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Epilogue

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The preceding fourteen chapters have been written at a good time to take stock of the field of Gamma Ray Bursts (GRBs). The extraordinary discoveries made over the last decade or so about a phenomenon that has been around for over four decades seem to have attained a mature state. Thousands of bursts have been observed, classified and followed up and it is now the special and rare cases, that are extreme by some important measure, that are most likely to advance our understanding as radically new $\gamma-$ray and X-ray observing capabilities are at least a decade away. On the theoretical front, some prescient inferences have been vindicated, phenomenological models that are usable by observers have been developed, and simulation has made great strides. The greatest challenge is to explore the underlying physical processes in much more detail and this is likely to require a new generation of high performance computers. Nonetheless, the GRB pace of discovery like much of contemporary astrophysics will likely exceed that in most other subfields of physical science.

I was asked to write a critique of where we are today and what I think will be the major developments going forward. My qualifications for this task are not promising. I have probably contributed most to the study of a high energy $\gamma-$ray stellar phenomenon unintentionally in the context of trying to explain variability of the lowest frequency radio emission from active galaxies and my largest attempt to work on what I thought was relevant turned out to be only applicable, at best, to X-ray bursting neutron stars. So, fortified by amnesia and presumption, let me start with a personal summary of the history as recounted with far more authority in the preceding chapters [1-6]. (I will designate the relevant chapter numbers with square brackets.)

15.1 Observation

The discovery of GRBs in the late 1960s is a fascinating and disturbing tale. Fascinating, because they showed up in searches for unannounced nuclear tests [1]; disturbing, given this context, because I have clear memories of listening to Soviet and American scientists argue furiously about the interpretation of their data. Theorists explored options located from within the heliosphere to beyond the quasars and showed such imagination that, I was once told, they were called upon to devise alternative explanations for a supposed, real, terrestrial nuclear explosion. Many hundreds of interpretative papers were written. The optimistic, if anti-Okhamist, viewpoint was that every one of them was correct for one burst! Still some options were left unexplored, most famously, comets of anti-matter falling on to white holes as suggested by Mal Ruderman in an otherwise comprehensive and spot on review of the options at the 1972 Texas symposium. (I recall of being present at a lunchtime conversation between Tommy Gold, Martin Rees and Ian Strong at the AAS meeting in San Juan in 1971 where they, too, laid out the choices quite clearly.)

15.1.1 BATSE and BeppoSAX?

Although cosmological explanations had been entertained right from the start, they were disfavored because of the unprecedented powers and outflow Lorentz factors and, especially, because the *Ginga* satellite reported cyclotron lines consistent with Galactic neutron stars as the source [2]. The situation changed in 1991 when the Burst And Transient Source Experiment (BATSE) on Compton Gamma Ray Observatory (*CGRO*) [3] was used to discover that the sky distribution of bursts was isotropic. This jolted the argument back towards extragalactic sources although halo models were still much discussed. BATSE also made clear that there were at least two types of GRB. Those with $\gamma-$ray durations more than two seconds and soft spectra and those with shorter durations and harder spectra [7]. Related phenomena, Soft Gamma Repeaters (SGR) and X-Ray Flashes (XRF) were also distinguished and studied [11].

Dramatic progress on the nature of GRBs came when the ingenious *Beppo-SAX* satellite, launched in 1996, allowed some bursts to be identified through their X-ray afterglows and distanced [4]. It became incontestable that most bursts were cosmological and Bohdan Paczyński's and others prescient views were vindicated. Furthermore, long bursts were found in regions of rapid star formation and soon some were associated with relativistic jets created in funnels that form along the rotation axes of a minority of core collapse supernovae, those that had lost hydrogen and perhaps helium envelopes. Less evidence was uncovered concerning the nature of short bursts but they were most commonly assumed to be associated with a neutron star binary coalescing due to the emission of gravitational radiation, largely because these events were known to occur at a similar rate to short GRBs and were expected to be powerful emitters of high energy radiation. This was supported when they were found located away from star-forming regions.

Afterglows were explored in detail using a rapidly expanding database of observations. It was deduced that the emission originated from the (relativistically) shocked circumstellar medium and was largely independent of the nature of the explosion. There were several lines of evidence that the outflow was mainly confined to a pair of jets - VLBI imaging, achromatic jet breaks seen first in optical monitoring and isotropic energies in excess of a stellar rest mass [6, 11].

The interpretation of afterglows [6,8] gave a context for explaining the prompt $\gamma-$ray emission as being caused by internal shocks in a baryon-dominated, ultrarelativistic, outflow with characteristic Lorentz factors ~ 100, emerging from a collapsing stellar photosphere [10]. Self-consistent, if *ad hoc*, models based upon the synchrotron and Compton processes were proposed and shown to be able to account for the observed spectra, which had to be strongly Doppler-boosted [8].

15.1.2 Swift and Fermi

The launch of *Swift* in 2004 greatly increased the number of bursts that could be studied in detail [5]. It consolidated the broad features of the long burst model, especially through identifying and studying the host galaxies [13], but showed that many bursts did not conform with this simple taxonomy and that the temporal evolution of both the prompt emission [7] and the afterglow [8] was far more complex and varied than had been appreciated and the taxonomy correspondingly richer. Tantalizing correlations of burst properties have remained controversial. *Swift* also demonstrated that short bursts could remain surprisingly luminous for many minutes which was not expected from a neutron star coalescence. Swift also pushed the redshift limit beyond $z = 8$ encouraging a belief that GRB might become a powerful probe of the very first stars in the Universe [14].

Finally *Fermi* was launched in 2008 and demonstrated that a minority of bursts emitted fairly prompt photons with energies in excess of 30 GeV. These indicated outflow Lorentz factors over a thousand in these cases so that pair production could be evaded [11]. The prompt arrival of these photons was used to demonstrate that high and low energy photons do, indeed, travel with a common speed which was reassuring to many and disappointing to a few [12].

15.1.3 New astronomy

What is clear from this brief summary is that understanding came fast after the launch of *CGRO* through the exploitation of new observational techniques. This was an impressive demonstration of the power of "multi-wavelength" and "time domain" astronomy with space and ground-based observatories working together and a remarkable accomplishment involving many groups collaborating, cooperating and competing [6,7,8]. The transformation of a field from one based largely upon incorrect speculation to one with a secure observational foundation was every bit as exciting as the nearly contemporaneous transformations that occurred in the study of exoplanets and cosmology.

15.2 Theory

Theoretical astrophysicists typically have considered GRBs differently from observers. Initially, they saw them as exercises in reverse astro-engineering, as challenges to understand how conventional basic physics could account for their extraordinary powers and rapid variability. Theorists developed the basic models outlined above [5, 7, 10, 11]. Much of this research was phenomenological and dependent upon simple prescriptions and parameterizations of physical processes like particle acceleration and field amplification that are not at all understood, in order to account for the prompt emission and the afterglows.

