Abstract.

This meeting covered the range of cosmic explosions from solar flares to \(\gamma\)-ray bursts. A common theme is the role of rotation and magnetic fields. New information from the Sun shows that a “magnetic carpet” contains most of the surface field that feeds the corona. Disk instabilities in protostellar disks may provide most of the growth of a protostar. Type Ia supernovae continue to give evidence for an accelerating Universe, and a rigorous examination is underway to characterize systematic effects that might alter the results. The binary evolution origin of Type Ia that explode as carbon/oxygen white dwarfs at nearly the Chandrasekhar limit remains a thorny problem. The discovery of the central point of X-ray emission in Cas A by CXO should give new insight into the core collapse problem in general and the nature of the still undetected compact remnant in SN 1987A in particular. Jets were described from protostars to microquasars to blazars to \(\gamma\)-ray bursts. Polarization studies of core-collapse supernovae lead to the conclusion that core collapse is not merely asymmetric, but strongly bi-polar. To account for normal core-collapse supernovae, the explosion must be jet-like in routine circumstances, that is, in the formation of neutron stars, not only for black holes. Given the observed asymmetries, estimates of explosion energies based on spherically-symmetric models must be regarded with caution. The strong possibility that at least some \(\gamma\)-ray bursts arise from massive stars means that it is no longer possible to decouple models of the \(\gamma\)-ray burst and afterglow from considerations of the “machine.” Although it began the supernova/\(\gamma\)-ray burst connection, it is difficult to fit SN 1998bw/GRB 980425 into any statistical picture that incorporates the high redshift events. The implied correlation of \(\gamma\)-ray bursts with star formation and massive stars does not distinguish a black hole collapsar model from models based on the birth of a magnetar. Current jet models do not discriminate the origin of the jet. Calorimetry of at least one afterglow suggests that \(\gamma\)-ray bursts cannot involve highly inefficient internal shock models. Essentially all \(\gamma\)-ray burst models involve the “Blandford Anxiety,” the origin of nearly equipartition magnetic fields in the associated relativistic shocks.
It is important to discriminate the origin of the $\gamma$-ray burst energy as thermal energy, kinetic energy or perhaps Poynting flux.

I INTRODUCTION

The Tenth October Maryland conference celebrated the rapid release of energy from objects ranging from protostars to active galactic nuclei. We were treated to an inimitable history as only Virginia Trimble can do it from her personal knowledge of the players and places and her voracious reading of the literature. Roger Blandford gave an overview with a focus on unsolved problems.

In this summary, I will present a brief summary of the invited review talks and selected poster presentations. I regret, especially, that I cannot do justice to all the latter. To a certain extent, I will present the great span of exploding objects we covered as reflected in the mirror of supernovae. There are three reasons for this: (i) this is the subject I know best; (ii) various aspects of supernova research were presented at length; and (iii) supernovae, I believe, are related to everything—and everything to supernovae. The degrees of separation are, in any case, rarely so great as six. A more specific theme I will underline is that to an ever-growing extent we are forced to consider rotation, magnetic fields, and asymmetries. In Section II, I will present some work from my collaborators in Texas and elsewhere that relate to this general theme. Section III gives some perspective and unresolved issues.

II SUMMARY OF PRESENTATIONS

A Stellar and Solar Flares

Blandford emphasized that there has been great progress recently in the study of the Sun that has led to a new and different understanding of the magnetic field of the Sun and its role in coronal heating. In particular, solar flares come from regions of relatively weak magnetic field where plasma can intrude. The magnetic field is higher in a “magnetic carpet” across the solar surfaces and it is from this layer of stronger field that “nanoflares” deliver energy to power the solar corona.

Linsky reviewed our understanding of flares from a variety of stellar sources. These flares are of great interest, but if other stars operate in analogy to the Sun, then flares may be only the tip of otherwise unseen magnetic activity in other stars. Ramaty emphasized the manner in which flares can be used to study the acceleration of particles. Kenyon outlined the great progress that has been made in terms of understanding the FU Ori phenomenon as a disk instability in a protostellar disk, pointing out that all the growth of a protostar
may arise during the phases of high luminosity and high mass accretion rate. Clearly, study of these phenomena, especially in the detail afforded by the Sun, can give us valuable insight into the processes of reconnection and coronal formation that are, in turn, crucial in order to understand accretion disks, winds, jets, and particle acceleration.

B Type Ia Supernovae

The use of Type Ia supernovae as “calibrated candles” by means of empirical brightness-decline relations has been startlingly successful. The tentative conclusion that there is a low matter density and a finite, positive cosmological constant has sent reverberations throughout astronomy and physics (Riess et al. 1998; Perlmutter, et al. 1999). Type Ia are more complex than can be described by the first versions of one-parameter brightness decline relations: ∆M(15) (Hamuy, et al. 1996), Multicolor Light Curve Shape (Riess, Press, & Krishner 1996), or stretch (Perlmutter et al. 1999). Theorists can, and have, invented many reasons why Type Ia might vary with look back times. On the other hand, the first order corrections have been remarkably successful in reducing the scatter in the data and providing constraints on cosmological parameters. In this conference, Kirshner and Aldering presented data showing that no significant evolutionary effects have yet appeared in the data. In particular, Aldering argued that refined analysis of error bars yields no statistically significant evidence that the early rise times are different in nearby events and those at redshift z∼0.5 (e.g. Reiss et al. 2000).

Nomoto outlined models for Type Ia evolution and possible systematic effects. Of particular interest is the recent calculation of Höflich et al. (1999) showing that, at lower metallicity, a star of a given mass will produce a smaller C/O ratio. All else being the same (ignition density, density of transition to detonation), a lower C/O ratio will lead to a somewhat brighter event with a faster decline. The one parameter brightness-decline relations would then interpret such an event as somewhat dim, just the effect interpreted as evidence for a cosmological constant. More modelling of this sort and comparison with data is necessary to elucidate these sorts of physical systematic effects.

