foremost for creating an environment in which dedication and hard work are both demanded and rewarded; for providing guidance, support and resources but at the same time thrusting (and trusting) me to find my way independently; and for his uncanny ability to dispassionately assess strengths and weaknesses, which has served to make me a better scientist and person. I really could not have wished for a better and more unique Ph.D. advisor, and I will always count Shri as a mentor, a colleague and a friend.

Although he has not been my official advisor, Dr. Dale Frail was involved in almost every aspect of my work from the very beginning. I thank Dale for an amazingly fruitful collaboration during the last five years , for introducing me to radio astronomy, for hosting me in Socorro during the summer of 2000, and for being a close colleague and friend despite the distance. I will forever remember the excitement and wonderful chemistry of our two-person radio afterglow team.

For their patience and friendship, for sharing their knowledge and expertise, and for bouncing ideas and schemes I thank the other members of the Caltech GRB group, Derek Fox, Alicia Soderberg, Josh Bloom, Paul Price, Sarah Yost, George Djorgovski, Fiona Harrison, Titus Galama, Dan Reichart, and recent arrivals Avishay Gal-Yam, Brad Cenko, and Dae-Sik Moon. I have learned much about GRBs, data reduction, and astronomy in general from all of them. I especially thank Re'em Sari for being a fountain of knowledge and a friend, always willing to share his wisdom; talking to Re'em has been like drinking from a firehose, but a few drops have been absorbed.

I thank the wonderful people at the VLA and AOC for providing and sustaining such an amazing instrument, and for supporting me as a young scientist when I made my first exciting discovery. I also acknowledge the great work and support of the staffs at the Keck and Palomar observatories, the James Clerk Maxwell Telescope and the Joint Astronomy Center in Hilo, and the Australia Telescope Compact Array and Australia Telescope National Facility. I have enjoyed visiting these facilities and interacting with the various people as much as I enjoyed the actual observing.

Many colleagues outside of Caltech have been instrumental in various aspects of this work. I thank the many collaborators and co-authors who donated their energy, expertise, and telescope time; their contributions are reflected and acknowledged in the individual chapters of this thesis. I thank the HETE, Beppo-SAX, IPN and INTEGRAL satellite teams for enabling the work I pursued in this thesis. Special thanks go to Len Cowie, who has been extremely generous in his support of my work on GRB host galaxies, and Ramesh Narayan who provided great insight into the workings of scintillation and has been a gracious host at the CfA.

At Caltech I have shared many discussions on GRBs, brown dwarfs, and the importance of statistics, as well as drinks and friendship with Bob Rutledge. Alice Shapley, Scott Chapman, Andrew Blain, Chuck Steidel, and Kurt Adelberger provided advice and invaluable information on high redshift galaxies, and Andrew MacFadyen has been a great resource for information on the physics and workings of collapsars. The members of my Candidacy and Thesis Defense committees, Fiona Harrison, Roger Blandford, Sterl Phinney, Andrew Lange, Sunil Golwala, Shri and Dale, provided great ideas for improving my thesis work.

While the last five years have been focused on research and astronomy, many friendships have made the process enjoyable and worthwhile. I thank the graduate students at the Caltech astronomy department for making life entertaining. In particular my classmates, Dave Kaplan and Micol Christopher, with whom I shared all the ups and downs of the last five years at Caltech. Dave has also been a constant resource of advice and insight into observing, data reduction, and MATLAB. I spent many lunches and post-Journal Club beers discussing politics, basketball, astronomy and life with Dave, Micol, Dawn Erb, George Becker, Bryan Jacoby and Ben Mazin. My officemates over the years deserve special recognition for putting up with me for endless hours day in and day out and for sharing their knowledge: Dave Vakil, Alice Shapley, Pat Udomprasert, Pranjal Trivedi, George Becker and Sean Moran. Over the years I have also enjoyed friendships outside of the Caltech astronomy community, Adi Adam, Roee Rubin, the Sari family, Elena Rossi, Davide Lazzati, the Dubowski family.

Of course, none of this would have happened without the love, support, and dedication of my amazing parents, Dorit and Arie, who continuously set an example and give me the tools for a happy, successful and fulfilling life; my wonderful brothers, Omri and Tom, whose warmth, intellect, sense of humor, and unbridled enthusiasm for their respective fields of study have provided a source of immense pleasure and happiness since the day they were born; and Alicia for being a truly unique person in every respect and for sharing her life with me.

Cosmic Explosions: The Beasts and Their Lair
by
Edo Berger

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 inhenert 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.

Contents

List of Figures

List of Tables

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

[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

[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, $\langle V/V_{\rm max}\rangle = 0.5$.

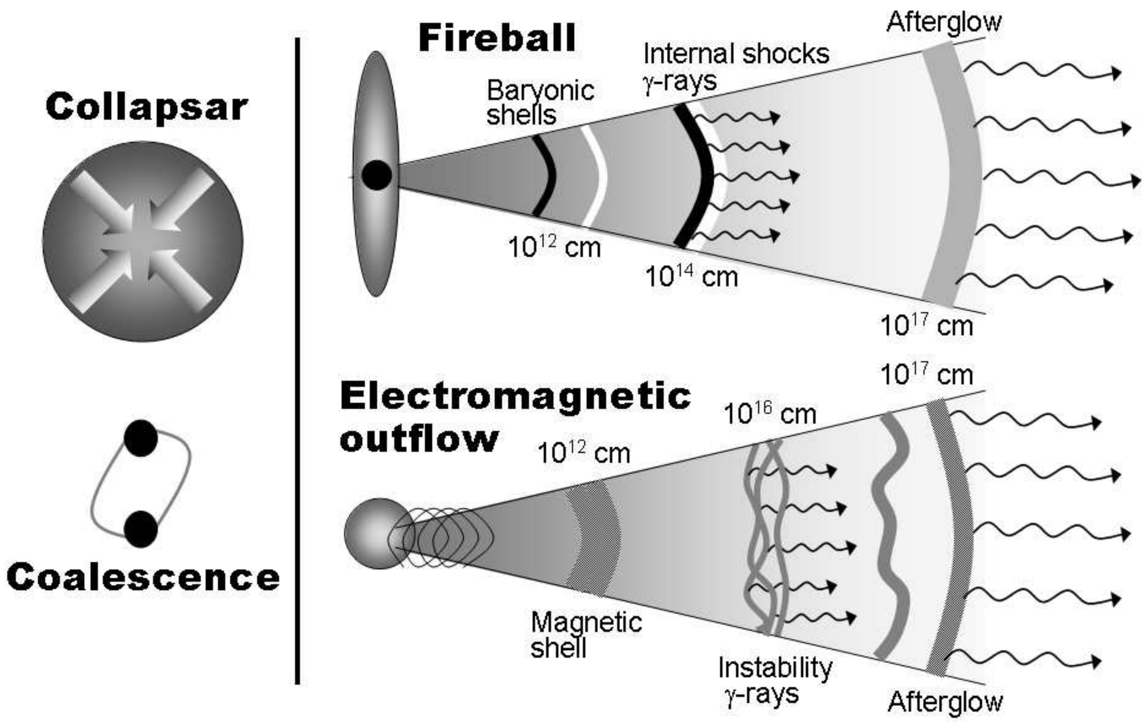

Figure 1.1: The energy scale of GRBs has focused attention on two progenitors models: coalescence of compact objects (NS-NS, BH-NS, BH-WD; e.g., Eichler et al. 1989) and "collapsars", accreting stellar mass black hole remnants, which power relativistic jets (Woosley 1993). Detections of supernova signatures 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

