CHAPTER 12

Summary and Future Directions

SECTION 12.1

The Diversity of Cosmic Explosions

At this point the reader has hopefully sensed the large strides made in our understanding of gamma-ray bursts and related cosmic explosions. Over the past seven years astronomers have addressed the basic issues: the distance scale (cosmological) and the broad progenitor system (massive stars). While some of the work presented here touches on the nature of the progenitors, I have focused my attention instead on the next logical step – a detailed investigation of the energy source(s) driving cosmic explosions.

Using several observational approaches, I showed that the output of the central engine in GRBs, X-ray flashes and perhaps even GRB 980425/SN 1998bw is nearly standard, with $E_{\rm rel}$ clustered on about 10^{51} erg. This result reveals a common energy source, and hence origin, for these various explosions and sets a quantitative constraint on engine models. However, the partition of the relativistic energy varies widely, with some sources dominated by ultra-relativistic ejecta and others by mildly relativistic matter. This process presumably maps a diversity in the properties of the progenitors, for example the rotation rate of the core and the metallicity of the star. Thus, while GRBs and XRFs are exemplified by their high-energy output, the prompt energy release is a poor indicator of the total relativistic yield. Building on this understanding, and motivated by the unique properties of SN 1998bw, I also showed that the high-velocity output of type Ibc supernovae varies considerably. In fact, the local fraction of explosions that are powered by an engine is less than a few percent, suggesting that such events contribute a small fraction of the local stellar death rate.

The main question left open in these studies, is whether we are missing a significant number of events at higher redshift which would bridge the two populations. The recent discovery of GRB 031203 suggests that some diversity may exist (Soderberg et al. 2004). This burst, located at $z = 0.105$ (Prochaska et al. 2004), shares several properties with GRB 980425, most importantly an energy release of about 10^{50} erg. However, unlike GRB 980425 the energy budget is dominated by the γ-ray emission. Are we beginning to witness the extension of the standard energy result to lower energy?

While the answer is not clear at present, it is instructive to consider what selection effects are at play in the present sample. Events with a low γ-ray energy have a lower limiting volume (Figure 12.1). For example, GRB 031203 could have been detected at the BATSE sensitivity threshold only to $z \sim 0.25$, while for GRB 980425 the limiting distance is only about 100 Mpc. The fact that two such events have been detected at low redshift raises the possibility that such bursts dominate the event rate at $z \gtrsim 1$, as long as evolutionary effects are not significant. It is important to keep in mind, however, that the limit on such events of $\lesssim 3\%$ of the type Ibc supernova rate (Chapter 8) ensures that they do not exceed the rate of "classical" GRBs by more than an order of magnitude. Similarly, analyses of non-triggered BATSE bursts (Kommers et al. 2000; Stern et al. 2001) do not indicate a significant increase in the slope of the $\log N/\log S$ relation that may arise from a local homogeneous population of faint bursts.