There were also discussions of possible sources of observational systematic bias. Suntzeff gave an excellent review of the observations and a cautionary note about comparing photometric results from different observatories that use slightly different filters sets and thus get slightly different results for standard stars in standard filters. There is a tendency for the deep searches to not follow up events that are at larger distance from potential host galaxies because of the ambiguity of association of the supernovae candidate with the host. Filippenko pointed out that there is some complementary bias against candidates that are close to the centers of host galaxies because those are sometimes passed over when classification spectra are obtained due to concerns about galactic
contamination. These selection biases in terms of the radial position on the galaxy may in turn be important at some level because the distribution of intrinsic luminosity and decline rate is known to vary with galactocentric radius (Wang, Höflich & Wheeler 1997; Riess et al. 1999; Howell, Wang & Wheeler 1999). A bias against events at low galactocentric radius might give a bias toward events that are more homogeneous in their properties, but less able to discriminate subtle differences in progenitor dependence. The success of the light curve brightness/decline relations to remove potential evolutionary effects by including sample events that span the full range of progenitor ages and metallicity in nearby events in spirals and ellipticals might thus be subtly affected.

My personal answer to the question of whether the Universe is accelerating is “probably yes.” My answer to the query of do we know for sure is “not yet.”

The physics of Type Ia supernovae was discussed, without which there will remain some doubt concerning the purely empirical treatment of Type Ia as cosmological probes. Pinto gave a summary of the basic understanding of why there is a brightness/decline relation. He noted that the observed relations can be produced in white dwarfs of constant mass, near the Chandrasekhar mass in the most successful models. In this context, if the nickel mass is increased the peak luminosity naturally goes up. Less obvious is that the temperature goes up resulting in a increase in the line opacity. This traps the energy from γ-ray decay, resulting in a slower decline, the process amply illustrated in previously published models (Höflich Khokhlov & Wheeler 1995; Höflich & Khokhlov 1996; Höflich et al. 1996).

The physical question that emerges from such an analysis is why the nickel mass should vary when the white dwarf progenitor mass is essentially fixed. This is presumably a product of initial conditions and the thermonuclear combustion of the white dwarf. The physics of the combustion was described by Hillebrandt and by Niemeyer. There has been great progress in recent years in applying concepts from terrestrial combustion physics to the Type Ia problem. Observations and theory suggest that the combustion begins with a relatively slow, subsonic, turbulent deflagration. To account for the distribution of intermediate mass elements in velocity in the outer layers of Type Ia explosions, there must be a transition to a much faster burning. The issue of whether there is a natural transition from subsonic deflagration to supersonic detonation has been discussed (Khokhlov, Oran & Wheeler 1997a,b,c; Niemeyer & Woosely 1997; Khokhlov, Oran, Wheeler & Chtchelkanova 1999; Montgomery, Khokhlov, & Oran 1998). Hillebrandt and Niemeyer raised the question of the difficulty of making a direct transition from deflagration to detonation and discussed the possibility that a speed up to a very rapid, but still subsonic deflagration was possible and adequate to account for the observations. It is not clear that a very rapid deflagration would not be unstable to evolution to a detonation. One thing that is clear is that the turbulent deflagration must be studied in three dimensions to get the sign of the tur-
bulent cascade (from large scales to small scales) correct and to understand that process in the context of spherical dilution and related effects (Khokhlov 1995).

Another major issue that arises in the context of the standard, Chandrasekhar mass model for Type Ia supernovae is the question of their prior evolution. How do white dwarfs grow to the Chandrasekhar mass sufficiently often to account for the observed rates of Type Ia? Nomoto described the models that currently seem to come closest to solving this long-standing issue. These models invoke a wind from the white dwarf so that a relatively rapid mass transfer rate from the companion does not glut the white dwarf with mass to yield a surrounding hydrogen-rich envelope, in violation of the observations. Rather, the excess mass can be blown off in the wind. Models show that the net accretion onto the white dwarf can be rapid enough to avoid degenerate hydrogen or helium ignition. Such ignition is inimical to the Type Ia process since a nova explosion will reduce the mass of the white dwarf, as discussed by Hernanz. Degenerate helium ignition produces a supernova explosion of the wrong properties, as outlined by Nomoto. In the wind models, the amount of hydrogen on the surface of the white dwarf when it explodes is sufficiently small to escape detection. For a given wind model, there are solutions that will give the desired properties of Type Ia progenitors with unstable mass loss from main sequence companions and stable mass loss on the thermal time scale from red giant companions with masses in the range 1 - 3 $\text{M}_\odot$. At lower metallicities, the wind could be less efficient and it may not be possible to produce Type Ia. This would give an epoch of turn-on of Type Ia with look back time.

One of the issues raised by these binary wind models is the reservoir problem. The amount of mass that is lost from the secondary is related to the mass that accretes onto the white dwarf, promoting its growth. This can be expressed by:

$$\Delta M_2 = \Delta M_{wd} \left(1 + \frac{M_{\text{wind}}}{M_{wd}}\right).$$

If the secondary only has a mass of 1 - 3 $\text{M}_\odot$, the wind model may work if the rate of loss to the wind is comparable to the rate of accretion onto the white dwarf. The companion loses only two grams for every gram that lands on the white dwarf. On the other hand, wind mass loss rates are not known very well in most circumstances, certainly not in this rather exotic one, and factors of a few may be important. If, for instance, the rate of loss to the wind is several times the growth rate of the white dwarf, then if the white dwarf must accrete several tenths of a solar mass to reach the Chandrasekhar limit, the small mass companion might not be able to provide enough. This, of course, depends on the initial mass of the white dwarf. If the supernova progenitor must grow from the mass of a field white dwarf, 0.6 $\text{M}_\odot$, the task is nearly insurmountable. If the initial mass of the white dwarf is substantially
higher, the task is easier. An important issue then becomes the initial mass
distribution of the white dwarfs, a function that is not well known at higher
white dwarf masses and which is undoubtedly affected by the very condition
of being in a binary system. Hernanz and Starrfield pointed out that there
are white dwarfs in binary systems with rather large masses, for instance that
in the recurrent nova system U Sco at about 1.3 $M_\odot$, so nature can do this,
 atleast occasionally.

It is still a high priority to obtain any information that will give us hints of
the nature of the binary system underlying Type Ia supernovae. If they are
hydrogen accretors, as the binary wind models suppose, the explosion should
take place next to a hydrogen-rich companion and within the wind. The
search for the stripped companion is important, but handicapped because the
hydrogen tends to lag the ejecta and is expected to show up, if at all, in the
nebular phase when the spectrum is complex and weak H$\alpha$ might be difficult
to detect. Suntzeff pointed out that the use of sensitive eschelle detectors
on the new generation of large aperature telescopes might give a new way to
search for the hydrogen swept up in the wind.

