Toward an Understanding of the Progenitors of Gamma-Ray Bursts

by

Joshua Simon Bloom

ISBN: 1-58112-169-5

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Thesis by
Joshua Simon Bloom

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

California Institute of Technology
Pasadena, California

2002

(Defended 1 April 2002)

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Acknowledgements

I first encountered my future thesis adviser, Professor Shri Kulkarni, at his colloquium on soft gamma-ray repeaters in 1993. I was a sophomore at Harvard and had just decided to concentrate in astronomy and physics for my undergraduate degree. I remember that afternoon vividly: his talk was explosive and Shri was ebullient and animated. In that one hour, he managed, with great gusto, to capture the essence of the field and left me intensely excited about a subject that I had known little about. I know now that such a talent is rare.

Shri is indeed a rarity. He is at once enthusiastic, brusque, contradictory, logical, forward-thinking, generous, unfathomably demanding, focused, multi-plexed, socio-politically charged, insightful, and unwaveringly pragmatic. While he is no ordinary exemplar for a graduate student, I could not have been luckier nor happier to have had such a person as a Ph.D. adviser. He constantly challenged me to attain technical excellence and strive for a deeper clarity in my work. He fostered my curiosity and enabled me, as both a person and a scientist, to shine. I cannot thank him enough for all that he has done for me.

I have been so enriched by interactions with so many over the past five years. From the amazing folks at the Palomar and Keck observatories to the X-ray and γ-ray satellite builders to co-authors whom I have never met face-to-face, this thesis reflects the strengths and dedication of literally hundreds of people. Dr. Dale Frail, who I had the great fortune to work with on no less than 29 published refereed papers, has been one of the most important influences in my development. I will forever consider Dale a mentor, colleague, and a good friend.

Dale and Shri's original little 1996 afterglow duo blossomed into no less than a full-fledged team of a researchers. I am indebted to all of the past and existing members of the "Caltech–NRAO–CARA GRB Collaboration" who, without fail, graciously shared their talents and energies with me. The individuals who contributed to my thesis work are either co-authors on the respective published papers or explicitly mentioned in chapter-specific acknowledgments. Here, I particularly thank Prof. S. George Djorgovski, Re'em Sari, Prof. Jules Halpern (Columbia University), Alan Diercks, Chris Clemens, Steve Odewahn, Paul Price, Edo Berger, and Dan Reichart. Our collective adventures in the outer-limits of astronomy have been a source of immense pleasure and gratification.

My past and current officemates have been each extraordinarily influential. I thank Ken Banas, Ben Oppenheimer, Alice Shapley, Kurt Adelberger, and Rob Simcoe for their friendship, support, and knowledge. Over our frequent coffee and sushi breaks, I spent hundreds of hours talking and sharing ideas with Pieter van Dokkum and Dan Stern. I learned a great deal from Pieter and Dan about galaxies, cosmology, and data reductions; I hold them in the highest regard both personally and professionally. I shall never be able to fully articulate just how important my peers and colleagues have been.

For the past three years, I have been supported by a Fannie and John Hertz Foundation Graduate Fellowship. Each year, the Fellowship is supposed to be awarded to "America's most promising technical talents...who can be expected to have the greatest impact on the application of the physical sciences to human problems during the next half-century." I would never profess to be such a person but I certainly will strive attain that lofty goal. Indeed, it has been an honor to serve as Hertz Fellow.

I heartily thank my thesis committee members: Profs. Fiona Harrison (chair), Shri, George, Marc Kamionkowski, Nick Scoville. From the onset to the end, they consistently and thoughtfully encouraged me to build this thesis with an eye on the big picture. I thank the staff in the Astronomy department for their support and Josep Paredes at the University of Barcelona for his hospitality.

Even with such stimulating work environments, no one could be (or, at least, should be) truly fulfilled without close friendships. In this respect, I am very pleased to also count among my confidants and partners in pursuit of happy and full life: Michelle Brent, Josh Eisner, Gordon Squires, Ken B., Ben O., Geoff Criqui, John Ciorciari, Jared Bush, Jamie Miller, Jessica Rovello, Steve Agular, and Mark Galassi. These are the people who helped sustain me and who were always there through my highs and lows.