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

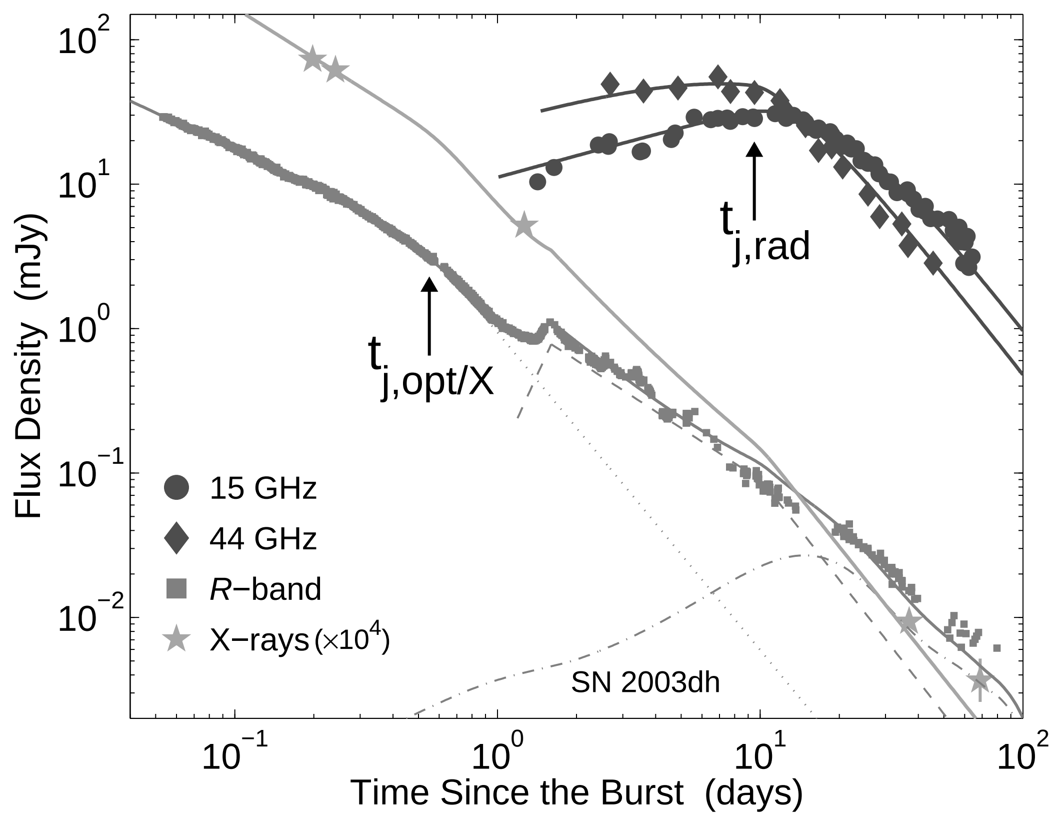

Figure 1.2: Radio to X-ray emission from the afterglow of GRB 030329 (Chapter 6). The solid lines represent models of synchrotron emission from a jet expanding in a medium of uniform density. The excellent match between the model and observations represents the success of the afterglow model in describing 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 this scenario (and the one in which the outflow is magnetically-dominated) is the production of long-wavelength, long-lived emission as the fireball sweeps up and shocks the circumburst medium — an "afterglow" (Figure 1.1). Given the greater ease of observing X-ray, optical and radio emission and a significantly longer duration (days to weeks instead to seconds), observations of GRB afterglows have provided great insight into the properties of GRB engines and progenitors; an example is shown in Figure 1.2.

It is perhaps one of the most remarkable points about GRB research that the predictions of afterglow theory have held up so well when confronted with data. It is therefore worthwhile to outline the salient features of the production and evolution of GRB afterglows. Following the emission of γ-rays, significant deceleration of the relativistic shell, with Lorentz factor Γ_0 and an energy $E_K \sim (E_0 - E_\gamma)$, begins when it sweeps up $\sim 1/\Gamma_0$ of its rest mass energy. For typical values, $\Gamma_0 \sim 100$, $E_K \sim 10^{52}$ erg and a density $n \sim 1$ cm^{-3}, the deceleration begins about 90 seconds after the burst when the radius of the shell is about 10^{17} cm.

Assuming the shock does not radiate efficiently[4] the kinetic energy $E_K = 4\pi R^3 n m_p c^2 \Gamma^2/3$ is constant and thus $\Gamma \propto R^{-3/2}$. In addition, the observer receives emission from a given shell at $t \approx R/8\Gamma^2 c$ (Sari 1997), and therefore the evolution of the radius and Lorentz factor are given by $R \propto t^{1/4}$ and $\Gamma \propto t^{-3/8}$. This self-similar evolution was discovered by Blandford & McKee (1976).

We now have strong evidence that GRB outflows are collimated in jets (see §1.5). The exact hydrodynamic evolution of a jet with an opening angle θ_j has to be solved numerically, but in general terms it follows the spherical evolution outlined above so long as $\Gamma \gtrsim \theta_j^{-1}$. At later times, the outflow expands sideways under its own pressure, resulting in an exponential decrease of Γ as a function of radius. Thus, $R \sim$ const and $\Gamma \propto t^{-1/2}$ (Rhoads 1997, 1999; Sari et al. 1999).

The spectrum and evolution of the afterglow emission are determined by combining the dynamical solution with synchrotron radiation (e.g., Waxman 1997; Sari et al. 1998). The Lorentz factor of the post-shock fluid is $\Gamma_s = \sqrt{2}\Gamma$, the density is $4\Gamma_s n$ and the energy density is $4\Gamma_s^2 n m_p c^2$. The typical assumption is that the post-shock electrons are accelerated to a power-law distribution, $N(\gamma) \propto \gamma^{-p}$, above a cutoff $\gamma_{\rm min} \approx 300\epsilon_e\Gamma_s$; the constant ϵ_e is the fraction of the shock energy that goes into the electrons. Similarly, a constant fraction is assumed to be contained in magnetic fields, $\epsilon_B = B^2/32\pi n m_p \Gamma_s^2 c^2$.

From basic synchrotron theory (e.g., Rybicki & Lightman 1979) and taking into account synchrotron cooling and self-absorption, integration over the electron distribution leads to a broken power-law spectrum; for example,

$$F_\nu \propto F_{\nu,m} \times \begin{cases} \nu^2 & \nu < \nu_a \\ \nu^{1/3} & \nu_a < \nu < \nu_m \\ \nu^{-(p-1)/2} & \nu_m < \nu < \nu_c \\ \nu^{-p/2} & \nu > \nu_c, \end{cases} \tag{1.3}$$

where ν_a is defined by the condition $\tau_{\rm syn}(\nu_a) = 1$, $\nu_m \equiv \nu(\gamma_{\rm min})$ is the frequency corresponding to the bulk of the electron population, $\nu_c \equiv \nu(\gamma_c)$ is the cooling frequency, and γ_c is the critical Lorentz factor above which the electrons lose a large fraction of their energy on the timescale of the system. The values of these break frequencies and the flux normalization are determined by the four basic parameters, E_K, n, ϵ_e and ϵ_B; other orderings of the break frequencies than those in Equation 1.3 result in different spectral shapes (e.g., Granot & Sari 2002). In the simple case of spherical expansion in a uniform medium $\nu_m \propto t^{-3/2}$, $\nu_c \propto t^{-1/2}$, $F_{\nu,m} =$ const and $\nu_a =$ const. Similar expressions have been obtained for a jet (Rhoads 1999; Sari et al. 1999) and for a blastwave expanding in a medium with a radial density profile (Chevalier & Li 1999).

The power of afterglow observations thus lies in the ability to directly infer the kinetic energy and

[4] During the first few hours of its evolution the blastwave is expected to lose about half of its energy to efficient synchrotron cooling (Sari et al. 1998). This will result in faster deceleration and slower expansion of the blastwave. Losses due to inverse Compton emission may further reduce the energy of the blastwave, but these are typically difficult to estimate given the paucity of X-ray data.