C Collapse

The process of core collapse is of great current interest both for its intrinsic
importance as a supernova triggering mechanism and for its potential connec-
tion to $\gamma$-ray bursts. Fryer gave an update on work to understand collapse,
especially the difficult problem of neutrino transport and the critical issue of
fall back which may determine whether a neutron star or black hole is left be-
hind in a successful supernova explosion. Fallback considerations suggest that
black hole formation could be common in stars with mass as low as 20 $M_\odot$, making SN 1987A right on the ragged edge of going either way, neutron star
or black hole. Fryer predicted that after a decade of concentration on mul-
tidimensional hydrodynamics and specifically protoneutron star convection,
the next decade would be one devoted to the effects of rotation and neutrino
transport. I think the former is unambiguously true and would add magnetic
fields to the mix. As for the latter, it is clear the neutrinos will continue to
play a large role since they must carry off the bulk of the binding energy of
the neutron star. It is not so clear that they will emerge as the final arbitrat-
ing physics of the success or failure of the explosion itself as the role of jets
becomes more clear, as discussed in §D.

A great new step toward understanding the outcome of core collapse came
with the launch of the new Chandra Observatory. The first obtained and
released image of Cas A represented an incredible debut. Although there
were hints of a central object in ROSAT data, the Chandra image showed
with unambiguous clarity the dim point of X-ray emission in the center of the
remnant. The issue of whether this is a cooling neutron star or an accreting
neutron star or black hole is now under debate. One thing is clear. This image gives us a new slant on similar issues in SN 1987A where the expected neutron star has still not revealed itself. If the object left behind in SN 1987A is similar to that in Cas A, then it is no wonder we have not seen it. The object in Cas A is very faint, less than a few $L_\odot$, perhaps as little as $10^{32}$ erg s$^{-1}$ (Tanenbaum, et al. 1999). One possibility to detect the central object in SN 1987A is to register the bolometric emission from the absorption and re-emission of any source within the ejecta. Heroic efforts to measure the bolometric luminosity still place it at more than $10^{33}$ $L_\odot$, more than 1000 times brighter than the object in Cas A. It may be that by searching diligently in the continuum between emission lines tighter limits can be obtained in SN 1987A, but detecting an object as faint as that in Cas A will be a challenge. Figuring out the nature of the object in Cas A will immediately give us new perspectives on SN 1987A. One of the issues will be to understand why this object is $10^4$ to $10^5$ times dimmer than the 1000 year old pulsar in the Crab nebula. If neutron stars with rapid rotation and strong magnetic fields are necessary to make jets in supernovae, Cas A and SN 1987A do not seem to qualify. There is, however, obvious evidence for some jet-like activity in Cas A and SN 1987A has its rings and asymmetric ejecta, so this story has a long way to run.

To take a step back, Davidson regaled us with his recriminations that we have worked so little on, and understood so little of, $\eta$ Carinae. He is exactly right. We have made a lot of progress modeling massive stars as spherically symmetric, but somewhere we may have taken a drastically wrong turn since we are very far from predicting the properties of $\eta$ Carinae from first principles. The lack of progess in understanding $\eta$ Carinae is not due to lack of interst or curiousity, but simply a lack of knowledge of where to start in this complex beast. Surely we must try. The mass of the star is likely to exceed 100 $M_\odot$, and so it must surely collapse or explode. It might be a $\gamma$-ray burst waiting to happen. The lobes and skirt are compelling in their beauty and simplicity and strongly reminiscent of the rings of SN 1987A. The details of ropes, strings, and jets are bewildering, as is the great outburst of the last century and the recent brightening. Once again the Chandra image of Cas A brings a new vision of this key object.

There is also much to entertain after the explosion. McCray outlined the three-ring circus that is beginning to ensue with the first lighting of the first blob in the inner ring of SN 1987A as the fastest ejecta collide with the most prominent protrusions. McCray revealed that the “knot” that has lit up may not have the enhanced N abundance reflecting CNO processing that is ascribed to the rings, but rather may be more representative of the ISM of the LMC. This would be an intriguing result. In any case, the next decade will be a three-ring circus replete with fireworks as the ejecta continue to interact with the ring. There is much to be learned about interstellar medium shock physics as well as the nature of the progenitor star and the ejecta.
D  Jets

The topic of jets has long been of central interest to astrophysics. There is a new concentration on relativistic jets because of their possible role in γ-ray bursts.

Livio gave an overview, pointing out that jets are ubiquitous, from protostars to γ-ray bursts. He suggested that they have a common mechanism powered by accretion, with the ejection velocity being comparable to the escape velocity from the surface of the central star or the inner edge of a surrounding accretion disk and the collimation by a surrounding magnetic field. This may even apply to jets from the nuclei of planetary nebulae, although it is not clear what the source of accreted matter is in that context. Possible jets from pulsars may represent an exception to this general mechanism. Again the images of the Crab pulsar from CXO show a jet-like protrusion that may help our understanding of these issues.

Another lesson is that the jets, especially those associated with black holes, are frequently relativistic. This was emphasized in the reviews of jets from blazars by Urry and of those from the binary black holes in “microquasars” by Greiner. Studies of these relativistic jets on both galactic and stellar scales with time-dependent, multiwavelength campaigns has great potential to teach us about how the jets form, are collimated, and propagate. The stellar cases are especially important because the activity plays out over a shorter timescale and is especially amenable to practical, detailed study.

Some of the greatest interest in jets is the possibility that they play a role in the origin of γ-ray bursts. Jets are discussed as a way of moderating the great energy requirements of the brightest bursts and there is some circumstantial evidence for collimation in the change of slope of some afterglow light curves (Rhoads, 1999; Sari, Piran, & Halpern 1999; Stanek, et al. 1999; Harrison et al. 1999). On the theoretical side, the models of Woosely, MacFadyen, and their collaborators have drawn great interest. These models are computed in the context of a “collapsar” model where a black hole forms by gravitational collapse in the center of a massive star. Rotation could lead to the formation of a disk surrounding the black hole. The disk, in turn, could generate strong neutrino fluxes that might provide an energy source by neutrino/antineutrino annihilation, or it could be the source of an MHD flow. Yet another alternative is that the spin of the black hole threaded by magnetic fields could generate energy by the Blandford-Znajek effect (Blandford & Znajek 1977). In the models discussed by MacFadyen & Woosley (1999), energy from neutrino annihilation is presumed to be deposited as thermal energy in a small region along the rotation axis. In their two-dimensional simulation, the expansion from this point is channeled by the density gradient of the surrounding Keplerian disk and is forced to proceed up the rotation axis. As the density at the jet base declines, thermal energy input at a given rate tends to provide an ever larger specific energy to the matter. The result is to promote the forma-
tion of a relativistic jet that is confined and collimated by the structure of the star. As emphasized by Woosley, the jet will trigger lateral shocks that can cause the outer mantle to explode. Woosley differentiated possible differences between situations involving production of the black hole by prompt collapse or by fallback.