This thesis is dedicated to all my friends and those six people that are closest to my heart, without whom thesis would not have been possible nor worthwhile. Anna, Bec, Mom, Dad, Nanny, and Pop-pop, thank you.

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Abstract

The various possibilities for the origin ("progenitors") of gamma-ray bursts (GRBs) manifest in differing observable properties. Through deep spectroscopic and high-resolution imaging observations of some GRB hosts, I demonstrate that well-localized long-duration GRBs are connected with otherwise normal star-forming galaxies at moderate redshifts of order unity. Using high-mass binary stellar population synthesis models, I quantify the expected spatial extent around galaxies of coalescing neutron stars, one of the leading contenders for GRB progenitors. I then test this scenario by examining the offset distribution of GRBs about their apparent hosts making extensive use of ground-based optical data from Keck and Palomar and space-based imaging from the *Hubble Space Telescope*. The offset distribution appears to be inconsistent with the coalescing neutron star binary hypothesis (and, similarly, black-hole–neutron star coalescences); instead, the distribution is statistically consistent with a population of progenitors that closely traces the ultra-violet light of galaxies. This is naturally explained by bursts which originate from the collapse of massive stars ("collapsars"). This claim is further supported by the unambiguous detections of intermediate-time (approximately three weeks after the bursts) emission "bumps" which appear substantially more red than the afterglows themselves. I claim that these bumps could originate from supernovae that occur at approximately the same time as the associated GRB; if true, GRB 980326 and GRB 011121 provide strong observational evidence connecting cosmological GRBs to high-redshift supernovae and implicate massive stars as the progenitors of at least some long-duration GRBs. Regardless of the true physical origin of these bumps, it appears that all viable alternative models of these bumps (such as dust scattering of the afterglow light) require a substantial amount of circumburst matter that is distributed as a wind-stratified medium; this too, implicates massive stars. Also suggested herein are some future observations which could further solidify or refute the supernova claim. In addition to the observational and modeling work, I also constructed the *Jacobs Camera* (JCAM), a dual-beam optical camera for the Palomar 200–inch Telescope designed to follow-up rapid GRB localizations.

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Preface

> But the reason so many of you live, work and study here is that there are so many more questions yet to be answered...And so I wonder,...Are we alone in the universe? **What causes gamma ray bursts?** What makes up the missing mass of the universe? What's in those black holes, anyway? And maybe the biggest question of all: How in the wide world can you add $3 billion in market capitalization simply by adding .com to the end of a name?
>
> William Jefferson Clinton
> 42nd President of the United States of America
> *Science and Technology Policy Speech*
> 21 January 2000, Caltech

These ponderances, spoken just before the bursting of the Internet "bubble," invigorated me. Rarely, I suspect, does a sitting president publicly ask the question that is the central endeavor of one's PhD thesis. But, given the topic and the timing—gamma-ray bursts, during one of the most enlightening periods of understanding of the phenomenon—perhaps we should not be surprised that this happened. Of course, the cynical view is that the President's speech writers had scoured the Caltech web site before his visit and encountered a number of the astronomy press releases that had been generated here over the years, drawing up a number of relevant questions for a Caltech-specific audience. The idealist view, one that is perhaps more comforting to accept, is that the question of what makes gamma-ray bursts really is on the minds not just of a few astronomers but on a much larger audience.

For those that are familiar with the phenomenon, this public appeal of gamma-ray bursts is almost assured—GRB descriptions are, after all, awash in superlatives. We now know, for instance, that GRBs are one of the *brightest* events in the universe, briefly reaching luminosities comparable to the integrated luminosity of a few hundred thousand galaxies. The bursts are some of the *rarest* well-studied transient events (only a few per galaxy per 10 million years) and probably represent the violent death and/or birth of the *most dense* objects known, namely black holes and neutron stars. Because of the extreme densities and accelerations of the masses involved in triggering a GRB, the events leading up to a GRB explosion holds the greatest promise of impulsively releasing as yet undetected gravitational waves.