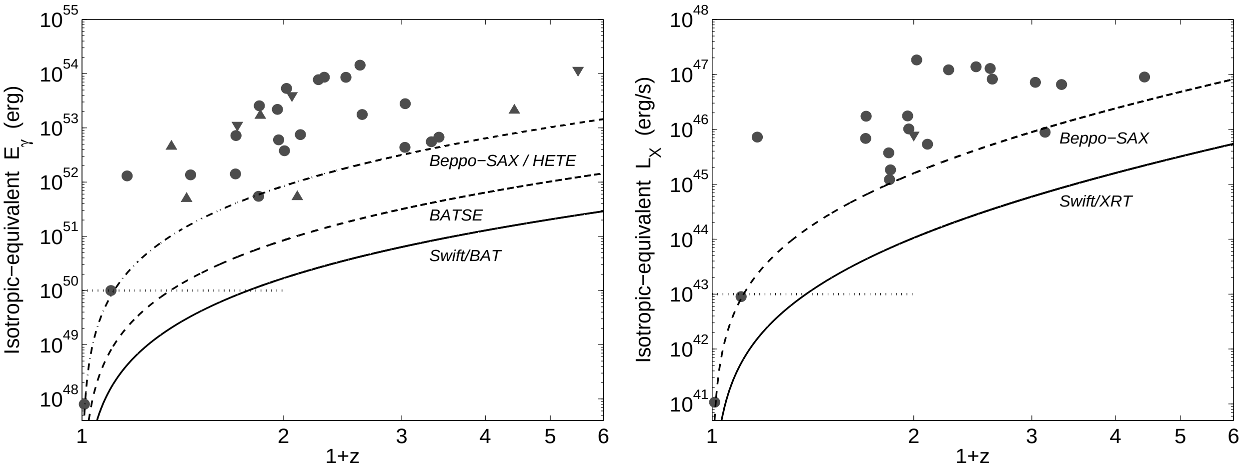

Figure 12.1: Isotropic-equivalent γ-ray energies (left) and X-ray luminosities of GRBs detected to date. The curves mark approximate detection thresholds for several missions. The increased sensitivity of *Swift* will allow the detection of events like GRB 031203 to $z \sim 1$. However, an actual redshift determination (which requires position from the afterglow) may be limited only to those events at $z \lesssim 0.4$.

In addition to the γ-ray bias, we also have to contend with a sensitivity threshold for the afterglow detections. In the X-ray band, both events could be easily detected at the distance limits determined by the γ-ray threshold. However, the bulk of such localizations in the present sample (e.g., from *Beppo-SAX*) are not sufficiently accurate for a redshift determination. In the optical and radio bands, which can provide arcsecond positions, the sensitivity threshold restricts the detection of the faint afterglows from such events to $z \lesssim 0.2$. Thus, it is possible that a sizable fraction of all GRBs lacking arcsecond positions (and hence a redshift) in fact occurred at low redshift!

A definitive answer will probably be available within the next year thanks to the launch of NASA's *Swift* satellite. This mission will overcome the selection biases detailed above in two ways. First, the γ-ray sensitivity is projected to be five times higher than that of BATSE. This will extend the limiting volume for the faintest bursts by about a factor of two. If these bursts follow $\log N/\log S \propto S^{-3/2}$ (but see e.g., Kommers et al. 2000), then the event rate will increase by as much as an order of magnitude. Perhaps more importantly, *Swift* will provide very accurate positions for the X-ray afterglows (≈ 10 arcsec) within several minutes of the burst. Thus, even in the absence of a subsequent optical and/or radio detection, a host galaxy and hence redshift could be identified. Thus, within several months of launch, *Swift* will likely allow us to determine whether the standard energy yield, as it has been determined from the current GRB sample, is in fact due to an observational bias.

SECTION 12.2 Cosmology with Gamma-Ray Bursts and Their Host Galaxies

The multi-wavelength investigation of GRB host galaxies presented in Chapters 9–11 provides an initial indication for the potential impact of GRBs on cosmological studies. The unique capabilities of *Swift* will dramatically increase the utility of GRBs as cosmological tools, both in the context of dust-obscured bursts and as lighthouses and signposts of massive star formation.

For the first time, the rapid and accurate localizations in both optical/near-IR and X-rays will remove observational bias as an impediment to the true fraction of dust obscured bursts. If the low fraction observed at the present persists, then this will likely support progenitor models that prefer low metallicity environments. For example, it has been argued in the context of collapsars (MacFadyen & Woosley 1999) that low metallicity helps keep the progenitor compact and reduces angular momentum losses from winds. However, a low metallicity also inhibits the shedding of the hydrogen envelope, suggesting that interaction with a close companion is required. Thus, the fraction of obscured bursts, while it may not provide insight into obscured star formation, will directly impact our understanding of the progenitors.

Similar insight is provided by an extension of the host galaxy work presented in Chapter 11. As mentioned in §1.6.2, GRB hosts tend to be faint in the rest-frame optical/UV. It is known however, that these bands suffer the effects of extinction and primarily provide an indication of the instantaneous star formation rate. I have therefore undertaken near-IR observations in conjunction with those published in the literature (Chary et al. 2002; Le Floc'h et al. 2003). The near-IR luminosities probe the total integrated stellar mass, since they are also sensitive to emission from old stars. The sample of GRB hosts has K-band,luminosities ranging from about -19.5 to -24 mag ($0.01 - 1$ L_*); see Figure 12.2. This hints at relatively low stellar masses.