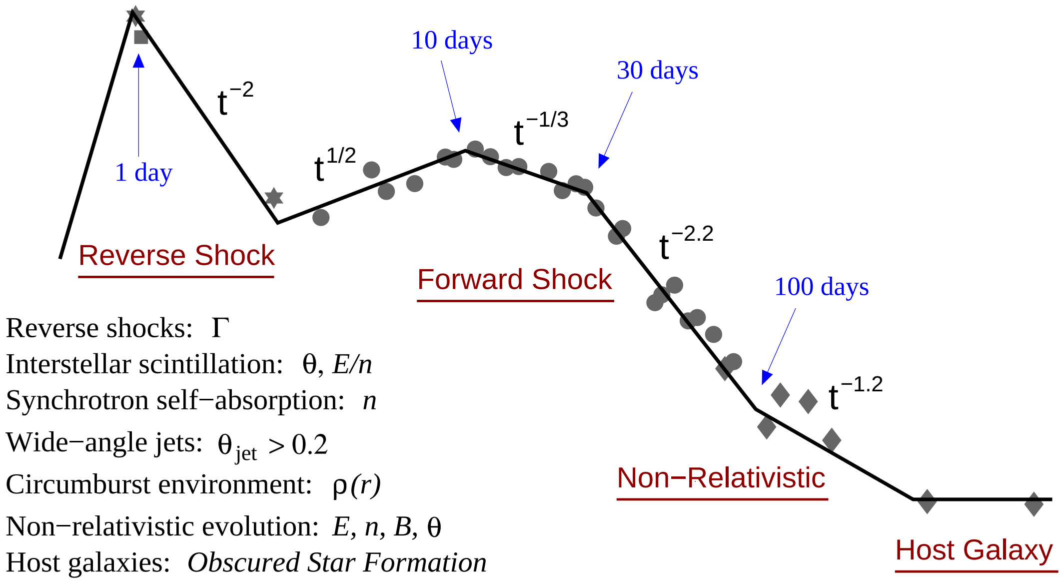

Figure 1.3: A composite afterglow light curve in the radio band scaled arbitrarily. Data are from GRBs 990123 (square; Kulkarni et al. 1999b), 020405 (stars; Berger et al. 2003d), 030329 (circles; Chapter 6) and 980703 (diamonds; Chapter 10). Timescales and scalings for the temporal evolution are indicated. The list summarizes aspects of the flux evolution which are unique to the radio bands and the physical insight they provide (Lorentz factor, Γ; source size, θ; energy, E; density, n; jet opening angle, $\theta_{\rm jet}$; density profile, $\rho(r)$; magnetic field strength, B; and obscured star formation rate).

geometry of the blastwave, the density and structure of the circumburst medium, and the micro-physical properties of the shock front. These parameters provide direct insight into the nature of the progenitor and the energy generation mechanism.

1.3.1 Radio Afterglows: Unique Diagnostics of the Energetics and Environments

Gamma-ray burst afterglows are a broad-band phenomenon requiring observations from radio to X-rays. However, the radio band provides some unique diagnostics of the afterglow physics and burst environment (Figure 1.3). To a large extent this is due to the slow evolution of the radio afterglow emission and its detectability for many weeks following the burst. This allows us to probe various phases of the dynamical evolution, as well as the burst environment over a factor of about ten in radius. Many of the results presented in this thesis take advantage of these unique aspects and I provide here a short summary (Figure 1.3).

At present, even with response times to GRB alerts of minutes, the radio band provides the best way to study the emission from the reverse shock (e.g., Soderberg & Ramirez-Ruiz 2003; Berger et al. 2003d), produced when the ejecta first decelerate (Sari et al. 1996). The properties of the reverse shock emission allow us to estimate the initial Lorentz factor. Optical observations require response on the timescale of the burst duration and have been made successfully only three times (Akerlof et al. 1999; Fox et al. 2003; Li et al. 2003). In the radio band, emission from the reverse shock has been observed several times since the peak happens about one day after the burst. In addition, the detection of reverse shock emission in the radio on this timescale most likely rules out a circumburst medium with a Wind (i.e., $\rho \propto r^{-2}$) density profile (Berger et al. 2003d).

The peak of the synchrotron emission from the forward shock is also missed in most optical and X-ray observations, and as a result these data alone cannot be used to infer the physical properties of the burst (Chapter 2). The radio band, however, directly traces the peak frequency and peak flux since those evolve through the band on a timescale of ~ 30 days. Moreover, only the radio band provides an estimate of the synchrotron self-absorption frequency, which is particularly sensitive to the density of the circumburst medium.

Radio observations are also well-suited for inferring the opening angles of wide jets, which are manifested at late time, $t \gtrsim 10$ days. On such timescales the host galaxy typically masks the optical afterglow, but in the radio band, the signature of such jets typically coincides with the peak synchrotron flux so wide jets are readily detected (Chapter 3). Similarly, since the long-term behavior is best studied in the radio, we can sometimes trace the transition to sub-relativistic expansion (Chapter 5), which occurs on a timescale of ~ 100 days (Frail et al. 2000c). These observations provide a beaming-independent estimate of the kinetic energy.

Finally, as the radio emission fades significantly we may detect emission from the host galaxy. At a typical redshift $z \sim 1$, the radio hosts detected to date have star formation rates in excess of 100 $M_\odot$ yr^{-1} (Chapters 10 and 11). These studies provide unique insight into the nature of GRB host galaxies and the environments most conducive for GRB progenitors.

Perhaps the most unique aspect of the radio emission is the existence of propagation effects in the form of interstellar scintillation (Goodman 1997; Walker 1998), which allow us to "resolve" the afterglow. These effects provided a confirmation of apparent superluminal motion (Frail et al. 1997), as predicted in the fireball model. More recently, very long baseline radio interferometry allowed us to resolve the afterglow of GRB 030329 and directly measure an apparent expansion velocity of $\sim 3-5c$ (Taylor et al. 2004).

SECTION 1.4
Summary of the Thesis: The Diversity of Cosmic Explosions and Cosmology with GRBs

Gamma-ray burst astronomy has matured considerably since the discovery of afterglows and the determination of the distance scale in 1997. Over the last few years we have addressed the preliminary question of what makes a GRB and we now know that they arise from the death of massive stars. Concurrently, in a manner reminiscent of quasar and type Ia supernova studies, I have focused on two paths: Understanding the diversity of these cataclysmic events, and using them as tools for cosmology. This thesis is thus motivated by two fundamental questions. First, *how diverse is the energy source driving cosmic explosions?* I address this question using afterglow observations to infer the true energy release of GRBs in the section entitled "The energetics of cosmic explosions". In the subsequent section, entitled "The Search for Engine-Driven Supernovae", I explore the relation between the two channels of stellar death using a radio survey of local type Ibc supernovae aimed at assessing their relativistic output.

The second question, *What is the relation between the host galaxies of GRBs and the population of field star-forming galaxies?* is addressed in part three, through a multi-wavelength study of GRB hosts and a comparison to other high redshift galaxy samples. This study provides additional insight, not available from optical studies alone, into the type of environments that may prove conducive to the formation of GRB progenitors.

Several methods are employed to attack the question of GRB energetics. In Chapters 2 and 3 I present the first use of full broad-band afterglow modeling to infer the physical properties of GRBs, along the lines of the discussion in §1.3. In both studies, the inference of jet collimation and the true energy release were only made thanks to the use of multi-wavelength data. A statistical study of beaming-corrected energies is discussed in Chapter 4, where I present a strong correlation between afterglow isotropic X-ray luminosities, a proxy for the fireball kinetic energy, and jet opening angles. The correlation indicates that for most bursts the kinetic energies are clustered within a factor of three. This clustering, coupled with a similar result from an analysis of the prompt γ-ray emission (Frail et al. 2001; Bloom et al. 2003b), places a quantitative constraint on central engine and energy extraction models. A beaming-independent assessment of the GRB energy scale using the radio emission from two bursts when the blastwave has decelerated to non-relativistic velocities is presented in Chapter 5. This analysis confirms that GRBs produce $\sim 5 \times 10^{51}$ erg, and independently validates the picture of strong collimation in GRBs.

Finally, I present in Chapter 6 detailed multi-wavelength observations of the nearby ($z = 0.168$) GRB 030329. The afterglow requires emission from two distinct collimated components. The first, which gave rise to the γ-ray and early afterglow emission, carried less than 10% of the total energy, $E_\gamma \sim 5 \times 10^{49}$ erg, while the second, mildly relativistic component dominated the late afterglow emission and had a typical energy. Following this example, we show that classical GRBs, XRFs and low E_γ events like GRBs 980425 and 030329 are unified through a common energy scale. This suggests that a single phenomenon is the culprit. The main difference between the various explosions appears to be the partition of energy between ultra-relativistic and mildly relativistic ejecta.