15.2.1 Gravity

However, before long, GRBs were recognized as opportunities to illuminate and elucidate great questions of relativistic gravity, astrophysics and cosmology. In addressing gravitation, theorists have mostly adopted general relativity and one of its crown jewels, the Kerr metric. (While most interpretations have GRBs heralding the birth of spinning black holes, even if the prime mover turns out to be a millisecond magnetar, unsolved problems in general relativity are highly relevant [11].) GRBs were then viewed as opportunities to exhibit properties of general relativistic black holes rather than as providing an arena where quantitative tests of the underlying theory can be performed. A key issue is the efficiency of energy extraction. Here, there are several channels: gas dynamical, radiation dynamical, electromagnetic, neutrino and gravitational radiation. These channels can be found in the context of models involving binary companions, accretion disks, single black holes and single neutron stars. There were many options to work through. Much progress eventually came from impressive two- and three-dimensional, high resolution numerical simulations, including general relativity, magnetic field and radiative transport [10]. In addition kinetic, particle in cell calculations gave important insights into the microphysics (e.g., Sironi & Spitkovsky 2009).

15.2.2 Astrophysics

The opportunities that GRBs offer for further astrophysical discovery have not been ignored. In particular the remoteness of the site of $\gamma-$ray emission from the source of the energy, has stimulated interest in three non-electromagnetic channels. The first of these is Very High Energy neutrinos, which was partly responsible for the construction of facilities like *IceCube* [12]. To date, no VHE $\gamma-$ray detections have been made but the sensitivity is such that a discrimination between hadronic and electromagnetic models is possible. The second is gravitational radiation and high frequency detectors like Advanced *LIGO* (Abbott et al. 2009) are expected to come on line in 2015. These should have the capacity to detect neutron star coalescence, perhaps ten per year, although it may take some luck to see as far as a short GRB. The third is less direct. Ultra High Energy Cosmic Rays with energies at source nearly as high as one Zeta electron Volt (160 J!) [12], are now much better measured and characterized. Acceleration of particles to these colossal (home run!) energies requires sources with quasar-like powers and, to some, GRBs are the most likely culprits [14]. Theorists have been very active exploring the many possible connections between these three major experimental endeavors and the study of GRBs

15.2.3 Cosmology

The report of a $z = 8.2$ GRB rekindled hope that they could be used as standard candles to perform cosmography and supply empirical measurements of the properties of dark energy [14]. This was not so unreasonable given the improbable success of SN Ia in this role. However, few still believe that this will be realizable especially given the advances already made using competitive techniques. More promising is the use of the first GRBs - precocious children of the very first stars to form in the Universe - to elucidate how the dark age ended (e.g., Morales & Wyithe 2010, [14]). This is still an area that is in great need of observational data as numerical simulations lack the resolution to compute the initial stellar mass function and the percolation of the ionizing photons through the clearing universe. However, the impressive progress in low frequency radio astronomy using arrays like *LOFAR* (Ter Veen et al. 2011) suggests that it is the search for the redshifted hydrogen line that is the more likely to win the race to specify the redshift when most of the reionization occurs. However, despite this, high redshift GRBs are proving to be useful, alongside Active Galactic Nuclei (AGN), through probing the absorption of γ ray and ultraviolet photons as they propagate through background radiation and intergalactic gas ([14], Abdo et al. 2010). Finally, GRBs have been used to demonstrate that γ rays of different energy really do travel at the same speed, that of light, supporting Lorentz invariance and in contradiction with some rather simplistic models of quantum gravity. This issue has become more conspicuous with the report of a “superluminal” neutrino velocity by the *OPERA* collaboration, a potentially exciting result that awaits confirmation by other collaborations (and theorists!) (http://operaweb.lngs.infn.it/).

15.2.4 Retrospective

In many respects, modeling GRBs has borrowed heavily from earlier experience in cosmology and the study of AGN. From the former came the theory of radiation hydrodynamics and our rapidly developing understanding of the connection between the evolution of galaxies and the births and deaths of the stars they host; from the latter we have adopted relativistic kinematics and gas dynamics, black hole astrophysics and rudimentary ideas about particle acceleration at relativistic shock fronts. Some lessons were learned quickly, others took much longer and some have yet to be absorbed but the debt has surely been repaid. To cosmologists, GRBs may yet turn out to be extraordinary tools, to the AGN community they offer a view of physical processes in relativistic jets produced by black holes and moving with ten times larger Lorentz factor, observed over length and timescales measured in trillions of gravitational radii of the underlying compact sources as opposed in millions in the case for AGN.

One field, which has had a more nuanced impact on the study of GRBs, has been the theory of advanced stellar evolution of massive stars. Part of the reason has been that we still do not have a well-accepted understanding of how a supernova explosion actually works. However, we do know how massive stars evolve and, with so many more events to observe, we have started to chronicle the "deviants" which may produce GRBs. Reconstructing the various evolutionary narratives through the vagaries of mass loss, angular momentum transport, and dynamical metastability, is turning out to be an important exercise [10].

15.3 Questions

There is much more that is knowable about GRBs. The exploitation of these new "messengers" - VHE neutrinos, gravitational waves and UHE cosmic rays or the careful monitoring of a single burst, fortuitously observed, may transform our understanding and convincingly rule out many current models. On the theoretical front, simulations, interpreted carefully, have the capacity to change several paradigms. I will now try to express some of this potential by discussing some key questions where I suspect that great progress may be made by the end of the decade.

15.3.1 Does a GRB herald the birth of a black hole?

In the earliest discussions of GRBs in the 1970s, it was widely suspected that the prime mover of a GRB was a neutron star or black hole. At first neutron stars seemed the more relevant as local models were pursued. In this case the energy release is primarily electromagnetic due to currents that cross the magnetic field lines within the star and exert a torque if the star is spinning, and release a stress if it is not. However, with the realization that most GRBs are cosmologically distant, the concern that the total energy release from a neutron star might be inadequate to account for the most energetic bursts shifted the argument towards black holes being the prime movers of GRBs. With the subsequent acceptance that GRBs were beamed so that energies of a thousandth the rest mass of a neutron star might suffice in most cases, and that short bursts are intrinsically less powerful, this is now less of an issue. However, there are other factors that could distinguish black holes from neutron stars.

15.3.1.1 Efficiency

Even though there are many important differences, the study of AGN assures us that black holes can release the rest mass energy of accreted gas with high efficiency, $\sim$ten percent. (The best demonstration of this proposition comes from a comparison between the total radiant energy of quasars and the masses of their dormant, massive black hole corpses, Soltan1982, which leads to efficiency estimates of order a tenth.) If a GRB is associated with the growth of a black hole to a mass of ∼10 solar masses, then this efficiency should be ample. By contrast, in the case of a neutron star, a very real concern is that thermal effects may render its effective radius much greater than ten gravitational radii so that the rotational kinetic energy as well as the stored magnetic energy, compliant with the virial theorem, is energetically inadequate for long bursts. So, other things being equal, this would seem to point to black holes. What is important, though, is that we could imagine a new generation of three-dimensional MHD numerical simulations of core collapse supernovae with sufficient resolution and enough of the relevant physics, including especially neutrino and photon transfer, to make this case solid [10].