A comparison of the GRB host optical and near-IR luminosities to those of other galaxy samples is illustrative. In the optical bands, GRB hosts generally have the same magnitude as a function of redshift as galaxies in the Hubble Deep Field (HDF; Cohen et al. 2000) or the Lyman break galaxies (LBGs; Shapley et al. 2003; Steidel et al. 2003, 2004). In the near-IR bands, on the other hand, GRB hosts are significantly fainter than most LBGs and all of the submillimeter-selected galaxies. However, they do have a similar magnitude distribution as a function of redshift compared to K-selected galaxies in the Subaru Deep Field (Kashikawa et al. 2003). Unfortunately, the latter only have photometric redshifts with $\delta z \gtrsim 0.5$ at faint fluxes. Clearly, the reason for the blue colors of GRB hosts is a low K-band luminosity rather than dust obscuration.

The absolute rest-frame luminosities are shown in Figure 12.2 in comparison to LBGs and submillimeter galaxies. The separation of the three samples is clear, with GRB hosts being significantly fainter in the near-IR and somewhat fainter in the optical. The rest-frame near-IR luminosities are generally thought to be related to the total mass of the galaxy since they trace light from old stellar populations, while the rest-frame optical is more sensitive to current star formation. If this is the case, then GRB hosts are likely less massive than LBGs and submillimeter galaxies, probably because they are in the initial phase of the star formation process. This will also result in somewhat lower optical luminosities, in agreement with the observed distribution.

We are therefore led to the following picture of GRB hosts. These galaxies are generally young, undergoing a first episode of starburst activity, and as a result tend to be less massive and possibly metal poor. A fraction of about 10%, however, have enough dust and a high star formation rate to produce a signal in the submillimeter band, but those are still less massive than the typical systems selected in the submillimeter. Thus, GRB selection appears to favor young starburst galaxies. This supports the inferences made based on the submillimeter and radio emission from GRB hosts. Therefore, one of the main scientific questions that GRB hosts can uniquely address are the processes that initiate the starburst process. Since these galaxies are detected at redshifts ranging at least from 0.1 to 4.5, the redshift evolution of this process may also be elucidated.

As a final note on the properties of GRB host galaxies I return to a point made earlier in this thesis. The current limit on spectroscopic redshift determination is $R \sim 25.5$ mag. Photometric redshifts extend this limit significantly, but there is no way to assess how accurate they are at low flux levels. On the other hand, GRB host galaxies of arbitrary brightness can have spectroscopic redshift measurements from absorption of the afterglow light as it traverses the galaxy. This technique also provides insight into the metallicity and dynamical state of the ISM of the host. As a result, we now have redshifts for six galaxies with $R > 26$ mag, which extend the luminosity function of high redshift galaxies an order of magnitude fainter (Figure 12.2). The volumetric corrections are difficult to assess for the GRB hosts, especially since selection effects (including γ-ray sensitivity threshold) have not been fully quantified. As a result, it is difficult to make a direct comparison with known luminosity functions. However, it is clear that there is a sizable population of galaxies, about a third of all GRB hosts, with luminosities well below $0.1L_*$.

The rapid localizations and rate of about 100 bursts per year from *Swift* will elevate the afterglows