In a complementary effort to trace the diversity of stellar explosions, I present in Chapters 7 and 8 a comprehensive radio survey of local type Ibc supernovae designed to assess the fraction that are powered by an engine. This study was motivated by the association of GRB 980425 with the type Ic SN 1998bw. Two competing models for this event have been suggested: A typical GRB observed well away from the axis of the jet, and a new class of explosions perhaps straddling GRBs and typical core-collapse supernovae. I focus on type Ibc supernovae based both on the precedent set by SN 1998bw and on the understanding that their envelope-stripped progenitors can give rise to observable relativistic jets. I use radio observations because those provide a direct probe of relativistic ejecta. Based on the observations I reach four primary conclusions. First, the high-velocity output of type Ibc supernovae varies considerably, possibly reflecting a range of progenitor properties. Second, I place an upper limit of 3% on type Ibc supernovae that can be associated with GRBs or powered by engines based on the lack of detectable relativistic ejecta. Third, even if GRB 980425/SN 1998bw was a transition object, similar events comprise a small fraction of the total supernova rate. Finally, optical properties are poor indicators of an engine origin.

Part three of the thesis, entitled “The Multi-wavelength Properties of Gamma-Ray Burst Host Galaxies”, presents the first radio and submillimeter observations and detections of GRB hosts, examines their properties in the context of other galaxy samples, and investigates the potential of GRBs for tracing dust-obscured star formation. In Chapter 9 I show that the lack of detected optical afterglows from the majority of the so-called dark GRBs is due to inadequate searches. As a result, the utility of GRBs in assessing the fraction of obscured star formation may be quite limited.

Chapter 10 revolutionizes our understanding of GRB hosts by extending their study to the radio band and by showing that GRB 980703 exploded within a nuclear starburst. Motivated thus, I have undertaken the first survey for radio and submillimeter emission from GRB host galaxies (Chapter 11). This study shows that several GRB hosts have star formation rates in excess of ~ 100 $M_\odot$ yr^{-1}, but these differ considerably from galaxies found in blank-field submillimeter surveys. In conjunction with optical and near-IR data I argue that GRBs likely arise in young starburst galaxies. This not only identifies GRBs as unique probes of recent cosmic star formation, but it also supports the consensus that GRBs arise from the most massive stars.

As is the case in all scientific endeavors, the studies described in this thesis raise many new questions on the diversity of stellar death and the nature of GRB host galaxies. The upcoming launch of the *Swift* satellite should provide new insight into these questions based on the increase in event rate and the more rapid and accurate localizations ($\sim 1-10$ arcsecond within a few minutes). This will naturally extend the potential of GRBs as unparalleled lighthouses for the study of the intergalactic medium and the interstellar medium of high redshift galaxies, and will sufficiently increase the sample of GRB hosts to allow a more meaningful comparison with other galaxy samples. We also expect that the higher sensitivity of *Swift* will uncover more low γ-ray energy events, and will settle the question of whether the observed clustering of the total energy is real or simply an artifact of sensitivity thresholds. I address some of these questions and future directions in Chapter 12.

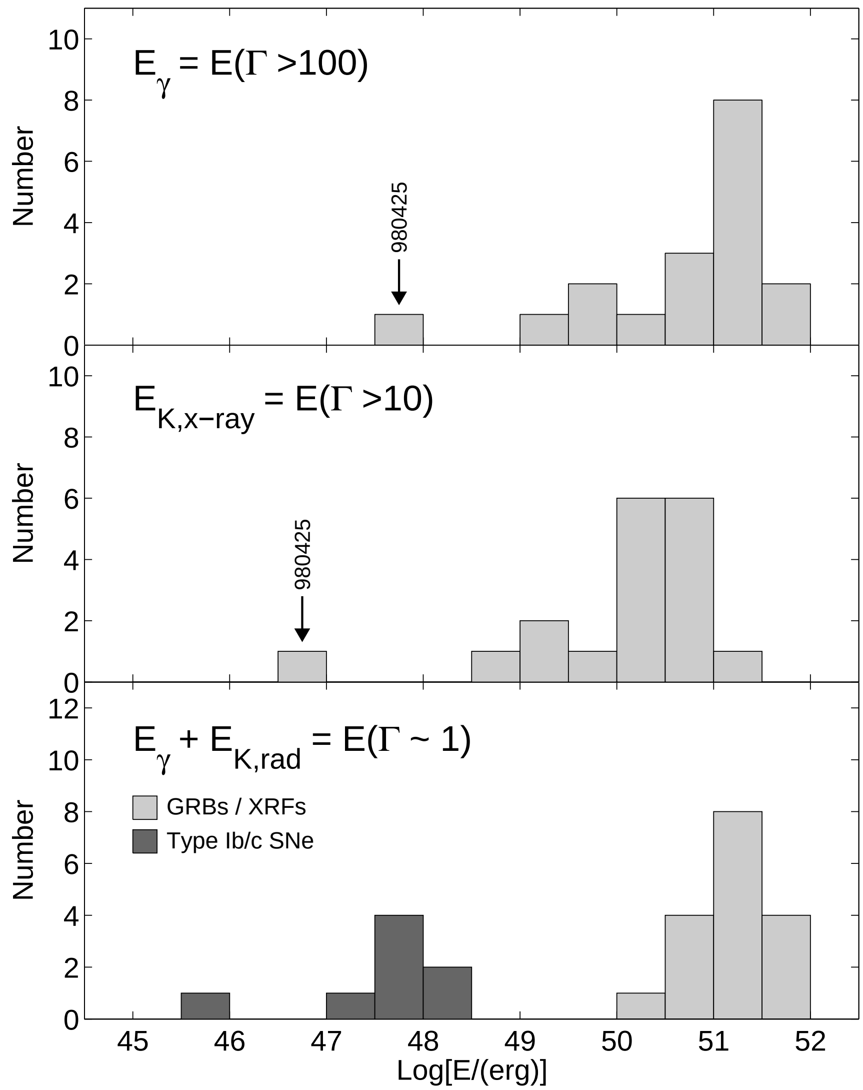

Figure 1.4: Histograms of various energies associated with cosmic explosions. *Top:* the beaming-corrected γ-ray energies tracing ejecta with $\Gamma \gtrsim 100$; *middle:* the beaming-corrected kinetic energy at 10 hours inferred from the X-ray afterglow ($\Gamma \gtrsim 10$); *bottom:* the total energy release including the kinetic energy inferred from the afterglow at late time. For the type Ibc supernovae this is the energy in the highest velocity ejecta ($v \sim 0.1 - 0.3c$) inferred from radio observations. The clustering of total energy is much stronger than E_γ or $E_{K,X}$ alone, indicating that in some cases the central engine channels the bulk of the energy in mildly relativistic ejecta. It remains to be seen whether the gap between cosmological GRBs and local type Ibc supernovae is occupied by intermediate energy explosions.

SECTION 1.5
Gamma-Ray Burst Energetics and the Search for Engine-Driven Supernovae

The true energy release of gamma-ray burst engines depends critically on whether the outflow is spherical or narrowly-collimated. In the past, collimation was discussed both as a way of avoiding baryon loading (Ho et al. 1990; Krolik & Pier 1991; Meszaros & Rees 1992; Mochkovitch et al. 1993) and in the context of bulk relativistic motion channeled in outflows with an opening angle $\sim 1/\Gamma \sim 0.01$ rad. It was later recognized that the actual collimation of the jet can be larger than the angle defined by relativistic aberration, $\theta_j \gtrsim 1/\Gamma$ (Meszaros & Rees 1997; Rhoads 1997). Consequently, the prompt γ-ray emission does not allow us to assess the degree of collimation and the true energy release. However, as the outflow decelerates, the visible fraction of the jet surface grows larger, and when $\Gamma \sim \theta_j^{-1}$, a jet can be distinguished from a sphere. For $\theta_j \gtrsim 0.5°$, this happens in the regime of afterglow observations and is manifested as a break in the afterglow light curves.

This behavior has now been observed in several cases, with jet opening angles spanning from about 3 to 30 degrees (Frail et al. 2001; Chapters 2–6). Consequently, the true energy releases are potentially reduced by several orders of magnitude. This raises two crucial questions. First, what determines the opening angles of the jets, and are they correlated with other observables? Second, given that the true energy release is not so dissimilar from that of supernovae and that the GRB event rate is also increased by a factor of θ_j^{-2}, what is the relation between GRBs and supernovae?