15.3.1.2 Rarity

We know that GRBs are a small minority, perhaps one in ten thousand, of all supernovae. By comparison, forming a black hole or a magnetar seems to happen at a rate that is about one percent of the supernova rate. Two additional factors could apply under either hypothesis to reduce the rate to the long GRB rate. Firstly, it is probably necessary to lose the outer hydrogen and helium envelopes of the star. This is believed to have happened in broad-line SN Ic which account for about one percent of all supernovae [10]. (The star would now be not much larger than the sun $\sim 10^{11}$ cm in radius. A jet that had to plow through the much more tenuous and distended helium and hydrogen envelopes might just make a very dull mushroom cloud.) Secondly, it may be necessary that the collapsed core be rotationally supported in order to create a GRB. In this case, the specific angular momentum of the collapsing gas should be just above the maximal angular momentum of the central object. Too little angular momentum, as current understanding of mixing and mass loss suggests, is the norm, will only produce a slowly spinning hole or neutron star; too much will create too large a disk that evolves too slowly. A further condition may be that the metallicity of the star be low, but the observational position here is unclear. Simulations showing which conditions do (and do not) produce ultrarelativistic jets in combination with observations, especially learning how to identify a star just before it explodes and infer its size and rotation, could transform this debate.

15.3.1.3 Wide field telescopes

LSST, which should be fully operational by the end of the decade, promises to be especially useful in this regard, especially if its observing sequence can be re-ordered to accommodate especially strong gravitational radiation signals (Abell et al. 2009). (*Pan-STARRS* is already providing a preview of what will be possible.) As the probability that *LSST* observes any GRB as it happens is $\sim 10^{-4}$, we will have to be a bit lucky to catch even one GRB *in flagrante delicto* over a ten year lifetime. However, observing several bursts a few minutes old is to be anticipated and a protocol will need to be negotiated to handle this. In addition, having a record of the pre-burst behavior of all identified, nearby southern hemisphere supernovae and GRBs with a few days cadence will be invaluable and may lead to pre-supernova or better still, pre-GRB signatures in the optical that can be sought over the half the sky. (*LSST* should have a reach for the purposes of seeing luminous GRB precursors comparable to that of Advanced *LIGO*; its high photometric accuracy should make it especially useful for detecting binarity.) If this is successful and we may learn how to anticipate supernovae and GRBs, then we can dream of observing them throughout the electromagnetic spectrum with the most powerful telescopes available. In particular, it will be very helpful if we can measure, bolometrically, the radii of pre-supernova and pre-collapsar stars. Analogous remarks apply to the retrospective and triggered study of supernovae and GRBs using *LOFAR*, conceivably complemented by *CCAT*. Radio/millimeter precursors seem less likely but are not impossible and we will have the opportunity to see if they are there.

15.3.2 Is spin important?

If we accept on these tenuous grounds that the prime mover is an accreting black hole, we still need to determine if the black hole spin is important. Spinning holes have three attractive features - they release more energy from accreted gas, they can contribute their own rotational energy and they define funnels to launch jets.

15.3.2.1 Efficiency of disk accretion

The efficiency of energy release through disk accretion can be nearly an order of magnitude greater per unit mass when the hole spins rapidly (e.g., Rees 1984). However, the energy liberated by the gas flowing through the disk must be released at a rate at least several billion times the Eddington limit. As has been argued elsewhere (Blandford & Begelman 1999), the consequence may not be that the energy be advected across the horizon but that it be carried off, one way or another, in a wind. This wind can provide a cocoon of outflowing gas that can protect the true ultrarelativistic jets from frictional interaction with the surrounding stellar envelope (at least in the case of the long bursts).

15.3.2.2 Rotational energy of hole

The spin energy of the hole itself is also available for powering the jets. Not only is this quantitatively appealing as up to 29 percent - more plausibly ten percent in practice - of the hole mass is available, it is also qualitatively reasonable because a classical black hole event horizon has an infinite work function and the only baryons likely to be present in the outflow should be limited to those that can diffuse in through the jet walls. A comparatively low baryon content in the outflow is a pre-requisite for a high terminal Lorentz factor [7, 11].

15.3.2.3 Funnels

A thick, radiation-dominated disk in a high spin Kerr spacetime naturally creates a pair of well-defined funnels close to the hole that can channel jet outflow. The shape of the funnel walls depends upon the manner in which angular momentum is transported and energy is dissipated.

15.3.2.4 Simulations

In order to put some flesh on these assertions based upon analytical models, it is necessary to carry out simulations. The results to date are encouraging. Time-dependent numerical relativistic MHD models, with a capacity to handle the boundary conditions at the event horizon as well as the less organized disk flow, have been run for thousands of dynamical times. After the transients have died away, the jets that form are persistent, exhibiting non-destructive, mainly helical instabilities. The jets propagate at least as far as $\sim$1000 gravitational radii with ultrarelativistic terminal velocity (e.g., McKinney & Blandford 2009). More recent simulations show high efficiency and a high speed disk wind when there is an abundant gas supply. Clearly much remains to be done but the viability of spinning black holes as GRB power sources seems to have been demonstrated. If current indications are substantiated, and it is possible to understand physically in more detail how and when ultrarelativistic jets are created, then it will be necessary to see if Schwarzschild holes can also create similar ultrarelativistic jets.

15.3.2.5 Active galactic nuclei

Many of the debates about the nature of GRBs have recapitulated similar debates concerning Active Galactic Nuclei (AGN) and X-ray binaries. The importance of black hole spin in the powering and formation of ultrarelativistic AGN jets is still undecided though we do know that many active black holes are spinning rapidly. Central to this discussion is the matching of AGN type Broad Absorption Line Quasar, Fanaroff-Rile (*e.g.,* Blandford 1990) type I radio galaxy and so on to the mass, mass supply rate and spin, as well as the environment and the viewing angle (e.g., Krolik 1998). A clear and well accepted set of matches could well inform the analogous discussion of GRBs.

15.3.3 What is the long and the short of it?

The first instincts of a scientist are invariably taxonomic, to assemble data on examples of some common phenomenon and to seek patterns that can be used as a basis for classification. Astronomers are fond of classes, populations and whimsical descriptors. However, as has been famously stated for GRBs, "When you have seen one GRB, you have seen one GRB". In other words the phenomenon "Gamma Ray Burst" almost defies any classification and now appears to include many quite different physical processes. In this sense GRBs are like main sequence stars and supernovae where the original optical spectroscopic typing has proved to be spectacularly inappropriate from the point of view of the underlying physical processes. In particular, we now know that the Soft Gamma Repeaters once classified as a type of GRB - are nearby magnetar explosions. In addition, we are not sure whether XRF and SN 1998bw = GRB980425 are feeble GRBs, off-axis GRBs or something qualitatively different [7].

15.3.3.1 The two second divide

Given this challenge, it is then somewhat remarkable that one early correlation (Kouveliotou et al. 1993) has stood the test of a much larger sample. Bursts that last longer than $\sim 2\,\mathrm{s}$ are systematically, spectrally softer than those with shorter duration. As is generally assumed, this points to at least two physical origins, most commonly a special collapsar for the long bursts and a merging neutron star for the short ones. However, there are also many exceptions, for example long bursts that cannot have associated supernovae or lack infrared afterglows. These have been argued to contradict the collapsar-merger dichotomy. This seems to be a suspect methodology. It would be remarkable if all "collapsars" produced γ ray displays that lasted longer than some fixed time given the strong relativistic beaming, and the intrinsically unstable fluid flows that are argued to underly the emission. It now seems more useful to define GRB classes that are based upon several criteria, such as energy spectra, location and beaming, simultaneously rather than just the duration. This approach is likely to be rather subjective, as is the case with the morphological classification of galaxies and AGN but, at least in these instances, it does work. It may be the best way to decide if we are observing more than two fundamentally different types of explosion.