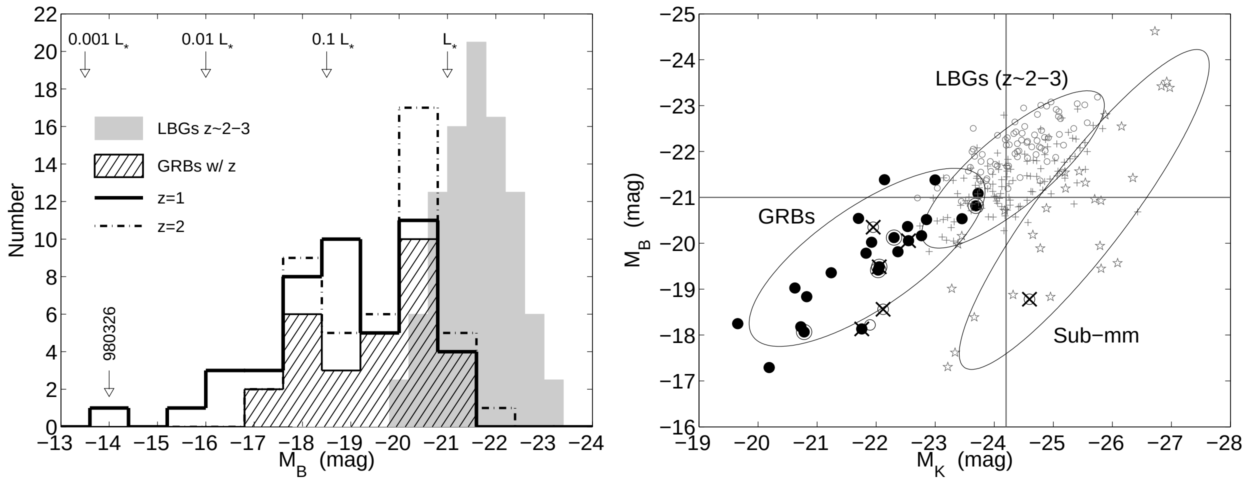

Figure 12.2: *Left:* Histogram of absolute rest-frame B-band luminosities for GRB host galaxies and Lyman break galaxies (LBGs). Gamma-ray burst hosts are typically fainter than $0.5L_*$, and they extend at least an order of magnitude fainter than LBGs. Of particular interest in the host of GRB 980326 for which Bloom et al. (1999) claim $z \lesssim 1$ based on strong evidence for an associated supernova. In this case, the host is nearly a factor of 1,000 less luminous than an L_* galaxy. *Right:* Absolute rest-frame B- versus K-band luminosities. The vertical and horizontal lines mark L_* galaxies. Submillimeter galaxies have the highest integrated stellar masses (i.e., K-band luminosities), while LBGs typically have the highest instantaneous star formation rates (i.e., B-band luminosities). Gamma-ray burst hosts are clearly separated and sub-L_* in both bands.

and host galaxies of GRBs to the forefront of IGM, ISM and star formation studies. At the present, the IGM is primarily studied using absorption spectroscopy of bright background quasars, which have revealed a filamentary structure with a wide range of column densities, and metal enrichment out to a redshift, $z \sim 4$ (Rauch 1998; Storrie-Lombardi & Wolfe 2000). Moreover, the highest redshift quasars (Becker et al. 2001), along with results from the *Wilkinson Microwave Anisotropy Probe* (Spergel et al. 2003), indicate that the Universe was re-ionized at $z \sim 7$ to 15. Unfortunately, IGM studies are limited by the ionizing effect of quasars on their local IGM (the "proximity effect"), the possibility that quasars can only probe the IGM to $z \sim 7$ (super-massive black holes possibly take several hundred million years to assemble), and the dust extinction associated with the highest density regions.

In the same vein, studies of the ISM in high redshift galaxies and its interplay with the IGM, which probes the role of feedback processes (e.g., galactic super-winds), are currently limited to the bright end of the galaxy luminosity function (e.g., LBGs with $L \gtrsim L_*$; (Adelberger et al. 2003)). Even these galaxies are typically not bright enough to elucidate the physical extent, velocity dispersion and covering fraction of super-winds, or their relation to metallicity, star formation and galactic mass.

Gamma-ray burst optical/near-IR afterglows are a unique and powerful tool in this context. The short-lived bursts (durations $\lesssim 100$ s) do not suffer from a proximity effect on scales larger than ~ 10 pc. Thus, the Lyα damping wing and metal systems near the host galaxy can be measured directly. Equally important, GRBs are at least as bright as quasars within the first few hours (Figure 1.6). This, along with explosion sites within the disks of high redshift galaxies (Bloom et al. 2002a), ensure that they can probe the ISM of *arbitrarily faint galaxies* over a wide range of redshifts. The latter is an important point since other studies relying on galaxy spectroscopy are limited to $R \sim 25$ mag.