That this central question—What causes gamma-ray bursts?—can even be asked now with a straight face is nothing short of remarkable. Not too long ago—pre-1997, to be precise—no one knew for sure from where GRBs originated. Was the origin of the bursts that of primordial anti-matter comets smashing into the Oort cloud (distance of scale of 100 pc; Dermer 1996)[1] or the re-connection of super-conducting cosmic strings (distance of scale of 10^{10} pc; Paczyński 1988) or some place more conventional (such as in our Galaxy or more distant galaxies)?

This remarkable ignorance, let alone the lack of any solid connection between GRBs and other known astrophysical entities, persisted for 29 years and 10 months after the first detection of a GRB. Then, in May 1997, shortly following the detection of the first long-lived emission following a GRB ("afterglow"), finally the first step was taken. An optical spectrum of the afterglow obtained at the Keck telescopes revealed the burst to have originated from at least a redshift of $z = 0.835$, proving that at least one GRB originated from "cosmological" distances.

This was the state of affairs when I began my PhD thesis at Caltech in the fall of 1997—just one GRB was known to be of a cosmological origin and a total of two afterglows had been discovered. My early interest in afterglow follow-up work stemmed from the belief that the intense study of afterglows would surely lead to physical insights about the nature of the afterglows themselves and GRB progenitors. Indeed, with over 30 GRB afterglows discovered and studied in the past five years, the community

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[1] 1 parsec = 3.085×10^{18} cm or 3.27 light-years

has solidified GRBs as of a cosmological origin and learned a great deal about the physical processes underlying afterglows. My thesis, however, focuses on the later issue, uncovering the progenitors.

The ultimate conclusion of this work—that most GRBs probably arise from the death of massive stars rather than the coalescences of massive compact binary stars—was rather unexpected since the predominant view in 1997 was that the latter objects were likely responsible for such bursts. The connection between GRBs and massive stars represents, as van Paradijs et al. (2000) have also pointed out, a harmonious and beautiful full-circle revelation: the first theory of gamma-ray bursts, posited by Colgate (1968) before GRBs had even be discovered, suggested that GRBs could arise during a supernova explosion.

Notes on the contents of this thesis: Thanks to the relative ignorance of the physics of GRBs and the small wavelength regime in which GRBs and their aftermath had been observed (X-rays to GeV gamma-rays), the introduction to a PhD thesis ten or even five years ago could realistically have captured the sum-total knowledge of the phenomena for the reader. Yet, after 5 heady years in the afterglow era, the information explosion[2] would surely require hundreds of pages for a comprehensive exposition of GRBs (think of writing a comprehensive review on galaxy evolution or supernovae).

This is not my intention with the scope of the following summary chapter; instead, I give a brief overview of the observations and current theoretical understanding of the phenomena.[3] Then I present some of the more salient topics related to progenitors and their host galaxies, drawing specific attention to the work in body of the thesis. For a more thorough review of the current state of the field, the reader is referred to Fishman & Meegan (1995) (GRB science pre-1997), Piran (1999) (fireball and afterglow physics), van Paradijs et al. (2000) (afterglow observations), and Fryer et al. (1999a) (progenitor models).

The next eight chapters were prepared for a total of five different journals, each, as such, with differing presentation and referencing styles. The audience for each article varied as well—the *Nature* article (chapter 7), for instance, was geared to a general science audience, while the *PASP* article (chapter 10) was written primarily for an astronomical instrumentation audience. In the interest of continuity, I have homogenized the referencing style and nomenclature from chapter to chapter.

In some chapters, I have also included some additional text and figures that were necessarily cut from the published article due to space constraints. In chapter 9, for instance, I include example γ-ray light curves of possible supernova–GRBs, and in chapter 7 I provide an expanded explanation of some of the data reduction methods. Looking back, some ideas in the chapters proved to be less salient (and correct!) than others and so there was the temptation to jettison the chaff. Since this thesis is comprised mostly of published articles that themselves (should) reflect the progression of the field, I have, however, tried to steer clear of constructing such a revisionist history. As such, all of the "new" ideas augmented to the published versions appeared first in submitted versions of the paper. Chapter 11 is designated as forum for redresses and epilogues to the body of this thesis.

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[2] As of mid-2001, GRBs entered the literature at a rate of 1.5 per day, 50% higher than the rate in 1994 (Hurley 2002).

[3] The first section of chapter 1 contains some of the text in the published version of chapter 6. The introduction of chapter 6 is commensurately abridged.