15.3.3.2 Neutron star mergers

So far, I have implicitly emphasized collapsars. However, the “short” bursts may turn out to be the more interesting because of their potential connection to gravitational radiation. The circumstantial evidence that we are witnessing a quite different mode of black hole formation via a neutron star binary in short bursts is really not very strong. However, we do know that these cataclysms must happen. We have seen a handful of much longer period binaries and understand their dynamics with exquisite precision. Nothing can stave off their fate in of order a hundred million years and the inferred merger rate makes them credible short bursts. Binary neutron stars are akin to double degenerate white dwarf systems, which are, once again, seen as candidate progenitors of SN Ia (e.g., Ruiter et al. 2010). Double degenerate mergers are inevitable while models based upon single stars require some fine-tuning to be viable.

15.3.3.3 Observational evidence and prospects

In addition, short bursts, which are closer (and shorter!), appear to be at least an order of magnitude less energetic than long bursts and, perhaps, less beamed as might be expected. The observation of X-ray precursors for a few short GRBs is broadly consistent with this interpretation. Typically what might be expected is that the lower mass neutron star will fill its Roche lobe first and transfer mass onto it companion releasing a lot of power in the process. This will actually lengthen the time to merger and the timing of the X-ray harbingers is not unreasonable if the mass ratio is significantly different from unity. (Note that there may be an interesting class of mergers where the mass transfer onto the more massive star might allow it to exceed its Oppenheimer-Volkoff mass prior to merger.) Finally, merging neutron stars are appealing sources of r-process elements and the details may present some indirect measurements of merger rates.

The best prospects for a breakthrough surely lie with Advanced *LIGO*, which could detect a signal from an inspiraling neutron star. (The prospect of detecting gravitational signatures of core collapse of single stars seem weaker though this is still well worth the search.) Already we know of several short bursts with $z \sim 0.1$ that ought to have been within the advanced LIGO range of several hundred Mpc. Knowing the position and timing greatly improves the sensitivity, of course. The direct gravitational positional accuracy will be several degrees and the need for more precise directions from coincident electromagnetic signals is clear. Currently, *Swift* provides many of the identifications. Needless to say, it is imperative that it be kept operational for as long as possible and supported by telescopes like *SVOM* (http://www.svom.fr/svom.html) and *UFFO* (http://uffo.ewha.ac.kr/).

A rather more challenging observation involves the interval between star formation and the merging of neutron star binaries. If this really is $>$ 300 Myr, as many authors have suggested, then the first short GRBs in the universe should not appear too early. If, for example, the first massive stars appear only at $z \sim 10$, short GRBs should not appear till $z < 7$ according to this arithmetic. Of course, as short GRBs are less powerful than their long counterparts, this measurement will require an improvement in sensitivity.

15.3.3.4 Plausibility arguments

The combined mass of the merger product exceeds the maximum mass of a neutron star and the combined angular momentum will exceed the maximum spin for a black hole of this mass. This makes it highly likely that a small fraction, perhaps 0.1 solar masses, will be cast off as a disk orbiting the hole as simulations corroborate (e.g., Rezzolla et al. 2011). The disk will radiate, just like the disk forming inside a core collapse supernova. However the radiation above the poles of the black hole may be lower than with a collapsar, and the outflow perhaps less energetic. The absence of the inertia of the infalling stellar envelope will presumably lead to less collimation and the loss of a stellar photosphere will allow the γ rays to escape sooner and the jets to create higher energy particles. Qualitatively, the principle features of the short bursts can be reproduced in this interpretation and again, numerical simulations seem to back this up.

15.3.3.5 Star formation

The long/short association with collapsars/mergers is supported by the realization that the long bursts are mostly associated with star forming regions while the shorter bursts are more broadly distributed ([13], Berger 2009). There are two factors that might depend in subtle ways upon the prior stellar evolution. Firstly, the formation of the second neutron star could happen with a range of initial semi-major axes and eccentricities and consequently with a range of merger times. Secondly, the formation of either neutron star, but especially the second can impose a strong kick on the binary system which may send it far away from its motherland even if the merger time is short. More measurements of proper motions of binary pulsars should help sort this out. Future pulsar searches are likely to find many more binaries and it may be possible to see if the distribution in eccentricity and period is consistent with them all having a long period formation or if there are significant numbers formed with shorter periods. More big telescope spectroscopy on the host galaxies of short bursts is well motivated and should lead to more secure redshifts and a better estimate of how near the closest ones ought to be.

15.3.3.6 Black hole-neutron star binaries

There has been some discussion of this possibility (e.g., Etienne et al. 2009). Today it does not seem so well motivated as an explanation of GRBs because it is presumably much rarer than the two neutron star configuration and any energetic advantage it might have now seems unnecessary. However, we hope to learn much more using *LIGO*. If short GRBs are all black hole-neutron star binaries, then it would beg the question of what happens to the binary pulsars.

15.3.3.7 Supernova remnants

Another clue may come from finding "orphan" supernova remnants, analogous to orphan afterglows. These ought to be far more common than GRBs themselves. Furthermore, they should show a distinctive morphology with two diametrically opposed holes punched out by the jets projected onto the sky if the supernova remnant is young enough and the jet powerful enough (Reynolds 2008). (Unfortunately W50/SS433-like objects would look rather simila; Margon 1984.) Perhaps as many as a percent of supernova remnants have this provenance. It would then be important to see if they do or do not have central neutron stars.

15.3.4 Are GRB jets radiation-dominated?

In the fireball model, as adapted to collapsars, it is supposed that the infalling gas has sufficient angular momentum to create a dense, centrifugally-supported funnel above a spinning black hole and that the radiation-dominated fluid flows along the channel and eventually punches out through the star to emerge in anti-parallel directions along the spin axis. Although this channel will take a few seconds to form, it should remain open for longer and allow a quasi-stationary jet outflow to develop.

15.3.4.1 Stationary flow

It is helpful to review some fundamental points. Consider, first, a source of radiation at the apex of a completely evacuated channel with minimum area $A_0 \sim 10^{12}$ cm^2 with specularly reflecting walls. A photon emitted by the source will emerge at the end of the funnel with the same energy as it started, perhaps $\sim 3kT_0 \sim 10\,\mathrm{MeV}$ characteristic of the central temperature exhibited by models and actually observed in SN1987a and well above the "Band" energy $E_0 \sim 100 - 400\,\mathrm{keV}$. However, this is not what happens. Instead, the radiation will quickly thermalize and equilibrate with electron-positron pairs with 1.5 times the number density and 1.75 times the energy density so that the scattering optical depth at the apex will be $\tau_\mathrm{T} \sim 10^{12}$. The gas will behave like a fluid with pressure a third the energy density. The photon and lepton distributions will be thermal and isotropic in some local Lorentz frame moving along the jet. In this case an adiabatic outflow, with power $L \sim 4P_0A_0c/3^{1/2} \sim 10^{51}\,\mathrm{erg\ s}^{-1}$, will decompress from a starting core pressure $P_0 \sim 10^{28}\,\mathrm{dyne\ cm}^{-2}$ to an envelope pressure $P^* \sim 10^{16}\,\mathrm{dyne\ cm}^{-2}$. (These numbers are quite model-dependent and only illustrative.) The mean photon energy in the co-moving frame will decrease to $\sim (P^*/P_0)^{1/4} \sim 10\,\mathrm{keV}$, while the bulk Lorentz factor is $\Gamma^* \sim (P^*/P_0)^{-1/4} \sim 1000$ so that the observed photon energy, roughly the product of these quantities is little changed after all. An observer located along the funnel axis would "see" quasi-thermal radiation from the stellar core. The next complication is that when the radiation temperature falls below the electron rest mass, the equilibrium pair to photon ratio will decline $\sim e^{-500/T(\mathrm{keV})}$. This will happen adiabatically so the photon temperature will be ~1.4 time larger than it would have been if the pairs had not annihilated, a relatively unimportant correction.