Gamma-ray bursts can also trace denser regions than quasars since the selection trigger (γ-rays) is impervious to dust and the afterglows reside within galactic disks. Preliminary studies reveal that damped Lyα systems associated with GRB host galaxies have the highest column densities observed to date (e.g., (Savaglio et al. 2003)), specifically for this reason (Figure 12.3). Along with quasars, which tend to probe the extended halos of intervening galaxies, GRB afterglows could provide a complete

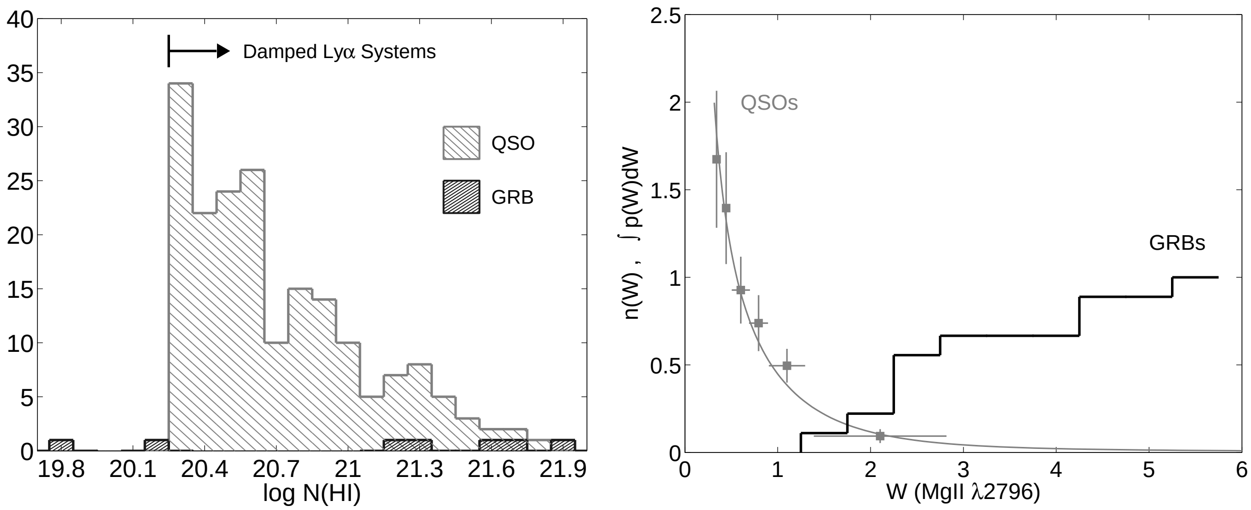

Figure 12.3: *Left:* Column densities of damped Lyα systems from QSO and GRB absorption spectra; data are from Curran et al. (2002) and Vreeswijk & et al. (2004). *Right:* Distribution of MgII equivalent widths from QSO (Steidel & Sargent 1992) and GRB afterglow spectroscopy. Clearly, GRBs trace significantly denser environments compared to quasars since they more easily probe the inner disks of high redshift systems (i.e., their host galaxies).

picture of the structure, metal distribution, and column density distribution as a function of both distance from the center of the galaxy and redshift.

Finally, the most exciting prospect is that GRBs may probe the Universe to a higher redshift than quasars since it is now thought that the first generation of massive stars may have formed beyond $z \sim 10$ (e.g., Barkana & Loeb 2001). Such bursts will probe the epoch of re-ionization with much greater precision than current studies and will provide otherwise inaccessible information about the structure of the IGM at $z \gtrsim 7$. In particular, an near-IR spectrum could provide a measurement of the Lyα optical depth, through the shape of the Lyα damping wing, and simultaneously trace the metallicity, through a measurement of the optical depth due to oxygen (e.g., using OI 1302Å; Oh 2002). The expected number of very high redshift bursts is a matter of speculation, both because the epoch of formation of massive stars is unknown and because it is not clear if these putative stars will even give rise to GRBs.