1.5.1 What is the True Energy Release of GRBs?

The total relativistic energy produced by gamma-ray burst central engines is

$$E_0 = E_\gamma + E_{\rm K,ad} + E_{\rm rad}, \tag{1.4}$$

where $E_{\rm rad}$ is the energy radiated away in the early afterglow when a sizeable fraction of the electrons cool significantly, and $E_{\rm K,ad}$ is the adiabatic component which powers the long-lived afterglow emission. An unexpected result stemming from the inference of jet opening angles for several GRBs is that the distribution of beaming-corrected γ-ray energies is significantly narrower than that of the isotropic values: $E_\gamma \approx 1.2 \times 10^{51}$ erg, with a 1σ spread of about a factor of two (Frail et al. 2001; Bloom et al. 2003b); see Figure 1.4.

In principle both $E_{\rm K,ad}$ and $E_{\rm rad}$ can be measured from detailed afterglow data. In practice, most bursts do not have adequate coverage to fully constrain the energy (Panaitescu & Kumar 2002; Yost et al. 2003). A more robust approach to estimating the *distribution* of kinetic energies is available, using the early X-ray luminosity (Chapter 4). This method is based on the fact that the flux at frequencies above the cooling frequency (i.e., X-rays) is proportional to $\epsilon_e E_K$ (Kumar 2000; Freedman & Waxman 2001), but is independent of the circumburst density and depends very weakly on ϵ_B. Therefore, the distribution of beaming-corrected X-ray luminosities is a direct proxy for the distribution of true kinetic energies. For a sample of twenty GRBs with known jet opening angles, the isotropic X-ray luminosity is strongly correlated with the beaming fraction, such that the true X-ray luminosities, and hence $E_{\rm K,ad}$, are nearly constant (Figure 1.4). Thus, the wide dispersion in both $E_{\gamma,\rm iso}$ and $E_{\rm K,iso}$ is simply a manifestation of the diverse opening angles[5] .

The reduced dispersion in true X-ray luminosity has other significant ramifications. Namely, since $\epsilon_e E_K \propto L_X Y^\epsilon$, with Y proportional to the isotropic X-ray luminosity and $\epsilon \equiv (p-2)/(p-1)$, the factor Y^ϵ should be nearly constant. Otherwise, there is no reason why L_X should be nearly constant. Thus, several conditions are necessary. First, the X-ray luminosity is dominated by synchrotron rather than inverse Compton emission since the latter depends sensitively on the density and ϵ_B, which vary considerably from burst to burst. Second, p must be relatively constant and have a value close to 2 to ensure that Y^ϵ does not vary significantly. Third, given that the combination $\epsilon_e E_K \approx$ const, this requires ϵ_e and E_K individually to be nearly constant. This would not be required if the two quantities are correlated, but there is no reason to assume that the shock microphysics depends sensitively on the kinetic energy. Finally, since both the prompt and afterglow emission are strongly correlated with θ_j, which is determined from afterglow observations, the standard energy result indicates that GRB jets are relatively homogeneous and maintain a simple geometry all the way from internal shocks ($\sim 10^{14}$ cm) to a radius of about 10^{17} cm. This analysis thus provides powerful constraints on the energetics,

[5] An alternative suggestion (Rossi et al. 2002) is that the inferred angles actually reflect the observer line-of-sight relative to the jet. In this case, GRB jets still have a standard energy, but they are structured with $E_\theta \sim \theta^{-2}$ and have the same opening angle in all cases. At present we are unable to distinguish between the two interpretations since the afterglow flux evolution in both models is nearly indistinguishable.

geometry and shock microphysics of GRBs.

While $E_{\rm rad}$ is difficult to estimate, the fact that both E_γ and $E_{\rm K,ad}$ appear to be nearly constant, indicates that $E_{\rm rad}$ is similarly distributed and probably does not represent a major fraction of the total energy budget. It therefore appears that $E_{\rm rel} \sim$ const with a value of few $\times\, 10^{51}$ erg.

Given the implications of the standard energy result, we would like to assess the energy content of GRBs *independent of assumptions about jet collimation.* Fortunately, the late-time radio emission affords such a tool since on a timescale $t_{\rm NR} \sim 65(E_{\rm iso,52}/n_0)^{1/3}$ d the blastwave becomes non-relativistic and approaches spherical symmetry even if it was initially collimated (Livio & Waxman 2000). Thus, I use the Sedov-Taylor self-similar solution to model the late radio emission from GRBs 970508 and 980703 and estimate the total kinetic energy of the fireball (Chapter 5). This approach has the added advantage that, unlike the γ-ray and X-ray studies, it can also trace any non-relativistic ejecta produced by the central engine. I find that $E_K \approx 5\times 10^{51}$ erg, thus confirming the energy scale and jet collimation.

Alongside the standard energy yield, the γ-ray and X-ray analyses also highlight a group of sub-energetic bursts, including GRB 980425, whose energies in ejecta with $\Gamma \sim 100$ (γ-rays) and $\Gamma \sim 10$ (X-rays) are at least on order of magnitude lower than typical values (Figure 1.4). The relation between these bursts and the "classical" cosmological bursts was recently revealed through observations of the nearby GRB 030329 (Chapter 6). Detailed, high precision, observations of this burst in the radio, millimeter, submillimeter, near-IR, optical and X-ray bands have pointed to a two-component jet in which the bulk of the energy is in mildly relativistic ejecta (Figure 1.2). Thus, the central engine of GRB 030329 produced the standard energy yield, but a fraction of only 5% was channeled in ultra-relativistic ejecta. A close examination of other sub-energetic GRBs reveals a similar picture. In particular, in GRB 980425 the total relativistic energy yield was $\sim 10^{50}$ erg (Li & Chevalier 1999), with a fraction of only 1% in ultra-relativistic ejecta.

As summarized in the closing chapter of part I, the emerging picture is the following. Cosmic explosions (GRBs, XRFs and SN 1998bw-like events) appear to have a nearly standard energy yield with a about factor of three spread. However, the partition of energy between ultra-relativistic and mildly relativistic ejecta varies considerably, such that E_γ is a poor indicator of the total energy yield. This forces us to both revise our view of gamma-ray bursts as events which are energetically dominated by γ-rays, and also address the question: what physical parameter(s) related to the engine and/or progenitor control the partition of energy between various levels of baryon loading?

1.5.2 Are Local Core-Collapse Supernovae Driven by Engines?

The search for astronomical γ-ray transients in the *Vela* data was prompted by the suggestion that supernovae might emit a pulse of γ-rays when the shock front first breaks out of the exploding star (Colgate 1968). However, no γ-ray emission was detected in coincidence with any known supernova. Talbot (1976) points that the if the GRB and supernova rates are similar, then the lack of association indicates that either: (i) GRBs, rather then supernovae, dominate the stellar death rate, or (ii) all GRBs are associated with supernovae but those are too faint to detect since the distance scale is larger than about 100 Mpc.

The cosmological origin of GRBs rules out case (i); in fact the GRB rate, even with the most optimistic correction for beaming ($f_b^{-1} \approx 500$) is about 0.5% of the rate of type Ibc supernovae (Chapter 8). On the other hand, over the past several years photometric and spectroscopic signatures of supernovae have been detected in association with several cosmological GRBs (e.g., Bloom et al. 1999; Stanek et al. 2003). It remains to be seen whether *all* GRBs are associated with supernovae.