The production of something like a supernova attendant to the propagation of the jet through the stellar core seems unavoidable. The jets made in this way can, in principle, be relativistic, and can, again in principle, yield γ-ray bursts. The open issues are whether collapse leads to jets, the nature of those jets, and the question of whether the jets will lead to γ-ray bursts of observable properties.

E Gamma-Ray Bursts

Fishman summarized the history of the γ-ray burst game and especially the invaluable role of BATSE on CGRO. BATSE had discovered 2612 bursts at the time of the meeting and added one more the evening the meeting ended. The smallest time resolved in a γ-ray burst is 200 microseconds. If interpreted in terms of an intrinsic light crossing time, that corresponds to a distance of less than 60 km. Fishman argued that despite some reports to the contrary, the short bursts are not homogeneous. They display, for instance, $V/V_{\text{max}} = 0.39$, significantly less than the homogeneous value of 0.5. There are also claims for anisotropy, but Fishman did not think those were well substantiated by the data.

Kulkarni summarized the recent history in the BeppoSAX era. Of special interest to γ-ray burst research and to this conference in particular are the recent reports by Bloom et al. (1999), Reichert (1999) and Galama et al. (1999) for supernova-like modulation of γ-ray burst afterglow light curves about three weeks after the γ-ray burst for two cases of classic γ-ray bursts. In the thinking of many people, this increases the already high probability that GRB 980425 was associated with SN 1998bw (Galama, et al. 1998). GRB 980425 does not, however, fit in the context of various statistical studies of, e.g. Schmidt (1999) on luminosity functions, of Ruiz & Fenimore (1999) on correlations of variability with luminosity, and Norris (1999) on energy-dependent phase lags. If SN 1998bw and GRB 980425 were the same event, the γ-ray emission process was very different than the more distant events.

Kulkarni reviewed the valuable radio data that has been obtained on afterglows. He pointed out that the failure to detect radio afterglows in some cases may simply be because the existing equipment, e.g. the VLA, is not sufficiently sensitive. He also reported on the calorimetry of one event, GRB 970508, for which late time radio observations could be modeled to obtain an estimate of the total energy radiated in the afterglow (Frail, Waxman & Kulkarni 1999). The result was $E_{\text{afterglow}}/E_{\gamma} << 1$. This is significant because the most pop-
ular models of internal shocks imply low efficiency (Kumar 1999) and hence a great deal more total initial kinetic energy in relativistic baryons (in synchrotron models) than in emitted γ-rays. The kinetic energy left from the initial γ-ray burst must all be dissipated in the subsequent interaction with the ISM and hence radiated in the afterglow. Taken at face value, this result does not support the inefficient internal shock model. The calorimetry depends on assuming synchrotron emission and hence nearly equipartition magnetic fields. The issue of how, and hence whether, equipartition fields arise in relativistic blast waves is very unclear, as emphasized at this conference by Blandford. More calorimetric information of this kind is clearly needed. Another object that gives some information of this sort is GRB 990123, the famous bright prompt optical burst (Akerlof et al. 1999; Kehoe et al. 1999; Kulkarni et al. 1999). The total fluence in the optical of that burst was substantially less than the isotropic equivalent fluence in γ-rays. On the other hand, a backward extrapolation of the optical afterglow intersects at a point above the prompt flash, so the relative balance of γ-ray burst to afterglow energy is uncertain. Kulkarni also raised the issue of whether the afterglow must be non-adiabatic in contrast with popular models. This could complicate the analysis and alter the energetics and hence the basic constraints on the processes of the γ-ray bursts and afterglows. There are models that avoid the problem of inefficient internal shocks by invoking a collision of the leading shock with the external medium (Fenimire & Ruiz 1999) or by “spotty” internal shocks (Kumar & Piran 1999).

Kulkarni gave a brief summary of what he termed as the indirect indications for a correlation of γ-ray bursts with massive stars, including the location in host galaxies and apparent correlation with star forming regions. He concluded that the data, indirect though it is, points to a collapsar model. This conclusion may be a bit too specific. The evidence points to a correlation with massive, short lived stars, but it contains no direct information on the specifics of the mass of the stars and certainly not whether the event involves the formation of a black hole. To be specific, the data are equally consistent with a massive star that makes a magnetar - a rapidly rotating, highly magnetized neutron star. Theory suggests that magnetars must be born rapidly rotating and must dump a great deal of rotational energy to slow to the long periods observed 10,000 years later in the soft γ-ray repeaters.

Gehrels outlined the exciting future for observations of γ-ray bursts. HETE II is scheduled for launch January 23, 2000 from Kwajalein Island. HETE II should bring the era of afterglow studies from short as well as long bursts and should produce a much higher rate of well-localized γ-ray bursts than BeppoSAX. This will make life for the observers doing ground-based follow-up even more hectic. SWIFT was selected as a MIDEX instrument just after the meeting. It is scheduled for launch in perhaps 2003. A great deal of work and discovery on γ-ray bursts will occur between now and then, but there should be much left for SWIFT to do. In particular, the prospect of
extending the detection to events at redshift of 10 to 20 is extremely exciting for cosmology as well as γ-ray burst research.

Mészáros summarized the theory of γ-ray bursts and their afterglows, so much of which he pioneered before the discovery of afterglows. He remarked that this progress was possible in part because of the fortunate circumstance that the physics of the internal shock region and that of the external shock/afterglow region can be decoupled from the physics of the “machine,” the process/object that actually produces the energy that is transformed into relativistic shocks and γ-rays. The field has developed to the point where, increasingly, this may no longer be true. For instance, depending on the choice of Lorentz factor and energy of the burst, the radius of the photosphere of the fireball could be less than the radius of the bare helium core that is invoked in jet models (Khokhlov et al. 1999; MacFadyen & Woosely 1999). In addition, there are issues, again arising in the context of massive star models, of winds. These high density winds will change the length scale of interactions to produce prompt optical output in reverse shocks and subsequent afterglows by external shocks. The era is upon us when we must begin to consider the machine self-consistently with the γ-ray burst and afterglow.