The ability of GRB afterglows to trace the ISM of their host galaxies is particularly powerful in the context of host galaxy studies. One of the main avenues of research at present is the interplay between galaxies and the IGM, especially the process of metal enrichment and the initial formation of stars. Current studies appear to favor a scenario in which galactic winds, presumably driven by supernovae, enrich the IGM (Adelberger et al. 2003). However, the faintness of the galaxies typically prevents a detailed physical understanding of how these winds arise and what influences their strength and duration. We can overcome this problem with a combination of GRB host galaxy spectroscopy and multi-wavelength imaging, providing information on star formation, and afterglow absorption spectroscopy, providing estimates of the metallicity within the galaxy, in the interface between the ISM and IGM, and in the IGM itself.

SECTION 12.3

Conclusions

The study of gamma-ray bursts has matured considerably since their discovery over thirty years ago. The determination of a cosmological origin for the long-duration bursts has focused attention on models in which GRBs arise from the death of massive stars, and this has now been confirmed by several lines

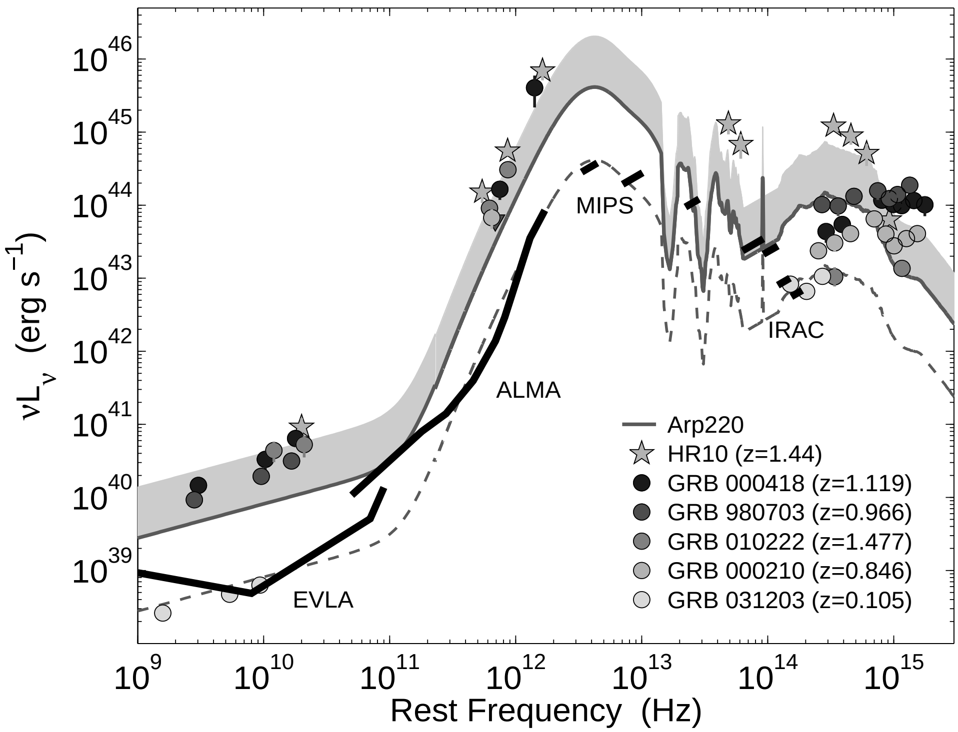

Figure 12.4: Broad-band spectral energy distributions for several GRB hosts detected in the optical/near-IR, submillimeter and radio bands. Also shown are the SED of the local starburst galaxy Arp 220. The thick black lines represent the 300-second sensitivity of the MIPS and IRAC instruments on-board the *Spitzer* space telescope, as well as the projected sensitivity of ALMA and the Expanded VLA. Clearly, these will extend the depth of host galaxy observations by at least an order of magnitude, allowing the detection of systems with moderate luminosities $\sim$ few $\times\, 10^{10}$ $L_\odot$.

of reasoning, most importantly, the spectroscopic detection of a supernova in association with a GRB. This realization has propelled the field of GRB astronomy in two directions, namely an investigation of the energy source giving rise to the explosion partly in the context of supernovae, and the use of GRBs as tools for the study of star formation and the metal enrichment history of the universe.