CHAPTER 1

Introduction and Summary

SECTION 1.1

History, Phenomenolgy, and Afterglows

Gamma-ray bursts, otherwise extinguished by the Earth's atmosphere, were discovered serendipitously (Klebesadel et al. 1973; Strong et al. 1974) by space-based US satellites designed to insure compliance with the Limited Nuclear Test Ban Treaty (signed July 25, 1963) by searching for the γ-ray emission that accompanies nuclear weapons testing. In gross properties, the 23 bursts presented in the discovery papers were not unlike the some 3000 observed to date by the many GRB-specific satellites that followed. One notable sub-class of the gamma-ray burst (GRB) phenomenon are the so-called "Soft Gamma-Ray Repeaters" (SGRs) which, since the late-1970s, have been definitively associated with highly-magnetized isolated neutron stars (magnetars) in our Galaxy or the Large Magellanic Cloud (LMC) (see Harding 2001 for review).

The duration of "classic" GRBs (i.e., those GRBs which are not SGRs), observationally determined as the time that the flux exceeds some threshold above the sky background level, ranges from a few milliseconds to thousands of seconds (e.g., Kouveliotou et al. 1996). The peak of the spectral energy distribution of bursts falls in the range of $\sim$50–1000 keV (Mallozzi et al. 1995) but both ends of this range likely exist due to the trigger inefficiencies of GRB satellites (see, e.g., fig. 3 of Lloyd & Petrosian 1999; although see Brainerd 1998).[1]

GRBs seem to occur at random times and from random locations in the sky, about 4 times per day at current detector thresholds. Though it was known that the sky distribution of GRBs appeared roughly isotropic for years, the *Burst and Transient Source Experiment* (BATSE), the prime workhorse of GRB astronomy in the early- to mid-1990s, placed the strongest constraints showing GRBs to be isotropically distributed to within a high degree of confidence (Meegan et al. 1992; see also table 8 of Paciesas et al. 1999).

Though, by 1995, no classical GRB had been definitively connected with any other astrophysical entity, the observed isotropy was taken by many as evidence for a cosmological progenitor origin. The paucity of faint bursts relative to the number expected if the bursts originated homogeneously in Euclidean space also served as evidence for a cosmological origin (e.g., Fenimore et al. 1993; Fenimore & Bloom 1995). During the "Great Debate" on the distance scale to GRBs (Nemiroff 1995), Paczyński (1995) argued for the cosmological origin of GRBs based primarily on these two points while Lamb (1995) explained how the same data were consistent with a galactic progenitor origin.[2] I attended the

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[1] Until very recently, a burst was not considered a GRB until its energy spectrum peaked above $\sim$ 30 keV. It is the adherence to this definition of GRBs that may be restricting a deeper insight into the nature of GRBs. If a burst is found to peak at lower-energies (a so-called X-ray Flash; XRF), but retains most of the other properties of classic GRBs, then it may simply be a GRB at a high redshift (one of remaining holy-grails of observational GRB astronomy). Heise et al. (2001) has recently written a nice admonition to the community about classification of such phenomena.

[2] That two such contrasting views on the same data existed should remind us of the quote from Antonio in the

Debate and thought that D. Lamb made a persuasive argument for Galactic scenarios despite the small theoretical parameter space then allowed by the isotropy and brightness distribution observations.

The main impedance to progress was the difficulty of localizing bursts to an accuracy high enough to unequivocally associate an individual GRB with some other astrophysical entity. Several concerted efforts were made to find counterparts (e.g., Schaefer et al. 1987; Vanderspek et al. 1994; Vrba et al. 1995; Frail & Kulkarni 1995; Greiner 1995), but we now know that such surveys were either too shallow or too delayed in time to catch rapidly fading GRB counterparts. Aside from the hope that GRBs would produce/induce emission at some other frequency, some counterpart searches were strongly motivated by (prescient) theoretical predictions for the existence of lower-frequency counterparts (Paczyński & Rhoads 1993; Mészáros & Rees 1993; Katz 1994; Mészáros et al. 1994). These "afterglow" models were a natural consequence of the (also prescient) predictions for cosmological GRBs from highly-relativistic outflow of a low-baryon-loaded fireball (Paczyński 1986; Goodman 1986; Mészáros & Rees 1992; Mészáros & Rees 1993).