F Type I X-ray Bursts

Bildsten and Swank summarized the progress made on understanding the Type I X-ray bursts, especially with the invaluable contribution of RXTE which has allowed new insight based both on new data and new understanding of old data. The Type I X-ray bursts are complementary to many of the other objects discussed here in other contexts. Unlike the magnetars in the soft γ-ray repeaters, for instance, which are highly magnetized and rather slowly rotating, the neutron stars associated with Type I X-ray bursts apparently have fast rotation and low magnetic fields. RXTE data of pulses from one source is interpreted as evidence for rotation at 300 Hz. Bildsten described the systematics of nuclear burning on the surfaces of neutron stars and interpreted the data as evidence for a hot spot ignited by a localized thermonuclear flash that is whipped around by the rotation. The lesson that fits in with the general theme of this summary is that the Type I X-ray bursts require asymmetry, rotation, and magnetic fields. Bildsten also outlined the possibility that nuclear burning in this ambiance could break out of the hot CNO and helium burning and run all the way up to heavy elements, including, for instance, species like krypton.\(^1\)

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\(^1\) This caused me to pose the following question: if Type I bursts make krypton(ite), did Jor-el and his son come from a planet orbiting a neutron star?
III POLARIZATION AND JETS IN NORMAL CORE-COLLAPSE SUPERNOVAE

To complement the theme of asymmetry, rotation and magnetic fields, I would like to summarize some work that we have done at Texas over the last five years. Like many people in the supernova community, we at the University of Texas got actively involved in the supernova/soft-gamma-ray repeater/magnetar/$\gamma$-ray burst topic with the advent of SN 1998bw and its possible connection to GRB 980425. We brought a different perspective to this issue because of work we have done on supernova spectropolarimetry.

We have been making spectropolarimetric observations of all accessible supernovae at McDonald Observatory (Wang et al. 1996; Wang, Wheeler & Höflich 1997; Wheeler, Höflich & Wang 1999; Wang et al. 1999). A summary of observations is given in Table 1. The result has been that most Type Ia have low polarization and hence are substantially spherically symmetric. Many have only upper limits of order 0.1 - 0.2%. A few have detected, but low polarization, of order 0.2%. We have obtained the first polarization of a “subluminous” Type Ia, SN 1999by which appears to show polarization at the 0.2% level. The polarization observed is consistent with theoretical models of delayed detonation models (Wang, Wheeler & Höflich 1997) and may be a useful probe of the combustion physics. We have detected one exception, SN 1997bp, which was observed a week before maximum light to have a polarization of about 1%. The polarization was low in post-maximum spectra, but this event remains a challenge to understand. It is important to establish whether such events are common, the physical reason for the large polarization, and whether or not there could be an asymmetric luminosity distribution that could affect estimates of cosmological parameters.

More importantly in the current context are our observations of presumed core-collapse events, Type II and Type Ib/c. We have found that all such events are polarized at about the 1% level and some much more so. So far there have been no exceptions in about a dozen events (a recent Type II, SN 199em, showed no detectable polarization in very early observations (Leonard, Filippenko & Chornock 1999), but further observations are planned that will peer deeper into the ejecta). There could be a myriad reasons for polarization, but our data suggest a very important trend: the smaller the hydrogen envelope, the larger the observed polarization. As examples of this trend, SN 1987A with a 10$M_\odot$ envelope had a polarization of about 0.5% (Méndez et al. 1988); SN 1993J with a small hydrogen envelope, $\sim 0.1M_\odot$, was polarized at the 1-2% level (Trammell, Hines & Wheeler 1993; Tran et al. 1997); a very similar object, SN 1996cb, may show polarization as high as 4%; Type Ic SN 1997X which showed no substantial hydrogen nor helium was polarized at perhaps greater than 3% (Wheeler, Höflich & Wang 1999); SN 1998S which shows characteristics of a Wolf-Rayet star (Leonard et al.
1999; Gerardy et al. 1999) showed polarization of about 3% before maximum (Leonard et al. 1999) and perhaps as much as 4% after maximum (Wang, et al. 1999).

Table 1. Supernovae with polarimetric measurements

<table>
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<th>SN</th>
<th>Type</th>
<th>P(%)</th>
<th>Intrinsic</th>
<th>SN</th>
<th>Type</th>
<th>P(%)</th>
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<td>SN1970G2</td>
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<td>Ia</td>
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<td>SN1983G6,7</td>
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</table>


These are difficult observations requiring special care in the reduction to remove the effects of the ISM (the latter greatly aided by wavelength and temporal coverage). Following Suntzeff’s cautionary notes on the difficulty of doing accurate photometry, Leonard referred to spectropolarimetry as “photometry from hell.” In addition, there is a pressing need to expand the statistical sample, especially with time-sampled data. Nevertheless, this trend suggests that the core-collapse process itself is strongly asymmetric and that evidence for that asymmetry is damped by the addition of outer envelope material.

The level of polarization we have observed for core collapse events, ∼ 1%, requires a substantial asymmetry with axis ratios of order 2 to 1 (Höflich 1995). Asymmetric explosions tend to turn spherical as they expand, so to leave a significant imprint in the homologously expanding matter requires a substantially larger asymmetric input of energy or momentum in the explosion process itself (Höflich, Wheeler & Wang 1999). In other words, the asymme-
tries we are observing require the underlying explosion to be driven by a jet. This conclusion is completely independent of any connection to $\gamma$-ray bursts, but, of course, the potential for this connection is clear (Wang & Wheeler 1998; Wheeler 1999). These factors led us to the hypothesis that the core collapse process is intrinsically strongly asymmetric, much more so than current collapse calculations involving convectively unstable neutron stars. It was in this context that we greeted the news of SN 1998bw and have continued to work on polarization, jet models of collapse, and their possible relation to other astrophysical phenomena.