15.3.4.2 Baryons

Next, add some baryons at the start of the flow and conserve their discharge so that the entropy per baryon σ is also conserved along with the power. Eventually, the relativistic internal energy density will be dominated by baryons of rest mass m_b (not necessarily the proton mass) and the Lorentz factor will saturate at a value $\Gamma \sim (kT_0/m_\mathrm{b}c^2)(\sigma/k)$. So for $\Gamma > 100$, about the minimum required for a typical GRB, $\sigma > 3 \times 10^4k$, which contrasts markedly with $\sigma \sim 1 - 3k$, which characterizes the collapsing core (σ is also much less than 6×10^9k, the cosmological value).

15.3.4.3 Neutrinos

Neutrinos have three important potential roles to play in GRBs. At energies ∼10 MeV, they may provide a thermostat within the collapsing core limiting the temperature of the gas by carrying off the internal energy. They provide one possible source of entropy at the base of the relativistic jet if they annihilate or are absorbed or scattered, although, as has been mentioned, this is not quantitatively promising. Finally if the outflows have a sufficiently powerful hadronic component they could be a source of VHE neutrinos. The ∼10 MeV neutrinos will be very hard to detect from the distances anticipated; less than 20 were seen from SN1987a at a distance of 50 kpc. Detecting VHE neutrinos coincident with GRBs using *IceCube*, however, remains possible. This would be a sign that GRBs are the source of the UHE cosmic rays [12].

15.3.4.4 Entropy

σ is really a measure of the number of photons per baryon and although this might, in principle, be increased by tapping the large kinetic energy density of the gas in the maelstrom close to the event horizon through turbulent viscous dissipation, there is probably at most 100 MeV/n of energy available which is insufficient. Neutrino and neutron (from iron photodisintegration) heating have also been invoked but the former, at least, may not be sufficient to power GRBs ([10], Rossi et al. 2006). Removing the baryons seems much more promising. This is what black holes do! The funnels formed by a combination of gravitational and centrifugal forces should define a converging flow for the accreting gas. The problem though is to feed the outflow when the radiation can only move relative to the gas with a tiny speed $\sim \frac{c}{\tau_T}$. These are well-posed challenges in radiation hydrodynamics and well worth additional consideration and simulation.

15.3.4.5 Dissipation

GRB outflows are less likely than Big Bang outflows to remain adiabatic. Mass and momentum transfer through the channel walls, mediated by turbulence (the Reynolds number is enormous, at least initially) in the flow should lead to photon production, a lower outflow speed and an internal energy that decreases more slowly with increasing radius. The way that this is likely to happen is that backscattering at the funnel walls will dilute the radiation density in the beam leading to net photon production to re-establish local thermodynamic equilibrium so long as bremsstrahlung, cyclotron radiation and double Compton scattering can achieve this on an outflow timescale.

If we ignore baryons and suppose that the jet power L decreases due to losses, while the flow of entropy Q increases due to photon creation in the flow, then the outflow Lorentz factor becomes modified to $\Gamma^* \sim (P^*/P_0)^{-1/4}(L^*/L_0)(Q_0/Q^*)$. (This is applicable outside the star where there are likely to be serious radiative losses.) If, for example, $L^* \sim L_0$ and $Q^* \sim 10Q_0$, then $\Gamma^* \sim 100$ and the observed, Doppler-boosted radiation temperature would be reduced by a factor ten to$\sim 300\,\mathrm{keV}$, comparable with the observed Band energy.

15.3.4.6 Mach number

Another concern with the adiabatic radiation fluid dynamical description is that a high Lorentz factor corresponds to a high Mach number. For a radiation-dominated equation of state, the Mach number is $3^{1/2}\Gamma$ and internal energy density is only a fraction $9/4M^2$ of the total energy density perhaps as small as 10^{-6} in few GRBs. Mach numbers over ten are hard to produce in carefully designed wind tunnels because surface irregularities and instabilities lead to more dissipation. The situation is surely much worse in a GRB where we are dealing with an intrinsically time-dependent flow with fluid boundaries. Indeed, it is striking that in fireball models, the flow is proposed to be accelerating more or less adiabatically inside the star where dissipation is most likely to occur and then to dissipate beyond the photosphere when it should be a free expansion!

There is another way to express this concern. Imagine an observer in the outflow at rest with respect to the star. In extreme, long GRBs, the radiation beam has to be collimated within a few arc minutes - not a lot larger than Venus in the night sky - in order for the pair production optical depth at the highest photon energy be less than unity. Separate parts of the outflow will be out of causal contact, a kinematic analog of what happens in the very early Universe after inflation. Any convergence in the flow velocity field will lead to oblique shocks, which can be just as dissipative as transverse shocks.

15.3.5 Is magnetic field the "dark matter" of GRBs?

The analogy to standard cosmology can be pushed further by recalling that a Universe comprising just photons and baryons was unable to account for the timing of the growth of structure while the Universe expanded and for this, and other, reasons a dominant cold dark matter component was invoked. Likewise, the early models of long GRBs postulated a radiation-dominated fluid with a small baryon component and now there are doubts that this can account for the γ ray emission. Some other agency may be required. The natural candidate is magnetic field.

15.3.5.1 Dark field

Indeed, many authors have concluded, either implicitly or explicitly, that the flow near the hole is mediated by electromagnetic field only to suppose that it then somehow vanishes. This seems unreasonable as it is very hard to eradicate field from astrophysical plasma and unnecessary as new mechanisms are then invoked to re-create the field in the $\gamma-$ray emission region. (Similar issues have arisen in discussions of Pulsar Wind Nebulae, where it has been commonly argued, until recently, that the magnetized outflow from the magnetosphere, becomes overwhelmingly gas-dominated so that it can decelerate when passing through a termination shock instead of remaining magnetically dominated and then dissipating through particle acceleration within the nebula as suggested by X-ray observations; Begelman 1998.)

If we assume that the jet flow is hydromagnetic throughout, this offers several advantages over a purely fluid dynamical model (e.g., Blandford 2002). The first is that the magnetic field itself provides another promising mechanism, in addition to the formation of a centrifugally-supported funnel, for excluding the low entropy per baryon infalling gas from the base of the jet at high latitude above the event horizon. Secondly the magnetic field can power the outflow either by dissipating as fast as it grows and increasing the entropy at the base of the jet through reconnection and wave damping (McKinney & Uzdensky 2011). (The radiation energy density will actually increase at the expense of the magnetic energy.) Thirdly, the field can convert the angular momentum of the hole into linear, electromagnetic momentum of a jet. Fourthly, the magnetic field can help confine the jet. Although an organized magnetic field should be mostly poloidal at the base of the jet, just above the horizon, it will become increasing toroidal as the altitude is increased. The associated hoop stress can help confine the jet just like in a Z-pinch. (The jet would be ultimately confined by the pressure in the surrounding star, although the confined pressure in the core of the jet can be much larger than the pressure in the stellar envelope when magnetic hoop stress is involved.)