The studies presented in this thesis provide quantitative constrains on GRB engine models:

- Gamma-ray burst outflows are narrowly collimated with a wide distribution of jet opening angles ($\sim 5-30^\circ$). The jets appear to maintain a simple geometry over a wide range of radii, with a double-jet structure in some cases. This argues against structured jets.

- There is a strong correlation between the energy per unit solid angle and the jet opening angles such that the total relativistic energy release is strongly clustered for GRBs, XRFs, and perhaps SN 1998bw-like events. Values range from about 5×10^{50} to 5×10^{51} erg.

- Type Ibc supernovae in the local universe are primarily powered by the quasi-spherical explosive ejection of the progenitor envelope. Less than 3% are powered by engines.

Whether there exists a population of intermediate sources bridging the supernova and cosmological GRB populations remains an open question.

Regardless of the detailed physics, the extreme luminosity and association with massive stars and star-forming galaxies, makes GRBs a powerful probe of cosmology. Initial studies conducted in the optical/near-IR, submillimeter and radio indicate that GRBs preferentially arise in young starburst galaxies, some of which exhibit extremely large star formation rates. The advent of *Swift* promises a sample of several hundred GRB hosts, some of which with unparalleled information on the metallicity and dynamics of the interstellar medium and intergalactic medium. Combined with advances in far-IR, millimeter and radio facilities, such as *Spitzer*, the Atacama Large Millimeter Array, the Expanded Very Large Array, and the Square Kilometer Array (Figure 12.4), GRBs are poised to make an impact in the quest for understanding the formation and evolution of galaxies and the intergalactic medium.

CHAPTER A

Additional Publications

SECTION A.1

Refereed Publications Related to Gamma-Ray Bursts

1. Berger, E., Soderberg, A. M., Frail, D. A., Kulkarni, S. R. 2003, ApJ, 587, L5
A Radio Flare from GRB 020405: Evidence for a Uniform Medium Around a Massive Stellar Progenitor

2. Lipkin, Y. M., Ofek, E. O., Gal-Yam, A., Leibowitz, E. M., Poznanski, D., Kaspi, S., Polishook, D., Kulkarni, S. R., Fox, D. W., Berger, E., Mirabal, N., Halpern, J., Bureau, M., Fathi, K., Price, P. A., Peterson, B. A., Frebel, A., Schmidt, B., Orosz, J. A., Fitzgerald, J. B., Bloom, J. S., van Dokkum, P. G., Bailyn, C. D., Buxton, M. M., Barsony, M. 2004, ApJ, 606, 381
The Detailed Optical Light Curve of GRB 030329

3. Frail, D. A., Metzger, B. D., Berger, E., Kulkarni, S. R., Yost, S. A. 2004, ApJ, 600, 828
A Late-Time Flattening of Afterglow Light Curves

4. Bloom, J. S., Fox, D., van Dokkum, P. G., Kulkarni, S. R., Berger, E., Djorgovski, S. G., Frail, D. A. 2003, ApJ, 599, 957
The First Two Host Galaxies of X-Ray Flashes: XRF 011030 and XRF 020427

5. Sheth, K., Frail, D. A., White, S., Das, M., Bertoldi, F., Walter, F., Kulkarni, S. R., **Berger, E.**. 2003, ApJ, 595, L33
Millimeter Observations of GRB 030329: Continued Evidence for a Two-Component Jet

6. Price, P. A., Fox, D. W., Kulkarni, S. R., Peterson, B. A., Schmidt, B. P., Soderberg, A. M., Yost, S. A., **Berger, E.**, Djorgovski, S. G., Frail, D. A., Harrison, F. A., Sari, R., Blain, A. W., Chapman, S. C. 2003, Nature, 423, 844
The bright optical afterglow of the nearby γ-ray burst of 29 March 2003

7. Frail, D. A., Kulkarni, S. R., **Berger, E.**, & Wieringa, M. H. 2003, AJ, 125, 2299
A Complete Catalog of Radio Afterglows: The First Five Years