At the same time, the growing recognition that GRBs have a standard energy yield, has given rise to a spate of "unification models". The most extreme of these models (Lamb et al. 2004) posits that GRBs and XRFs have a common energy scale determined by the lowest energy event detected in the sample, XRF 020903 with a prompt energy release of only 10^{49} erg. The jet opening angles required to lower the energy scale to such values are a factor of about ten times smaller than the generally-accepted values. As a result, the GRB event rate is a factor of 100 higher than previous estimates, leading to the

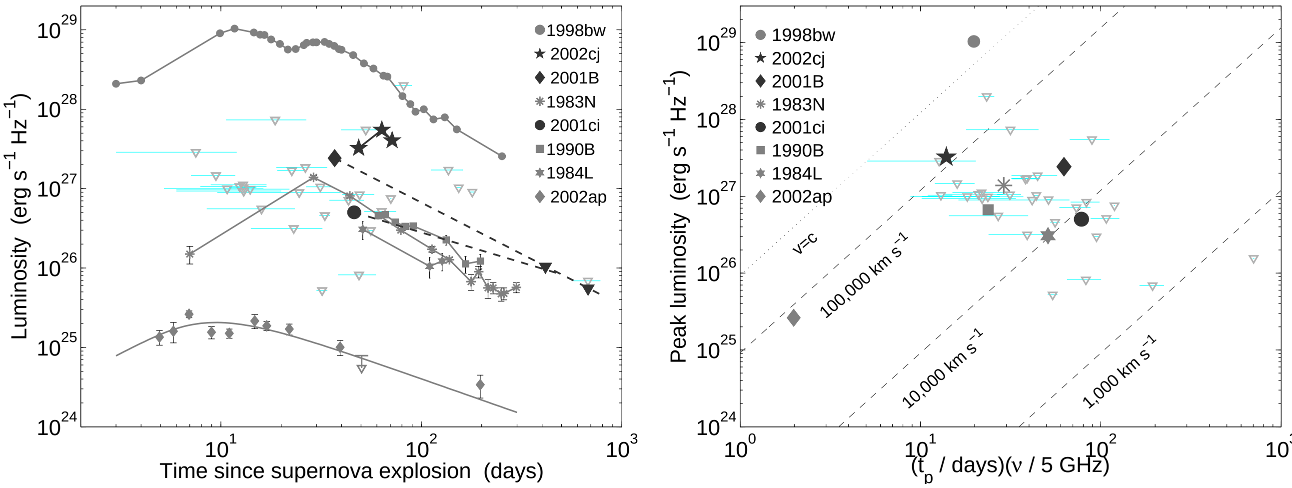

Figure 1.5: *Left:* Radio light curves of type Ibc supernovae and upper limits for the non-detections (triangles). The uncertainty in time for the non-detections represents the uncertain time of explosion. *Right:* Peak luminosity plotted against time of the peak for the same supernovae. The diagonal lines are contours of constant average expansion velocity (Chevalier 1998). Clearly, none of the sources observed to date were as luminous as SN 1998bw or exhibited relativistic expansion, suggesting that most type Ibc supernovae are not powered by engines.

condition that nearly all type Ibc supernovae give rise to GRBs — a true unification scheme.

We can assess such claims and shed light on the relation between GRBs and supernovae through studies of local type Ibc supernovae. If some of these supernovae are simply GRBs pointed away from us, then the fraction with strong radio emission (produced when the outflow is nearly spherical) is tied to the beaming angles and ranges from 0.5% to $\sim$ 100%. However, an intermediate population of sources will be independent of the GRB rate, and one suggestion (Norris 2002) is that nearly 25% of all type Ibc supernovae should exhibit engine signatures.

The origin of SN 1998bw and similar events may therefore be assessed with radio observations of a large sample of type Ibc supernovae. To this end I conducted a radio survey of such supernovae between late 1999 and the end of 2002. This study shows that less than 3% of type Ibc supernovae are powered by engines (Figure 1.5). In fact, the high-velocity ejecta detected in some cases and the inferred energies (Figure 1.4) can be easily explained as the tail of the ejecta velocity distribution (Chapters 7 and 8). The wide range of radio luminosities, spanning at least four orders of magnitude, presumably reflects the sensitivity of high-velocity ejecta to the properties of the progenitor (e.g., size, density gradient). In addition, several supernovae which were classified as “hypernovae” based on their similarity to SN 1998bw in the optical band, lack strong radio emission. This indicates that the optical emission is not a reliable probe of an engine origin (Chapter 7). This may not be surprising given that the optical emission arises from radioactive decay of ^{56}Ni, whose production may not be unique to the explosion mechanism.

It is therefore apparent that only a minor fraction of local type Ibc supernovae are powered by engines, ruling out the claimed fractions of 25% (Norris 2002) and $\sim$ 100% (Lamb et al. 2004). We still cannot distinguish models in which SN 1998bw-like events are off-axis GRBs with typical jet opening angles from those in which they are transition objects. However, even if the latter proves to be the case, such explosions represent only a small fraction of the local stellar death rate.

SECTION 1.6

Cosmology with Gamma-Ray Bursts and Their Host Galaxies

The localization of GRB afterglows to arcsecond accuracy has enabled the detection of host galaxies underlying the burst positions. Studies of these galaxies have been focused on two primary paths. First, their detailed astrophysical properties provide indirect clues to the nature of GRB progenitors. Thus, observations indicate that GRB hosts are star-forming galaxies and may have relatively low metallicity, perhaps an indication that the production of GRBs favors such environments. In addition, the angular offsets of GRBs relative to the distribution of starlight, has been used statistically to favor massive stars as the progenitors (Bloom et al. 2002a).

Equally important, GRB host galaxies can be used to study the evolution of star formation and galaxy formation. In this context, present studies are still limited by the biases and shortcomings of optical/UV, submillimeter and radio selection techniques. In particular, optical/UV surveys may miss the most dusty, and vigorously star-forming galaxies, and it is not clear if the simple prescriptions for correcting the observed star formation rates for dust extinction (e.g., Meurer et al. 1999) actually work at high redshift. Submillimeter surveys have uncovered a population of highly extincted galaxies with star formation rates of several hundred $M_{\odot}$ yr^{-1} (e.g., Smail et al. 1997), but uncertain positions have made it difficult to measure their redshifts. Finally, studies in both the radio and X-ray bands suffer from contamination by active galactic nuclei. Perhaps the most severe limitation of all studies, particularly in the submillimeter and radio, is that they are flux limited and may potentially miss the bulk of the star formation if it occurs in faint galaxies.

Against this backdrop, GRBs afford a unique way of selecting high redshift galaxies in a way that overcomes some of these selection effects. In particular:

- The galaxies are selected with no regard to their emission properties in any wavelength band
- The dust-penetrating power of the γ-ray emission results in a sample that is completely unbiased with respect to the global dust properties of the hosts
- The redshift of the galaxy can be determined via absorption spectroscopy of the optical afterglow allowing a redshift measurement of arbitrarily faint galaxies (the current record-holder is the host of GRB 990510 with $R = 28.5$ mag and $z = 1.619$; Vreeswijk et al. 2001b)
- GRBs are detectable to very high redshifts, should they exist there ($z \gtrsim 10$; Lamb & Reichart 2000)

Naturally, GRB selection may have its own biases, but it is safe to conclude that GRB hosts provide a new perspective on star formation studies, which is at least subject to a different set of systematic problems than the optical/UV and submillimeter approach.

In addition to the insight afforded by host galaxy studies, it has also been suggested that the fraction of GRB afterglows strongly obscured by dust can act as a surrogate for the fraction of obscured star formation. This is of great interest since galaxy surveys in various bands, give rise to different conclusions (e.g., Madau et al. 1996), partly because they are based on secondary indicators, such as the amount of re-processed starlight and the amount of UV absorption. On the other hand, *so long as GRBs are not biased with respect to the cosmic star formation,* the GRB approach is direct and possibly offers the best estimate of obscured star formation.