It is of interest to consider the ratio of the pressure to the magnetic stress, β, in the jet. If the transverse radius is r, the flow is adiabatic and the MHD perfect, then $\beta \sim \left(\frac{\Gamma}{r}\right)^{2/3}$, which should vary slowly suggesting that a flow that is magnetically-dominated at its origin is likely to remain as such. However, neither of these two conditions is likely to be satisfied in practice and β can either grow or decay with radius.

15.3.5.2 Fast mach number

There is another general dynamical difference between an electromagnetic and a fluid outflow and this can best be expressed in terms of the effective Mach number. The addition of electromagnetic field to the outflow increases the effective sound speed so that the fraction of internal energy increases for a given flow speed. High speeds are robust to internal dissipation and shocks are much weaker and consequently less relevant to particle acceleration. The full description of wave speeds in a magnetohydrodynamical flow is complex depending upon the direction relative to the magnetic field, the anisotropy in the pressure tensor and the response of the pressure to compression. In one simple and relevant case suppose that we have a radiation-dominated strongly scattering gas with pressure P and a cold ion gas of density ρ, the wave speed s perpendicular to the magnetic field B is given by $(s/c)^2 = (4P/3+B^2/\mu_0)/(\rho c^2+4P+B^2/\mu_0)$. The wave speed can become arbitrarily close to the speed of light as the magnetic stress increases relative to the presure. Indeed, an ultrarelativistic outflow can remain subsonic in this sense.

15.3.5.3 Stability

A static pinch is an axisymmetric, axial current surrounded by toroidal magnetic field. The Lorentz force is directed radially inward and opposed by a pressure gradient. Pinches are notoriously unstable and are especially prone to axisymmetric and helical instabilities. However, in the case of a GRB jet, a modicum of stability should be conferred by the super-Alfveńic motion along the jet axis, the lateral expansion of the jet, relativistic effects and the component of magnetic field along the jet axis. In addition, a slower outflowing wind from the surface of a disk or torus can also provide a stabilizing buffer. Simulations support these assertions and show that the instabilities do not become strongly nonlinear and disruptive. Instead, jets jitter and quiver about a mean flow velocity.

15.3.5.4 Field growth

In order to be effective in a typical long GRB, the magnetic field must grow to around $10^{14} - 10^{15}$ G about the field strength of a magnetar by the time the inflow reaches the horizon. (The associated current will be $\sim$1 ZA!) The interior of the pre-collapse star is likely to be magnetized and the flux will be concentrated during the inflow. Subsequent growth on a dynamical timescale through magnetorotational and related instabilities will further increase the field and it remains an open question whether its strength can attain the required values fast enough. What does seem to be established by 3D GRMHD simulations is that if a strong poloidal field can develop through dynamo action in the disk then ultrarelativistic jets can form and propagate out through the star. The same outcome is found if sufficient entropy production is introduced in a non-relativistic fluid supernova model. The challenge now is to repeat these calculations with more complete models that self-consistently evolve the magnetic field from much lower strength with sufficient spatial resolution to allow turbulence to develop. Fortunately, the techniques and computing capacity are still improving rapidly enough to enable these investigations in the near future.

15.3.5.5 Mergers

There are far greater challenges in considering outflows associated with short bursts. If these really are merging neutron stars, then the specific angular momentum when the stars become a contact binary is about the same as that of a near maximally rotating black hole with mass ~2.8 solar masses. In other words, it is quite likely that a small fraction of the combined mass, perhaps a few tenths of a solar mass, is in a disk. This material is likely to be highly magnetized to start off with and the field should subsequently grow. However the ratio of the outer to the inner disk radius is unlikely to be large, rather like the disks associated with cataclysmic variables. If a disk does form, then the argument that jets are magnetically driven and collimated seems even stronger than with long bursts associated with collapsars. (The field strength may not be quite so high, though.) Recent relativistic MHD simulations (Rezzolla et al. 2011) provide an impressive demonstration of this scenario.

Note, though, that the physical conditions associated with short bursts are likely to be quite different from those associated with a long burst inside a star. A jet in a collapsar propagates through roughly five decades of radius and ten of pressure, confined by a dense stellar envelope and is likely to be launched with a high radiation temperature ~10 MeV. However, the only transverse confinement of a merger jet is likely to be from a wind produced by a small disk and the outflow is likely to diverge quickly and become optically thin. Another way that magnetic fields could have a major impact on short burst models is if the neutron stars are highly magnetized ($\sim 10^{12}\,$G not the $\sim 10^{9}\,$G of old neutron stars). This suggests another mechanism for explaining occasional X-ray precursors of short bursts as there will be a release of electromagnetic energy rising with time t relative to burst $\sim (-t)^{-9/8}$ prior to mass transfer.

15.3.5.6 Observational opportunities

There are several opportunities for exploring long and short GRBs if we can find closer, more powerful bursts - and observe them promptly. *VLBI* observations of radio and mm afterglows provide a check on the energetics, the degree of beaming and the nature of XRF and low power bursts.

15.3.6 Why do we observe GRBs instead of X-ray bursts?

There is still debate about the prompt radiation mechanism in the relativistic outflow, in particular whether the γ rays are emitted by the synchrotron or Compton processes or something more exotic. Furthermore, there is no agreement as to how the electrons (and positrons) are accelerated to great energy if we are observing synchrotron radiation. Here, some comparisons with other sources may be helpful.

15.3.6.1 Pulsar wind nebulae, blazars and tidal destruction

The time-averaged spectrum of a pulsar wind nebula, of which the famous Crab Nebula is the best-known example has a “Bactrian” form with the first hump comprising primarily synchrotron radiation and the second primarily inverse Compton scattering. The separation is pretty clean despite the fact that the source is inhomogeneous. The crossover energy is at about 500 MeV. Interestingly, this is just above the energy $\sim \alpha^{-1} m_e c^2 \sim 100\,\mathrm{MeV}$ where, for synchrotron emission, the radiation reaction force on an emitting electron (or positron) exceeds the Lorentz force (Abdo et al. 2011). The recently reported GeV flares from the Crab Nebula, with variability timescales as short as a few hours, appear to be localized around this cross-over energy suggesting that the synchrotron emission mechanism is at work and that particles can be rapidly accelerated until radiation-reaction limits the particle acceleration, in this case at PeV energies. This, in turn, implies that the particles have to be accelerated and radiate in a fraction of a Larmor period. Blazars, likewise exhibit synchrotron and Compton peaks but their cross over energies can range from $\sim$10 eV to $\sim$10 MeV correlated roughly inversely with the total luminosity of the source.