In large measure the localization problem was due to both the transient nature of the phenomena and the fact that the incident direction of γ-rays are difficult to pinpoint with a single detector; for example, the typical 1-σ uncertainty in the location of a GRB using the *Burst and Transient Source Experiment* (BATSE) was 4–8 degree in radius (Briggs et al. 1999). The Interplanetary Network (IPN; see Cline et al. 1999) localized GRBs using burst arrival times at several spacecrafts throughout the solar system and provided accurate localizations (3 σ localizations of $\sim$few to hundreds $\times$ sq. arcmin) to ground-based observers; however, the localizations were reported with large time delays (days to months after the GRB).

The crucial breakthrough came in early 1997, shortly following the launch of the *BeppoSAX* satellite (Boella et al. 1997). On-board instruments (Frontera et al. 1997; Jager et al. 1997) were used to rapidly localize the prompt and long-lived hard X-ray emission of the GRB of 28 February 1997 (GRB 970228) to a 3 σ accuracy of 3 arcmin (radius) and relay the location to ground-based observers in a matter of hours. Fading X-ray (Costa et al. 1997a) and optical (van Paradijs et al. 1997) emission (afterglow) associated with GRB 970228 were discovered. Ground-based observers noted (Metzger et al. 1997c; van Paradijs et al. 1997) a faint nebulosity in the vicinity of the optical transient (OT) afterglow. Subsequent *Hubble Space Telescope* (HST) imaging resolved the nebulosity (Sahu et al. 1997) and showed that the morphology was indicative of a distant galaxy (Sahu et al. 1997). We now know the redshift of this faint, blue galaxy is $z = 0.695$ (chapter 5, Bloom et al. 2001a).

The next prompt localization of a GRB yielded the first measured distance to a GRB through optical absorption spectroscopy: GRB 970508 occurred from a redshift $z \geq 0.835$ (Metzger et al. 1997b). The first radio afterglow was detected from GRB 970508 which, through observations of scintillation, led to the robust inference of super-luminal motion of the GRB ejecta (Frail et al. 1997; see below). These measurements (along with the dozen other redshifts now associated with individual GRBs) have effectively ended the distance scale debate and solidified GRBs as one of the most energetic phenomena known (see Kulkarni et al. 2000; Frail et al. 2001). One of the most remarkable aspects of GRB science (e.g., Wijers et al. 1997) was the enormous success, as evidenced by the observations of GRB 970228 and GRB 970508, of the theoretical predictions for the existence and behavior of GRB afterglows (Paczyński & Rhoads 1993; Mészáros & Rees 1997a; Vietri 1997).

The cosmological nature of GRBs now frames our basic understanding of the physics of GRB phenomena. The general energetics are well-constrained: given the observed fluences and redshifts, approximately 10^{51}–10^{53} erg in γ-ray radiation is released in a matter of a few seconds in every GRB (see fig. 1.2). The GRB variability timescale suggests that this energy is quickly deposited by a "central engine" in a small volume of space (radius $r \lesssim 1000$ km) and is essentially optically thick to γ-ray radiation at early times. This opaque fireball of energy (see below) then expands adiabatically and relativistically until the γ-ray radiation can escape; there, the GRB is thought to arise from the interaction of internal shocks initiated by the central engine (e.g., Fenimore et al. 1999).

<u>Merchant of Venice</u>, Act I,iii: "Mark you this, Bassanio, The devil can cite Scripture for his purpose."