8. Li, W., Filippenko, A. V., Chornock, R., **Berger, E.**, Berlind, P., Calkins, M., Challis, P., Fassnacht, C., Jha, S., Kirshner, R., Matheson, T., Sargent, W., Simcoe, R., Smith, G., Squires, G. 2003, PASP, 115, 453
SN 2002cx: The Most Peculiar Known Type Ia Supernova

9. Frail, D. A., Yost, S. A., **Berger, E.**, Harrison, F. A., Sari, R., Kulkarni, S. R., Taylor, G. B., Bloom, J. S., Fox, D. W., Moriarty-Schieven, G. H., Price, P. A. 2003, ApJ, 590, 992
The Broadband Afterglow of GRB980703

10. Galama, T. J., Reichart, D., Brown, T. M., Kimble, R. A., Price, P. A., **Berger, E.** Frail, D. A., Kulkarni, S. R., Yost, S. A., Gal-Yam, A., Bloom, J. S., Harrison, F. A., Sari, R., Fox, D., Djorgovski, S. G. 2003, ApJ, 587, 135
Hubble Space Telescope and Ground-based Optical and Ultraviolet Observations of GRB 010222

11. Galama, T. J., Frail, D. A., Sari, R., **Berger, E.**, Taylor, G. B., & Kulkarni, S. R. 2003, ApJ, 585, 899
Continued Radio Monitoring of the Gamma-Ray Burst 991208

12. Fox, D. W., Price, P. A., Soderberg, A. M., **Berger, E.**, Kulkarni, S. R., Sari, R., Frail, D. A., Harrison, F. A., Yost, S. A., Matthews, K., Peterson, B. A., Tanaka, I., Christiansen, J., Moriarty-Schieven, G. H. 2003, ApJ, 586, L5
Discovery of Early Optical Emission from GRB 021211

13. Fox, D. W., Yost, S., Kulkarni, S. R., Torii, K., Kato, T., Yamaoka, H., Sako, M., Harrison, F. A., Sari, R., Price, P. A., **Berger, E.**, Soderberg, A. M., Djorgovski, S. G., Barth, A. J., Pravdo, S. H., Frail, D. A., Gal-Yam, A., Lipkin, Y., Mauch, T., Harrison, C., Buttery, H. 2003, Nature, 422, 284
Early optical emission from the gamma-ray burst of 4 October 2002

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The redshift determination of GRB 990506 and GRB 000418 with the Echellete Spectrograph Imager on Keck

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Discovery of GRB 020405 and its Late Red Bump

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GRB 010921: Strong Limits on an Underlying Supernova from the Hubble Space Telescope

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The Broadband Afterglow of GRB 980329

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GRB 011121: A Massive Star Progenitor

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GRB 010921: Discovery of the First High Energy Transient Explorer Afterglow

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The Unusually Long Duration Gamma-ray Burst GRB 000911: Discovery of the Afterglow and Host Galaxy

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The Diversity of Cosmic Explosions: Gamma-Ray Bursts and Type Ib/c Supernovae

2. Berger, E. 2003, to appear in proceedings of “IAU Colloquium 192, Supernovae: 10 Years of 1993J”, Valencia, Spain 22-26 April 2003, eds. J. M. Marcaide, K. W. Weiler; astro-ph/0309713
How Common are Engines in Ib/c Supernovae?

3. Berger, E., Kulkarni, S. R., & Frail, D. A. 2002, American Astronomical Society, 201st AAS Meeting, #84.03; Bulletin of the American Astronomical Society, Vol. 34, p.1243
Calorimetry of GRB afterglows – a Direct Measure of the Fireball Energy

4. Berger, E. 2002, to appear in proceedings of the ”Gamma-Ray Bursts in the Afterglow Era: 3rd Workshop”, ASPCS, in press; astro-ph/0304346
Radio Afterglows of Gamma-Ray Bursts: Unique Clues to the Energetics and Environments

5. Berger, E. 2001, to appear in Proc. of the Gamma-Ray Burst and Afterglow Astronomy 2001: A Workshop Celebrating the First Year of the HETE Mission; astro-ph/0112559
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