A SN 1998S

SN 1998S was discovered on March 2, 1998. It showed strong narrow emission lines and is thus characterized as a Type IIn. Some of the narrow emission lines were of high excitation, reminiscent of Wolf-Rayet stars and SN 1983K (Niemela et al. 1985) and subsequently showed emission of carbon monoxide and possible evidence for dust formation that are consistent with an origin in the core of a massive star that is not decelerated by a substantial hydrogen envelope (Gerardy et al 1999). Leonard et al. (1999) were very fortunate to be at Keck II with a spectropolarimeter and got an excellent set of data on March 7, still about 0.5 magnitude and two weeks before maximum. They have interpreted their data in terms of an interaction with a disk of circumstellar hydrogen which also shows up as a double (in fact triple) peaked H$\alpha$ profile at late times. The polarization might have been as high as 3%.

The light curve declined rather rapidly after maximum unlike some Type IIn, so it has been called Type IIn(pec). About 60 days after the explosion (20 days after maximum) it went into a steeper decline and then leveled off to a slower decline about 80 days after maximum. This slower decline is, in V, still a little steeper than expected for $^{56}$Co decay.\footnote{\url{http://oir.www.harvard.edu/cfa/oir/Research/supernova/spectra}} We obtained data on SN 1998S at McDonald Observatory on March 31, about 10 days after maximum and again on May 1, 60 days after the explosion, 40 days after maximum and just before the light curve started to decline rapidly. The McDonald data is consistent with that of Leonard et al. following a locus nearly parallel (but perhaps somewhat shifted) in the Q,U plane. The polarization on May 1 could be as high as 4%.

Polarization of this level forces us to abandon more timid phrases like “asymmetric supernovae.” Recall that the maximum polarization from an infinitely thin, internally illuminated, electron scattering disk is about 12% (Chandrasekhar 1950). On this scale a polarization of 4% is very large. For this event, and perhaps for others with this level of polarization, it is appropriate to talk about “bi-polar supernovae,” not merely asymmetric supernovae with the implication, perhaps, of irregularities rather than large, well-ordered
imprints of basically asymmetric geometry. In principle an infinitely thin, internally illuminated rod could be 100% polarized, but we do not think this geometry corresponds to the observations and the dynamics of the events.

**B Jets and Magnetars**

To explain the polarization data of routine core collapse supernovae, we need an explosion mechanism with a strong, indeed, bi-polar asymmetry that can survive the dynamics of expansion and remain substantial in the homologous phase. We need a jet. To account for normal supernovae we must have jets in routine circumstances, that is, the formation of a neutron star and not restricted to the more rare circumstances of the possible formation of a black hole. This statement is independent of the likelihood that in rare cases or different circumstances such a jet might yield a $\gamma$-ray burst.

The obvious place to look for jets in frequent core collapse events is in the rotating, magnetic collapse of a neutron star with the equivalent dipole magnetic field ranging from “typical” values like the Crab pulsar to the extreme values associated with magnetars and soft $\gamma$-ray repeaters (Kouveliotou et al. 1998). This environment gives a framework in which to quantitatively address questions of physics that are germane to the nature of the core collapse process in general and to potential $\gamma$-ray production. The physics that could be at play in such a collapse has recently been considered by Wheeler et al. (1999).

Rotation and magnetic fields have a strong potential to create axial matter-dominated jets that will drive strongly asymmetric explosions for which there is ample observational evidence in Type II and Type Ib/c supernovae, their remnants, and in the pulsar velocity distribution. The potential to also create strong flows of Poynting flux and large amplitude electromagnetic waves (LAEW) serves to reinforce the possibility to generate bi-polar explosions. These bi-polar explosions will, in turn, affect nucleosynthesis and issues such as fall-back that determine the final outcome to leave behind neutron stars or black holes. In addition, the presence of matter-dominated and radiation-dominated jets might lead to bursts of $\gamma$-rays of various strengths. The issue of the nature of the birth of a “magnetar” in a supernova explosion is of great interest independent of any connection to $\gamma$-ray bursts. Highly magnetized neutron stars might represent one out of ten pulsar births. Production of a strong $\gamma$-ray burst is probably even more rare.

Wheeler et al. (1999) show that the contraction phase of a proto-neutron star could result in a substantial change in the physical properties of the environment. When the rotating, magnetized neutron star first forms there is likely to be linear amplification of the magnetic field and the creation of a matter-dominated jet, perhaps catalyzed by MHD effects, up the rotation axis. The rotational energy of the proto-neutron star is typically about $10^{51}$ ergs. The energy of the proto-neutron star is sufficient to power a significant
matter jet, but unlikely to generate a strong $\gamma$-ray burst. The matter jet could generate a smaller $\gamma$-ray burst as seems to be associated with SN 1998bw and GRB 980425 by the Colgate (1974) shock acceleration mechanism as it emerges and drives a shock down the stellar density gradient in the absence of a hydrogen envelope, e.g., in a Type Ib/c supernova.

As the neutron star cools, contracts, and speeds up, two significant things happen. One is that the rotational energy increases. The energy becomes significantly larger than required to produce a supernova and sufficient, in principle, to drive a cosmic $\gamma$-ray burst if the collimation is tight enough and losses are small enough. For a neutron star with a period near 1 millisecond the rotation energy can be substantially in excess of $10^{52}$ ergs. The rotational energy of the contracted neutron star is radiated away in the form of a Poynting flux or LAEW at the frequency $\Omega_{NS}$. If efficiently utilized and collimated, this energy reservoir could make a substantial $\gamma$-ray burst. The luminosity is estimated to be

$$L_{EM} \simeq 4\pi R_{LC}^2 \frac{c}{4\pi} |\vec{E} \times \vec{B}| \simeq \frac{\mu_{NS}^2}{R_{LC}^4} \frac{c}{e^3} \simeq \frac{R_{NS}^6 B_{NS}^2 \Omega_{NS}^4}{c^3},$$

assuming the LAEW to be generated at $R_{LC}$ and the magnetic moment of the neutron star to be $\mu_{NS} = B_{NS} R_{NS}^3$. For the conditions of the contracted neutron star which has initiated an $\alpha - \Omega$ dynamo, we expect

$$L_{EM} \simeq 4 \times 10^{52} \text{ erg s}^{-1} \left(\frac{R_{NS}}{10 \text{ km}}\right)^6 \left(\frac{B_{NS}}{10^{16} \text{ G}}\right)^2 \left(\frac{\Omega_{NS}}{10^4 \text{ s}^{-1}}\right)^4,$$

which will last for a duration of several seconds.