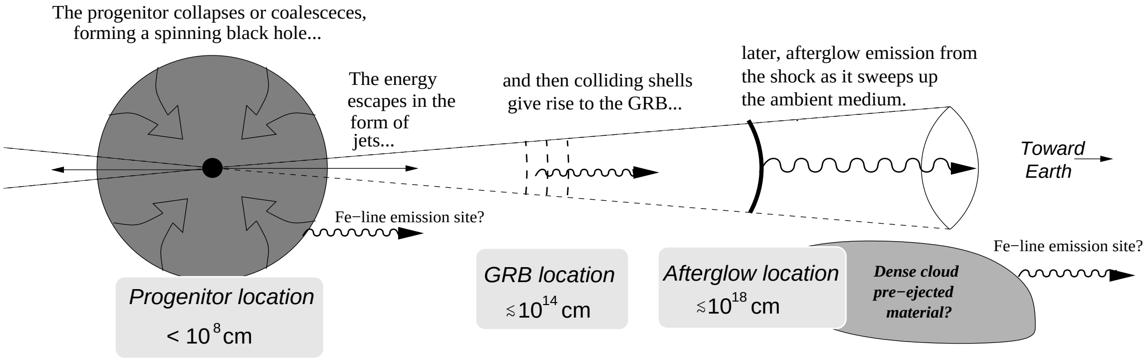

Figure 1.1 Anatomy of a gamma-ray burst explosion. The dark circle represents the newly formed spinning black hole at the center of an imploding star (or merging compact binary system). The long-lived afterglow emission that we see arises from the swept-up material; in this material, relativistic electrons radiate sychrotron light in an amplified magnetic field. Due to the extreme velocity of the jet, the whole sequence of events is compressed in time as viewed from Earth.

The short variability timescale of a GRB and high total energy release would tend to imply that the optical depth to pair-production at the explosion site is exceedingly high ($\tau_{\gamma\gamma} \gtrsim 10^{12}$) yet GRB spectra are optically thin. It was recognized in the mid-1980s that this so called "compactness problem" can be avoided by invoking relativistic motion (Goodman 1986; Paczyński 1986). If the surface of emission of γ-rays is moving toward the observer at a bulk Lorentz factor Γ, then the optical depth to pair-production is reduced due to two effects. First, the fraction of photons that can pair-produce in the frame of the moving surface is lower than inferred by an outside observer (by Γ^2 for a flat spectrum), who measures a blue-shifted spectrum. Second, special relativistic effects allow for the emission radius to be larger by Γ^2 than the variability estimate (about 10^{14} cm rather than 10^8 cm). By requiring that $\tau_{\gamma\gamma} < 1$, the source of GRB emission must be moving with $\Gamma \gtrsim 100$ at the time of the GRB.

The coupling of the fireball energy to any entrained baryons will tend to stall the outward expansion of the flow. Specifically, if the total energy in the fireball is E_0 ($\approx 10^{51}$ erg), then the total amount of baryonic mass allowed in the flow is $M = E_0/\Gamma c^2 \lesssim 10^{-5} M_\odot$. The elegant solution to the compactness problem, then, places an important constraint on the nature of GRB ejecta (see also Piran 1999): the fireball must be nearly devoid of baryons.

After the GRB, the relativistic blastwave continues its outward expansion and begins to sweep up the ambient medium. Taking $n = 1$ cm^{-3} to be the density of the surrounding medium, the blastwave begins to slow considerably by a radius $R \approx (E_0/4m_{\rm H}c^2\Gamma^2)^{1/3} \approx 10^{16}$–$10^{17}$ cm and some of the kinetic energy is then converted into internal motion within the shock (Mészáros & Rees 1993). Here m_H is the mass of a hydrogen atom. The transient afterglow phenomenon, thought to arise at this radius, is likely due to synchrotron radiation arising from the interaction of the relativistic ejecta and the ambient medium surrounding the burst site (see van Paradijs et al. 2000; Kulkarni et al. 2000; Djorgovski et al. 2001, for reviews).

Indirectly, the initial Γ of some GRBs have been constrained in the context of the compactness problem and early-time observations of afterglows (e.g., Mészáros et al. 1993; Sari & Piran 1999a; Ramirez-Ruiz & Fenimore 2000; Soderberg & Ramirez-Ruiz 2002). By noting an abrupt quenching of scintillation behavior a few days after GRB 970508, Frail et al. (1997) showed that the afterglow emitting region must have grown with apparent superluminal speeds, observationally solidifying relativistic motion as a fundamental property of GRBs.