1.6.1 Are Dark Bursts the Key to Understanding Dust-Obscured Star Formation?

One of the main observational results stemming from several years of GRB follow-ups at optical wavelengths is that about 60% of well-localized GRBs lack a detected optical afterglow, the so-called dark bursts (Taylor et al. 2000; Fynbo et al. 2001; Lazzati et al. 2002; Reichart & Yost 2001). In only a handful of cases we have direct evidence that the optical emission was obscured by dust, based on a

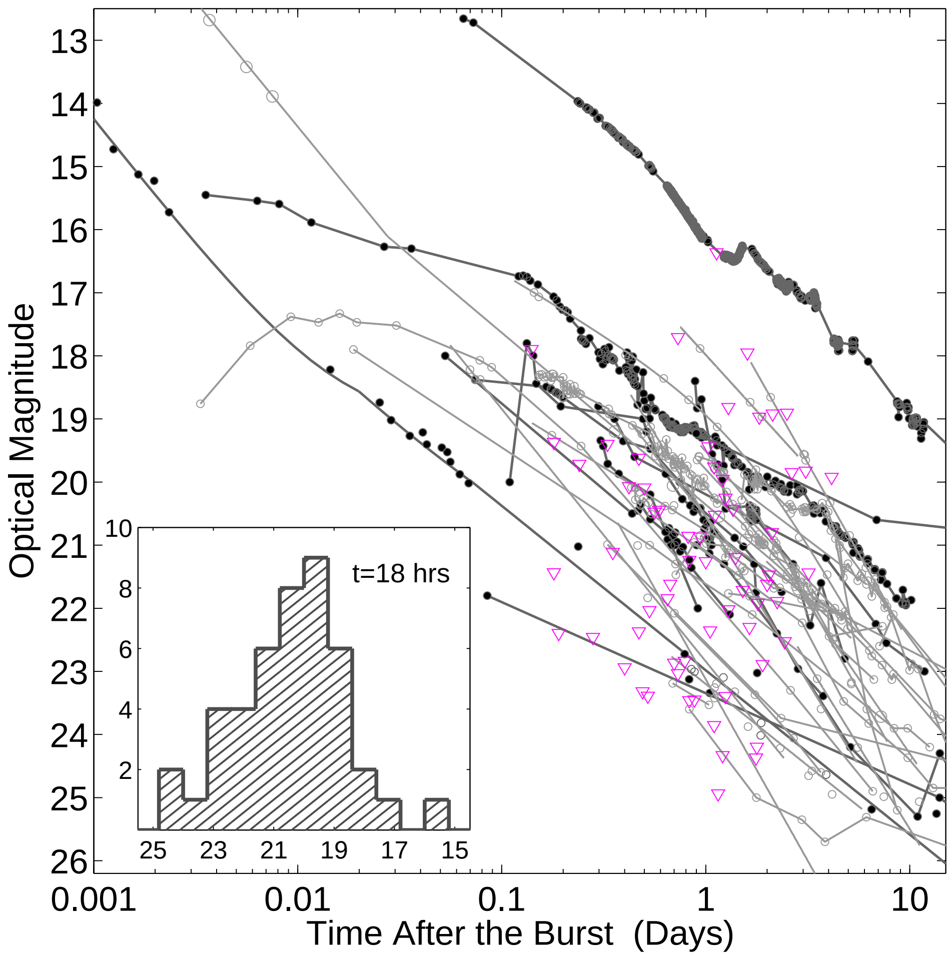

Figure 1.6: Optical light curves of 44 GRBs along with upper limits for 65 well-localized bursts. Darker shade indicates bursts localized with the *HETE* SXC for which the afterglow detection rate is about 90%. Contrary to claims that non-detections are the result of dust obscuration, the figure shows that many can simply be the result of faint afterglows. Thus, it is likely that afterglows obscured by dust comprise a small fraction of the total sample. The inset shows the wide distribution of optical magnitudes at 18 hours after the burst, extending to $R \approx 24.5$ mag.

comparison to the X-ray and/or radio emission (Djorgovski et al. 2001a; Piro et al. 2002). An alternative explanation is a high redshift, leading to absorption of the optical light in the Lyα forest. However, when host galaxies of dark bursts have been detected, the redshifts are invariably $z \sim 1$ (Djorgovski et al. 2001a; Piro et al. 2002).

Still, several authors have argued that most dark bursts are obscured by dust within their local environments (e.g., Lazzati et al. 2002; Reichart & Price 2002), and this led to the conclusion that over 50% of the cosmic star formation happens in obscured regions (Kulkarni et al. 2000; Djorgovski et al. 2001b; Ramirez-Ruiz et al. 2002; Reichart & Price 2002).

However, observations of GRB 020124 presented in Chapter 9 show that this is probably not the case. The optical emission from this burst was faint and faded relatively quickly, but the upper limit on dust extinction is $A_V < 1$ mag. Thus, with a delayed response this burst would have been classified as dark, despite the apparent lack of obscuration. A comparison to all non-detections available at this time reveals that the majority can be due to similarly faint, but non-extinguished, bursts; see Figure 1.6. If this is in fact the case, then the fraction of obscured star formation could not be easily inferred from GRBs lacking an optical afterglow.

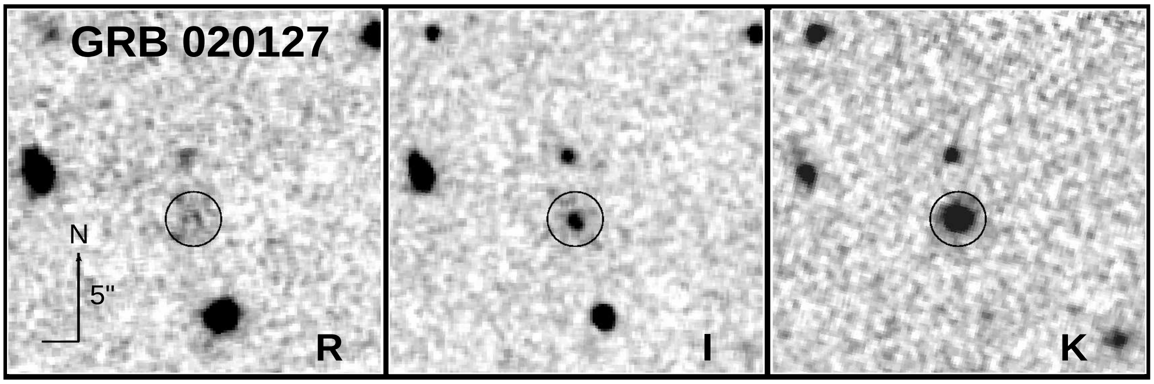

Figure 1.7: Keck optical and near-IR images of a 20 arcsec field around the position of the optically dark GRB 020127. The detection of X-ray and radio afterglows resulted in the detection of the first extremely red GRB host galaxy, with $R-K\approx 6$ mag. This host stands in direct contrast with the color distribution of nearly 40 GRB hosts for which $\langle R-K\rangle\approx 2.5$ mag.

The advent of the Soft X-ray Camera (SXC) on board the *HETE* satellite made it possible to place strict limits on the absence of optical emission, based on the accurate and rapid localizations. Surprisingly, of the thirteen bursts localized with the SXC, twelve had optical afterglows detected. The high detection rate confirms that the vast majority of past non-detections were simply due to inadequate searches. This is summarized in Figure 1.6. Thus, the fraction of truly dark bursts is $\sim 10\%$. Since GRBs are related to the formation of massive stars, and therefore explode within the stellar birth-site, this result raises three interesting possibilities: (i) Gamma-ray bursts do not occur in environments representative of the bulk of cosmic star formation, (ii) current values of the obscured fraction of star formation, $\sim 50-90\%$, have been severely over-estimated, or (iii) GRBs can efficiently destroy circumburst dust along the line of sight (Waxman & Draine 2000).

While the solution to this puzzle is not yet resolved (but see also §1.6.2), we can place some limits on the possibility of significant dust destruction. The radius out to which dust is destroyed depends on the the luminosity of the prompt optical/UV flash associated with the burst, $R_{\rm dest}\approx 10(L_{\rm UV}/10^{49}\,{\rm ergs}^{-1})^{1/2}$ pc (Waxman & Draine 2000). We now know (Fox et al. 2003; Li et al. 2003) that the the typical luminosities are at least an order of magnitude fainter than the first such flash detected, from GRB 990123 with an isotropic luminosity of about 10^{49} erg s^{-1} (Akerlof et al. 1999). Thus, the typical radius to which dust is destroyed is most likely less than 1 pc. In addition, since GRBs are highly collimated, dust will only be destroyed efficiently within the initial jet opening angle. As a result, when the jet begins to spread sideways (§1.5) the amount of extinction should increase. However, there is no clear evidence for such a chromatic effect following the time of the jet break in the optical/near-IR bands. Thus, while dust destruction is an inevitable process, it is not clear that it can explain the low fraction of dust-obscured bursts. Still, this process does complicate any mapping of the obscured GRB fraction to the fraction of obscured star formation.