Another type of source which may provide a clue as to the emission physics is the faux GRB110328A $=$ Sw$1644+57$, (*e.g.,* Bloom et al. 2011), which is associated with the nucleus of a LMC-scale, star-forming galaxy. Most of the bolometric power appears to be observed in the X-rays but there could be a high opacity along the line of sight at other energies. At a redshift of $z = 0.35$, the emission has exhibited short bursts with variability timescales of minutes over an interval of months. The peak isotropic power was $\sim$

3×10^{48} erg s^{-1} and the isotropic energy a tenth of a solar mass. Sw1644+57 is generally, though not universally, believed to be a tidal disruption event associated with a central massive black hole. If this interpretation is correct, it does support the inference that collimated, relativistic outflows are made very easily when the mass supply rate to a black hole is extremely high and that these outflows are able to radiate efficiently.

15.3.6.2 Pair production

We have noted that the Band energies are $E_0 \sim 200(500)$ keV for long(short) GRBs. If these were the only photons to be emitted, they could be associated with the thermal radiation from the stellar core, with a significant entropy increase along the way through sharing the energy among more photons especially at energies $< E_0$ to account for the low energy spectral slope. (Actually, a "thermal" component is sometimes observed.) The photons would be below the pair production threshold and could escape freely from the photosphere. However, the observed γ ray spectrum is highly non-thermal with appreciable emission of photons of energy far in excess of the pair production threshold with energies up to $E_{\rm max} >> E_0$ that can be guessed as typically ~ 3 GeV but can be larger than 30 GeV. If these photons are to evade pair production then the outflow Lorentz factor Γ has to be typically 100 and as much as 1000 in extreme cases and the comoving photon energies are $\sim$30 MeV. (These models are nothing more than attempts to thwart the natural inclination of the outflow to maintain thermal equilibrium.)

A simple estimate gives that the pair production opacity at threshold,

$$\tau_{\rm pp} \sim \frac{L_\Omega(>\Gamma^2 m_{\rm e}^2 E_{\rm max}^{-1})\sigma_{\rm pp} E_{\rm max}}{m_{\rm e}^2 R c \Gamma^4}$$

must be of order unity at the "gammasphere" at radius $R = R_\gamma(E_{\rm max})$, where the pair production opacity is $\sigma_{\rm pp} \sim 0.2\sigma T$, R is the emission radius, estimable from the either the overall duration, t, of the burst as $\sim \Gamma^{-2} ct$ or the variability, δt, and L_Ω is the power per sterad. Typically, at threshold, 10 GeV photons pair-produce on 1 MeV photons all within an outwardly-directed cone of angle $\sim 30'$ at a "gammasphere" radius $> 10^{13}$ cm about 100 times the photospheric radius, whereas, exceptionally, the soft photons are of order 30 keV, the angle is $\sim 3'$ and $R \sim 10^{15}$ cm. Note that it is very hard to see how the highest energy photons can be emitted from close to the photospheric radius of a precursor star. Most discussions of the escape of $\gamma-$rays assume a single outflow speed and a homogeneous source. It is important to carry out radiative transfer calculations using unsteady, relativistic hydromagnetic simulations where there are relativistic random motions of the emitting plasma and highly inhomogeneous opacity distributions [7]. The results may turn out different from those based upon simple, analytical estimates.

15.3.6.3 Internal shocks

There is therefore a need to add a significant high energy tail to the photon distribution outside the photosphere. In the context of a baryon-loaded, radiation-dominated jet, the most popular way to effect this transformation has been to postulate that internal shocks form in the outflow caused by variations in the jet speed imprinted near its source. These shocks, with high Mach number and compression ratio would then be responsible for the local *in situ* particle acceleration.

15.3.6.4 Magnetic acceleration

I have argued that internal shocks are not such good accelerators if the magnetic energy density is comparable with the particle energy density or greater. In this case the shock compression is limited, along with the efficacy of particle acceleration. High compression is still possible for shocks propagating along the field and this could be relevant in the boundary layer that is likely to develop at the jet wall. However of much greater importance, if there is a large scale Poynting flux is the ∼100 ZV of motional potential difference that should develop between the core of the jet and its walls. The associated electric fields are also large. A steady, uniform flow will not accelerate particles. However, as mentioned above, as soon as some instability or jitter, to which hydromagnetic flows are highly susceptible, develops, this field provides a ready mechanism to tap the energy of the outflow and dissipate it in the form of rapid acceleration of relativistic electrons and positrons. The notion that these flows are dissipative from well inside the star to the free expansion propagation outside the star invites the inference that we see most of the γ ray photons from close to the “gammasphere”. This effect could be sought in the *Fermi*-LAT data.

15.3.6.5 Gamma-ray emission

The cooling times of the emitting particles are typically much shorter than the dynamical times of the flow and so local particle acceleration must be fast. Detailed models have been developed under fluid dynamical conditions. For emission at 30 MeV in a typical burst, synchrotron radiation in a comoving equipartition field ∼10 MG with energies up to ∼15 GeV, Larmor radii, cooling and acceleration lengths ∼5 cm (comparable for reasons given above) will suffice. If the emission is due to the Compton process, 50 MeV electrons may suffice but the cooling lengths are still very short [7]. Central to these arguments is a need to be clear about the kinematics of the emission. The prompt γ rays, unlike the afterglows, might come from a preferred radius through which plasma is flowing at relativistic speed or could be mostly associated with the "working surface" of the jet after it breaks out of the star.

15.3.6.6 Variability

An important feature of GRBs is that they exhibit rapid variability. This is a property that they share with blazars, some of which have been reported to vary on timescales of minutes at ~TeV energies perhaps shorter than the light crossing time of the massive black hole. Typical long GRB fluctuation times are ~10 ms, longer than the corresponding time scale for a stellar black hole. It is tempting to associate GRB variability with instability at the jet source. However, this does require that the outflow velocity gradient be low enough to prevent smearing of the variability by the time the flow exits the star. For this reason, local instability, consistent with the cooling timescales discussed above, amplified by relativistic motion seems a more plausible source of the observed variation.

15.3.6.7 Simulation

An impressive amount of kinetic simulation effort has already been expended on a variety of GRB models and although we still are not sure which is most relevant to GRBs, there is no question that the general lessons about the behavior of magnetized, relativistic plasma are highly valuable. The efficiency, fidelity and resolution of modern "particle in cell" codes enables the dynamics of large number of electrons, positrons and protons to be tracked and combined to act as sources of electromagnetic field (e.g., Sironi & Spitkovsky 2009).

15.3.7 Why are GRBs so diverse?

One striking feature of the γ ray observations of GRBs is that they are so diverse. They span a huge range of spectral properties and durations and all of the purported correlations and proposed taxonomic classes have turned into strongly contested trends. Similar comments apply to the prompt emission early afterglow transition that has been observed so well by *Swift* [5]. These traits carry over to the main afterglows, which exhibit a similarly broad range of properties. This is surprising. After all, a shock is a shock is a shock is a shock and yet they seem to behave quite differently from one another for no apparent reason.