There have now been tentative detections of transient X-ray line features in five GRB afterglows (e.g., 970508 and 970828 Piro et al. 1999; Yoshida et al. 1999). The most convincing detection so far comes from observations of the afterglow of GRB 991216 (Piro et al. 2000). Individually, the observational significance of the line detections are marginal, but on the whole there appears to be a good case for line emission features in the afterglow of some GRBs. If so, there must exist dense matter in the vicinity of the explosion (e.g., Weth et al. 2000; Vietri et al. 1999; Lazzati et al. 2000). Mészáros & Rees (2001) have also suggested that the Fe lines may be produced if some of the waste energy from the central engine heats up a "bubble" of matter from the progenitor, a natural consequence of jets propagating in a dense stellar interior. The bubble breaks out from the progenitor remnant on a timescale of hours to days. Figure 1.1 depicts the relative locations of the suggested sources of the X-ray line emission from a generalized progenitor.

Like most other high-energy phenomena, it is now widely accepted that gamma-ray burst emission is collimated (or "jetted"). Observationally, jetting should be manifested as a (variable) polarization signal in the afterglow (Ghisellini & Lazzati 1999; Sari 1999); such signatures have been detected in some GRB afterglows (Covino et al. 1999; Wijers et al. 1999; Björnsson & Lindfors 2000; Rol et al. 2000). The observed evolution of GRB afterglows, often showing a break in the light curves from 0.5–50 days, also appear to conform to basic predictions from the dynamics of jetted outflows (Rhoads 1999; Sari et al. 1999). Aside from relaxing the overall energy requirements, the establishment of jetting in GRBs also implies that the true rate of GRBs in the universe is substantially higher than previously believed (by a factor of ∼550, Frail et al. 2001).

SECTION 1.2

Proposed GRB Progenitor Scenarios

While the GRB emission and the afterglow phenomenon of long-duration bursts are now reasonably well-understood, one large outstanding question remains: what makes a gamma-ray burst? Specifically, what are the astrophysical objects, the "progenitors," which produce GRBs? Those theoretical progenitor scenarios which have remained feasible in the afterglow era are principally constrained by the following considerations:

- The implied (isotropic) energy release in γ-rays are typically 10^{-3}–10^{-1} times the rest-mass energy of the Sun. The estimated efficiency of conversion of the initial input energy (either Poynting flux or baryonic matter) to γ-rays ranges from ∼1% (e.g., Kumar 1999) to as much as ∼60% (e.g., Kobayashi & Sari 2001); therefore, the best-guess estimate of the total energy release (including neutrino and gravitational-wave losses) is roughly comparable to the rest-mass energy of one solar mass.

- The GRB variability timescale (few ms) observed implies that the energy deposition takes place in a small region of space (radius of $c \times 1$ ms ≈ 300 km). The range in total burst durations suggest that the central engine must live for less than one second and up to thousands of seconds.

- The inferred rate of GRB occurrence (table 1.1) and the lack of burst repetition (e.g., Hakkila et al. 1998) suggest that GRB events are rare and catastrophically destroy the individual progenitors.

The progenitor scenarios which most naturally explain these observables fall in to three broad classes—the coalescence of binary compact stellar remnants, the explosion of a massive star ("collapsar"), and the accretion-induced collapse of a differentially rotating compact object ("DRACO"; Kluźniak & Ruderman 1998). An active galactic nucleus (AGN) origin is another possibility, whereby a main-sequence (MS) or white-dwarf (WD) is tidally disrupted near a super-massive black hole. In such scenarios, however, the variability timescale still requires the energy source to be stellar-mass objects (Carter 1992; Cheng & Wang 1999).

Here, I briefly summarize the popular progenitor models and refer the reader to Fryer et al. (1999a) for a more in-depth review of the black-hole accretion disk progenitors models. Figure 1.3 depicts a schematic compilation of the major progenitor scenarios for classic GRBs along with references for the