1.6.2 What Is the Nature of GRB Host Galaxies?

The properties of GRB host galaxies impact our understanding of the progenitor systems and at the same time provide unique insight into star formation and galaxy evolution. Preliminary work, focused primarily on optical observations, has shown that GRB host galaxies span a wide range of redshifts ($z=0.1-4.5$) with a peak at $z\approx 1$, and a wide range of magnitudes ($R\approx 18-30$ mag) with a peak at $R\approx 25$ mag. The rest-frame B-band luminosities range from about -16 to -21 mag, i.e. $\approx 0.01-2$ L_*, with the host galaxy of GRB 980326 likely having $M_B\approx -14$ mag (0.002 L_*). Star formation rates obtained from optical indicators (e.g., Hα) range from less than 1 $M_\odot$ yr^{-1} to about 50 $M_\odot$ yr^{-1}. Finally, low metallicities have been claimed in a few cases (e.g., Fynbo et al. 2003), but it is not clear

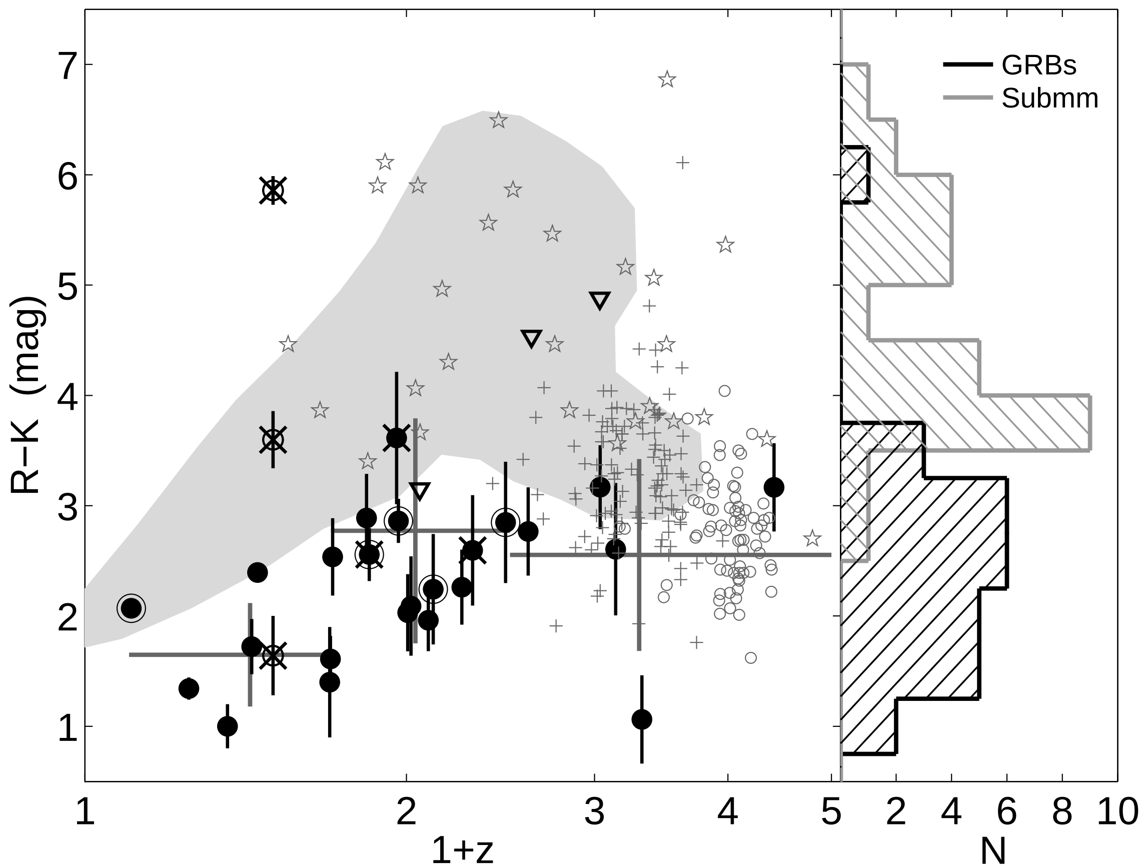

Figure 1.8: Optical/near-IR $R-K$ color plotted versus redshift for GRB hosts (filled circles), Lyman break galaxies (pluses and open circles), submillimeter galaxies (pentagrams) and K-selected galaxies in the Great Observatories Origins Deep Survey (shaded region). GRB host galaxies, including those hosting dark bursts (crossed symbols) and those detected in the radio and/or submillimeter bands (circled symbols) are significantly bluer than all other galaxy samples. This suggests that GRBs select galaxies in the early stages of their formation and starburst process.

if this is true for all GRB hosts.

While the redshift, brightness, and star formation distributions are extremely diverse, the colors of GRB host galaxies are strikingly uniform and blue. The average $R-K$ color for the sample is about 2.5 mag, with a spread of only 1 mag (Figure 1.8). It is important to note that the hosts of dust obscured GRBs are also blue, indicating that the colors of GRB hosts are not due simply to a selection against dusty (and hence red) galaxies. However, the sole exception to date, the host galaxy of GRB 020127 with $R-K \approx 6$ mag qualifying as an Extremely Red Object (Figure 1.7), did host one of the few genuine dark GRBs detected to date.

As with the GRB and afterglow phenomena themselves, a careful study of host galaxies requires multi-wavelength observations. The optical/near-IR bands provide excellent sensitivity, but they cover a small fraction of the spectral energy distribution, and are also affected by dust obscuration. However, radio emission, arising from a combination of thermal emission from HII regions and synchrotron emission from supernova remnants, is unaffected by dust and therefore provides an estimate of the total star formation rate. Similarly, far-IR emission, arising from dust-reprocessed stellar UV light, probes the obscured star formation rate. For galaxies beyond $z \sim 1$ the dust spectrum can be probed with submillimeter observations.

The initial detections of long-wavelength emission from GRB hosts occurred serendipitously. I detected radio emission from the host of GRB 980703 while monitoring the afterglow evolution (Chapter 10), while in the case of GRB 010222 we detected a persistent submillimeter source which dominated the early emission from the afterglow (Frail et al. 2002). In the former, the radio emission emanated from a region more compact than the optical host, pointing to a nuclear starburst. Furthermore, the burst position was less than 300 pc from the center of the starburst, establishing a direct connection between the GRB and the region of most intense star formation. Finally, the radio emission requires a star formation rate of about 300 $M_\odot$ yr^{-1}, compared to only 10 $M_\odot$ yr^{-1} inferred from optical spectroscopy (Djorgovski et al. 1998). A similar fraction of obscured star formation was inferred in the case of GRB 010222.

The recognition that we may be missing the bulk of the star formation, along with the possibility that GRBs preferentially select ultra-luminous starburst galaxies gave impetus to a comprehensive radio and submillimeter survey. Observations with the VLA and SCUBA reveal that about 15% of all GRB host galaxies are detectable at these wavelengths (Chapter 11), for the first time confirming observationally predictions from various cosmic star formation histories (Ramirez-Ruiz et al. 2002). However, none are as bright as the submillimeter galaxies that have been detected in blank field surveys. This may not be surprising given that these galaxies are rare, $N(>5\,\mathrm{mJy}) \approx 0.15$ arcmin^{-2} (e.g., Scott et al. 2002).

Despite the broad agreement with theoretical predictions, typical submillimeter galaxies have red optical/near-IR colors, $\langle R-K\rangle \approx 5$ mag, consistent with the idea of dust obscuration. As mentioned above, GRB hosts are very blue, and those detected in the submillimeter and radio with $\langle R-K\rangle \approx 2.4$ mag, are indistinguishable from the overall distribution (Figure 1.8). Thus, GRBs are intrinsically bluer since they explode preferentially in a different environment compared to submillimeter galaxies. I argue that GRBs tend to select younger starbursts in which a larger fraction of the most massive stars, which dominate the blue light, are still shining. This scenario meshes nicely with the growing realization that GRBs arise from the death of massive stars. Independent of the exact scenario, it is clear that GRB hosts detected in the submillimeter and radio represent a population of galaxies that is generally missed in current submillimeter surveys.

Since the initial starburst phase lasts a small fraction of the total lifetime of the galaxy, GRBs allow us to uniquely probe a phase of the star formation process that is generally missed in current star formation studies. The inclusion of GRB hosts may therefore significantly alter our understanding of where and under what conditions the bulk of the cosmic star formation takes place.