The second important factor the accompanies the contraction and spin-up of the cooling neutron star is that the light cylinder contracts significantly, so that a stationary dipole field cannot form and the emission of strong LAEW occurs. Tight collimation of the original matter jet and of the subsequent flow of LAEW in a radiation-dominated jet is expected.

The LAEW will propagate as intense low frequency, long wavelength radiation. The LAEW “bubble” could be strongly Rayleigh-Taylour unstable, but still may propagate selectively with small opening angle up the rotation axis as an LAEW jet. Alternatively, the impulsive production of LAEW could render the stellar matter nearly irrelevant as a confining medium. If a LAEW jet forms, it can drive shocks which may selectively propagate down the axis of the initial matter jet or around the perimeter of the matter jet. The shocks associated with the LAEW jet could generate $\gamma$-rays by the Colgate mechanism as they propagate down the density gradient at the tip of the jet or there could be bulk acceleration of protons to above the pion production threshold. The protons could produce copious pions upon collision with the surrounding wind, thus triggering a cascade of high energy $\gamma$-rays, pairs, and lower-energy $\gamma$-rays in an observable $\gamma$-ray burst. Yet another alternative is that the LAEW could
eventually propagate into such a low density environment that they directly induce pair cascade.

The matter-dominated jet requires 5 to 10 seconds to reach the surface of the neutron star, just about the time for the neutron star to cool, spin up and launch the second, faster, more energetic jet. The second, LAEW-driven jet propagating out at nearly the speed of light could thus arrive at the surface of a bare helium core at just about the time of the earlier MHD jet launched when the protostar forms, but which propagates more slowly. The natural time scale for any γ-ray burst is about 5 to 10 sec, the cooling, spin down time for the neutron star, but shorter times scales could be associated with the shock breakout, and instabilities in the LAEW production process or in the flow. The question of what fraction of the pulsar energy goes to drive quasi-spherical expansion and what fraction propagates as co-linear LAEW clearly requires greater study.

Issues of uncertain physics aside, it is clear that this mechanism might not be robust in the production of γ-ray bursts, but might produce γ-ray bursts of varying strength depending on natural variation in the circumstances of a given collapse event. Any γ-rays emitted by any of these processes are likely to be strongly collimated. The luminosity of the emitted radiation will depend on the geometry of that emission. The energy produced by the spin-down of the pulsar could emerge from the stellar surface along the axis of a low-density matter jet, or in an annulus surrounding a high density jet. Either of these cases will give a Lorentz factor that depends strongly on the aspect angle of the observer. Computation of the resulting luminosity is thus distinctly non-trivial.

C Jets and Bi-Polar Supernovae

It remains to be proven that newly formed neutron stars can produce jets. In the meantime, one can study the dynamics of jets and their impact on the stars in which they are generated. A preliminary study in which conditions were selected to represent the sort of MHD jet found by LeBlanc & Wilson (1970; see also Müller & Hillebrandt 1979; Symbalisty 1984) has been presented by Khokhlov et al (1999). This study has been extended to explore a range of jet energies and stellar configurations, both bare helium cores and red supergiants.

The code developed by Khokhlov (1998) is an Eulerian adaptive mesh code based on the Piecewise Parabolic Method. The calculations are fully three dimensional. The adaptive mesh gives excellent resolution. The finest scale corresponds to a uniform grid of some $10^{10}$ cells. The adaptive mesh also allows great dynamic range. For the jet models this ranges from $2^{12} \sim 10^4$ to $2^{19} \sim 10^6$. The imposed jets are cylindrically symmetric and the initial stellar model is spherical. The resulting jets are thus highly cylindrically symmetric, but this is not imposed in the dynamics, only the initial conditions. The jet
dynamics are sufficiently rapid for the models computed that Kelvin/Helmholz instabilities have little time to form.

Figure 1 shows the distribution of the jet matter (unspecified in the computation, but presumably rich in iron-peak elements), and of the oxygen layers of the star. The former reflects the bi-polar nature of the jet flow. The latter shows the effects of the lateral shocks that compress the oxygen into an equatorial shell. This will, in turn, affect the line profiles of the oxygen observed in the nebular phase. These profiles are presented after 4.84 seconds when the jet breaks through the surface of the helium core. They must be followed into homologous expansion before any direct connections to observations can be made.

We have also studied models with red giant envelopes. The code allows us to follow the jet in a single calculation from the center of the star out through the extended envelope. We find that energetic jets can penetrate the hydrogen envelope, but that more modest jets cannot. The latter can still induce an asymmetric, bi-polar explosion.

**IV ISSUES AND PERSPECTIVES**

I will dwell in this final section mostly on issues of the supernova/\(\gamma\)-ray burst connection since that is a topic of such excitement and the one highest on my personal interest scale.

The drive to understand \(\gamma\)-ray bursts must address issues of inhomogeneity. Is the mechanism related to massive stars or not? Is the machine related to neutron stars or black holes or both? When are winds important, when only the ISM as a working surface and catalyst for external shocks? The Lorentz factor \(\Gamma(t, \theta)\) is almost surely a function of time and angle. Another important issue is the degree of collimation. A break in the afterglow light curve can signify that a relativistic jet has slowed to subrelativistic speeds and
is beginning to expand laterally. Alternatively, the interaction of a blast wave with a dense wind can produce qualitatively the same result. This spirit of inhomogeneity has been nicely captured by Chevalier & Li (1999) who have analyzed which events are most likely to have occurred in massive star winds and which have not (see also Frail et al. 1999). Table 2 gives a compilation of the results of Chevalier & Li.

Table 2. Gamma-Ray Bursts and Afterglows

<table>
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<th>Redshift</th>
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<th>Jet</th>
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<td>980519</td>
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<td>ISM</td>
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One of the most interesting issues is whether γ-ray bursts arise in neutron stars or black holes, or both. Black holes almost certainly exist. They are observed in galactic cores and in binary X-ray sources. In addition, black holes make relativistic jets. This is again seen in both active galactic nuclei and in the binary X-ray sources, especially the microquasars. We also know neutron stars exist, and the soft-gamma ray repeaters have provided evidence that magnetars exist. The magnetars may have dipole fields of $10^{14}$ Gauss or more, substantially above the limit where the magnetic field affects quantum electrodynamics. The question of the nature of the birth event of a magnetar is clearly an important one, independent of issues of connections to γ-ray bursts. Another important fact is that all core-collapse supernovae are polarized and that there is growing evidence that the explosion must be, not just irregular, but bi-polar. By demographics, this must apply to events that form neutron stars, not just the more rare events associated with black hole formation.