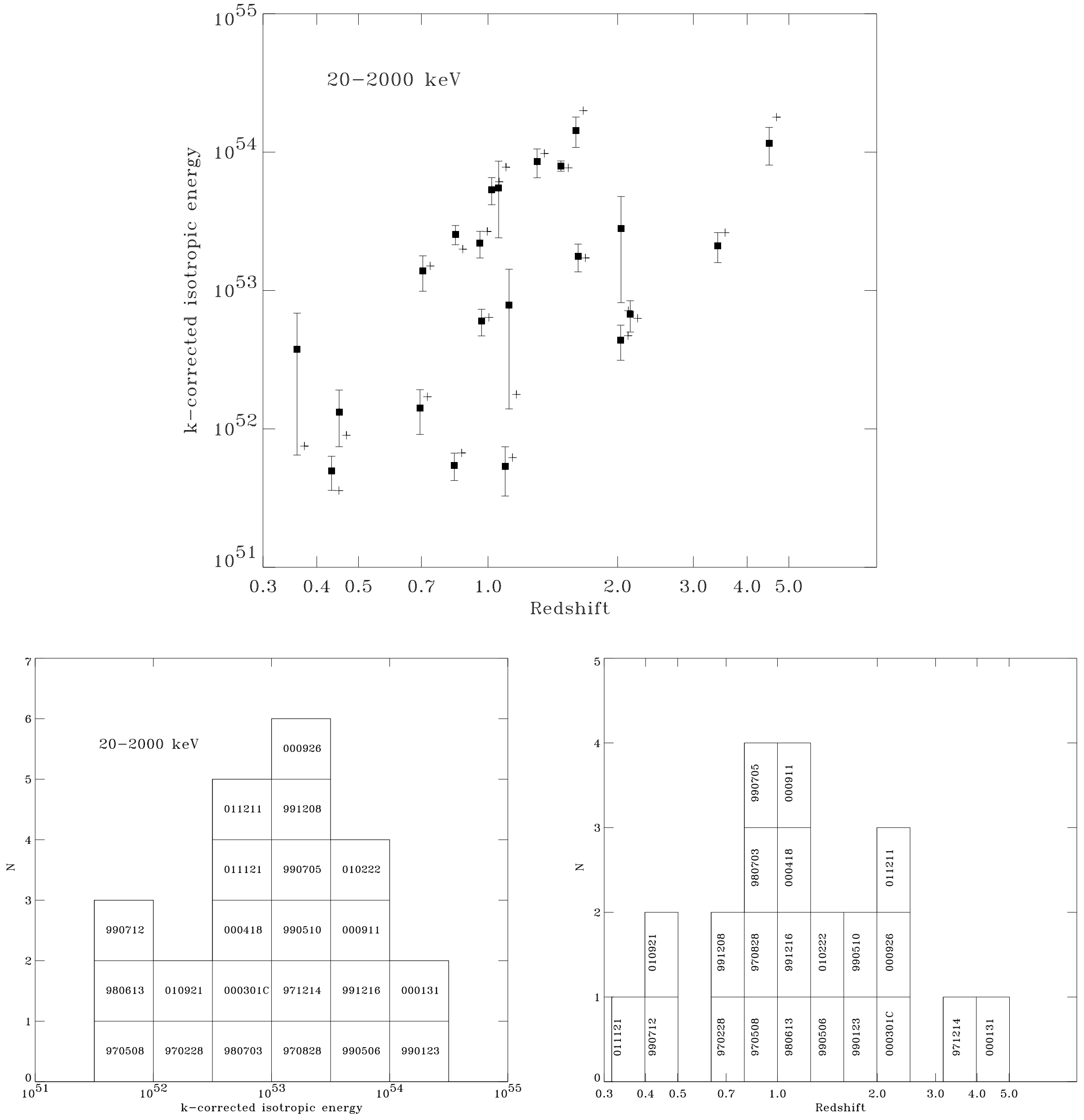

Figure 1.2 The redshift and energy distributions of the 22 cosmological GRBs with known redshift. At top, the k-corrected prompt energy release versus redshift in the restframe 20–2000 keV bandpass assuming isotropic emission. The 2 σ error bars are shown as well as the derived energies if no cosmological k-correction is applied (denoted as a cross "+"). At bottom left, the histogram of k-corrected GRBs energies. At bottom right, the observed redshift distribution of GRBs with measured redshifts. Note that while this observed distribution is reflective of the true GRB rate as a function of redshift, this is not, in general, the true GRB rate: for example, owing to a lack of strong star formation lines at observer-frame optical wavebands, there is a strong selection against finding emission-line redshifts in the redshift range $1.7 \lesssim z \lesssim 2.5$. Figures adapted and updated from Bloom et al. (2001b).