One issue is then what this circumstantial evidence is telling us about the nature of neutron stars and black holes and their possible relation to γ-ray bursts. Table 3 gives some features of the astrophysical events we are attempting to relate, as discussed by various speakers at this meeting. Urry noted that blazars never drop below 1% of the peak flux during fluctuations, whereas some γ-ray bursts have gaps with no detectable flux. Livio characterized jets as arising from conditions with $v_{\text{jet}}/v_{\text{esc}} \sim 1$, a condition clearly related to the value of $\Gamma$ in the jet.

Table 3. Properties of Black Hole Systems and Gamma-Ray Bursts
One of the suggestions from Table 3 is that, left to their own devices, black holes produce relativistic jets, but they do not, in the context of AGNs and microquasars, produce the highly relativistic flows thought to occur in γ-ray bursts. This may mean that black holes cannot produce γ-ray bursts or it may mean that the circumstance of a black hole in a γ-ray burst system must be substantially different. One possibility for the latter is that the black hole can not be in a relatively isolated environment, but must, for instance, be surrounded by baryons, by a star, to help focus and amplify the flow to very high Lorentz factors. Another point is that there is some tendency to think that the canonical γ-ray energy of a γ-ray burst is about $10^{52}$ ergs with higher apparent energies being due to collimation. If this is so, then the possibility of a neutron star generator is still alive. Possibilities are the collapse of an iron core and the birth of a magnetar, accretion induced collapse, or the merger of two white dwarfs. On the other hand, if the production of γ-rays is inefficient and substantially more than $10^{52}$ ergs of total energy is required, then the possibility of a neutron star progenitor will die.

SN 1998bw continues to play a large role in the on-going debate concerning the supernova/γ-ray burst connection. A comparison of the properties of “normal” hydrogen and helium deficient Type Ic supernovae and the peculiar SN 1998bw is instructive. Type Ic are polarized. SN 1998bw was polarized. Type Ic probably require a jet-like flow of energy and matter to produce a bi-polar explosion. So does SN 1998bw. Routine Type Ic presumably leave behind neutrons stars. The speculation is that SN 1998bw left a neutron star or a black hole. The current evidence is mute on which. Routine Type Ic require about $10^{51}$ ergs of kinetic energy. SN 1998bw requires $\gtrsim 10^{52}$ ergs if the explosion was spherical. We know the explosion was not spherical, so this energy estimate is somewhere on the continuum from uncertain to misleading to wrong. If the explosion produced a photosphere with a 2 to 1 axis ratio, then, with proper aspect of angle of the observer, it might require only $\gtrsim 10^{51}$ ergs (Höflich, Wheeler & Wang 1999). One can also argue that this value is on the same continuum from uncertain to misleading to wrong until quantitative non-spherically symmetric radiative transfer is done. Even if energies in excess of $10^{52}$ ergs are required for SN 1998bw and other events, this does not necessarily mean they made black holes. This energy is certainly in the range that could come from tapping the rotational energy of a new neutron star.

Another important issue is to begin to consider the γ-ray burst and after-

<table>
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<th>Object</th>
<th>$\Gamma$</th>
<th>$L/L_{Edd}$</th>
<th>$L_{interpulse}$</th>
<th>$v_{jet}/v_{esc}$</th>
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<td>blazar</td>
<td>$\sim 10 - 20$</td>
<td>$\sim 1$</td>
<td>$\gtrsim 1%$</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>microquasar</td>
<td>$\sim 10$</td>
<td>$\sim 1$</td>
<td>$??$</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>γ-ray burst</td>
<td>$&gt; 100$</td>
<td>$\gtrsim 10^{12}$</td>
<td>sometimes $\sim 0$</td>
<td>$c - \epsilon$</td>
</tr>
</tbody>
</table>
glow mechanisms self-consistently in the context of the “central machine” and its environment. Specifically, there are issues that must be faced in contemplating an origin of γ-ray bursts in massive stars. The star is there, and so, presumably, is the dense wind such stars are expected to shed. Consideration of the star and wind will affect the development of the γ-ray burst in a relativistic “impulse” or “wind” and the density of the environment must affect the length and time scales over which the afterglows are produced.

The production of shocks and radiation surely depend on the manner in which the energy is delivered. In the currently most popular model for γ-ray bursts and afterglows, a large kinetic energy is produced in a relativistic wind that either has irregularities imposed on it from the “machine” or develops irregularities by instability in the flow. These irregularities produce “internal shocks” and the γ-rays. The residual kinetic energy propagates into the external medium to produce an “external” shock and the afterglow. A possible alternative is that energy is delivered, for instance at the outer boundary of a helium core rather than from near the last stable circular orbit of an isolated black hole, by a strong Poynting flux. This Poynting flux could lead, via pair formation, directly to γ-rays. The residual energy of the pairs would then be needed to power the afterglow. The difference in these two processes might be substantial. For instance, Usov (1999) has pointed out that in a strong Poynting flux, internal shocks are impossible because there can be no relative motion of the advected particles. Another issue as he expressed it in this meeting is the “Blandford Anxiety,” the origin of the nearly equipartition magnetic fields that are invoked and/or derived in these models. An intense Poynting flux could deliver the magnetic field directly to the environment where a γ-ray burst is triggered, if not in the larger region of the afterglow.

The bottom line is that the near future of the study of cosmic explosions, like the recent past, is likely to continue to make our heads spin. The objects we study not only spin, they are magnetic and asymmetric. Coping with that should lead to great insight and progress.

ACKNOWLEDGMENTS

I am grateful to the organizers for the invitation to the meeting and an excellent scientific program and to all the speakers for holding my attention through the whole conference. Special thanks go to the staff for ensuring that the meeting arrangements went smoothly and to the students who toted the microphones around the hall so we could all be heard. I am especially grateful to my colleagues Peter Höflich, Lifan Wang, Alexei Khokhlov, and Elaine Oran who have taught me so much about explosions on and off the Earth. This research was supported in part by NSF Grant 9818960 and a grant from the Texas Advanced Research Program.
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