15.3.7.1 Relativistic beaming

A large part of this variation may be an inevitable consequence of relativistic beaming. The relativistic Doppler factor is $D = \Gamma^{-1}(1 - (V/c)\cos\theta)^{-1} \sim 2\Gamma(1 + \Gamma^2\theta^2)^{-1}$ where θ is the viewing angle. The observed flux from a discrete source is $\sim D^3$, evaluated at the transformed frequency $D^{-1}\nu$. Suppose that $\theta \sim \Gamma^{-1} \sim 0.01$ so that $D^3 \sim 10^6$. A change of θ to 0.008 without changing Γ would roughly double the observed flux. It will be interesting to see if simple source models can be constructed that exhibit variability from local sources in the prompt emission region on ~10 ms timescales. It will then be possible to elaborate these into models that include emission mechanisms such as those discussed above. The interpretation of the "achromatic" breaks in the afterglow light curves, which were reported prior to *Swift* and which now seem to be much more confusing, is an area that should get more attention as it is central to attempts to measure jet beaming and speeds

15.3.7.2 Mass loss

Collapsars should be associated with star-forming regions as their host stars cannot move far before they explode. Mergers are more problematic as some binary neutron stars may be "kicked" with high speed and can travel across the host galaxy before the GRB happens. The environment in which the GRB occurs may be quite different from that of a massive stellar nursery such as a molecular cloud. It is reasonable to suppose that the huge heterogeneity in external densities that have emerged from GRB afterglow modeling may be a simple reflection of the highly varied and quite anisotropic stellar mass loss just prior to the supernova [9]. All of this can be probed through careful X-ray, optical and infrared observation of the brighter bursts both during and following the afterglow, the circumstellar gas and dust. X-ray lines have been reported but not generally corroborated. It is possible that collapsar progenitors have binary companions and so there could be a class of GRBs where the prompt emission is partially occulted, but the late afterglow is not.

Now, three Giant Segmented Mirror Telescopes are currently scheduled to come online early next decade at a time when there should be overlap with the James Webb Space Telescope (*JWST*). This combination should be especially powerful. Again having an accurate position will be a boon and it is vitally important that a *Swift* type X-ray telescope be operational then. These observations will also, of course, be a remarkable probe of the host galaxy.

15.3.8 Why should physicists care?

GRBs have caught the attention of physicists for several reasons: they are extreme astrophysical phenomena which give us a glimpse of the behavior of matter under conditions that we will never replicate on Earth and which might lead to the acceleration of Ultra High Energy Cosmic Rays. In addition, they are cosmologically distant and, although far from a homogeneous population, could be used to study cosmology and probe the contents of intergalactic space.

15.3.8.1 Extreme astrophysics

GRBs are extreme for many reasons. They surely exhibit the maximum energy densities invoked in discussion of any cosmic source excluding the Big Bang. They are most likely to represent the formation of black holes and if the collapsar and merger models can be validated then GRBs provide valuable empirical information on the behavior of massive black holes with millions of times more mass. The inferred outflow Lorentz factors $100 < \Gamma < 1000$, are greater than those associated with AGN. They may be smaller than those associated with PWN, though. If, as I have argued is likely to be the case, GRBs are, at heart, electromagnetic phenomena, then the EMFs, currents *etc* are unprecedented and the magnetic fields at the source are at least as strong as those associated with magnetars over $10^{14}\,\mathrm{G}$. This is far above the quantum electrodynamical critical field and allows QED to be used in a regime well beyond any laboratory experiment.

15.3.8.2 Ultra high energy cosmic rays

Particle physicists have mostly exhibited a quite remarkable indifference to the observation of UHECR with individual energies $\sim 10^8$ times those accelerated at the *LHC* and center of mass energies in collisions with the atmosphere 10^4 times as high. It should be noted that the nature of the interactions and, consequently, the composition – protons or iron – is quite controversial and it should be possible to sort this out and learn about physics between the energy scales accessible on Earth and the GUT scale. Conversely the data from $p-p$ collisions at the *LHC*, especially when it is in operation at 14 TeV (CM) may help determine the composition of UHECR.

Given the extreme character of GRBs, it should not be surprising that they have been proposed as sources of UHECR [12]. (Prompt supernova explosions that do not create GRBs have also been proposed as UHECR sources.) There is little argument with the proposition that GRBs, both individually and collectively, have the power to account for UHECR (though the particle acceleration that we have to invoke to account for the prompt γ rays is far more modest). However the range of a UHE cosmic ray to photopion production in the intergalactic medium in the presence of microwave and higher energy photons is quite limited - $\sim$30 Mpc at the highest energy. This means that perhaps a thousand galaxies contribute to the sources. Now although the speed of a cosmic ray lags that of a photon by $\sim$1fm s^{-1} or $\sim$ 300 m per Hubble time, the presence of small amounts of intergalactic magnetic field will lead to stochastic deflections through angles ϕ. The number of GRBs contributing the flux at any one time would then be of order $3(\phi/1^\circ)^2$ per galaxy. It is also possible that discrete sources could be seen if the deflections are small. However, the same processes that limit the range in the intergalactic medium can prevent a UHECR from escaping "the most luminous objects in the Universe". Nonetheless, given the problems associated with the three alternative sources that are generally acknowledged - AGN, millisecond magnetars, and circum-cluster shock fronts GRB sources should not be ruled out. As more events are accumulated at *Auger-S*, we should know if the composition of the highest energy particles is hydrogen or iron and if nearby, discrete sources can be distinguished. This should help us see if GRBs are responsible.

15.3.8.3 Cosmology

As described above, there is a realistic expectation that GRBs will contribute alongside low frequency radio telescopes and *JWST* to probe the epoch of re-ionization and Population III stars and that we will ultimately learn much from the combination of these observations [14].

15.3.8.4 Lighthouses of the Universe

Finally, it is worth remarking that GRBs are proving to be useful as probes of the intergalactic medium and X-ray and dust absorption features can be produced by the host galaxy and the IGM along the line of sight. This may turn out to be one of the best probes we have of the Universe when it was only $\sim$500 Myr old.

15.3.9 Should we worry about GRBs?

GRBs are enormous explosions that happen frequently throughout the Universe with little prior warning. They are consequently quite frightening. How valid is this concern?

15.3.9.1 Environmental impact

There is no denying the scientific and popular appeal in connecting cosmic catastrophes to our history, as many books and movies can attest. The arithmetic is simple but highly uncertain. There have been $\sim 10^8$ supernovae in the Galaxy over the life of the solar systems. Perhaps as many $\sim 10^6$ of these were GRBs and as many as $\sim 10^4$ had jets directed towards us - one per million years. The closest event would be about 100 pc away; the last one would likely be ~10 kpc distant. The closest event would irradiate the earth with ~100 J m^{-2} of high energy radiation or very roughly a radiation dose of ~300 mJ kg^{-1} for an astronaut on the Moon, Mars or points in between. This is about a tenth of a fatal dose for humans. The most recent GRB is likely to be $\sim 10^{-4}$ times as intense.

For comparison, note the figures for SGR1806$-$20 at 14 kpc, which rattled our ionosphere with a fluence of $\sim$ 1 mJ m^{-2} (Inan et al. 2007). More striking are giant solar flares which are a million times more intense, $\sim 10^3$ J m^{-2}. They can disrupt radio communications and artificial satellite orbits and kill astronauts beyond low earth orbit. It has been estimated that the ozone layer would be destroyed with an event only a hundred times the power of the largest solar flare measured to date (Kopp et al. 2005). Fortunately this would require the release of more magnetic energy than is contained in the whole solar corona and so is unlikely to occur. However, what these crude estimates do demonstrate is that the largest extraterrestrial radiative threat to life comes (and assuredly came) either directly or indirectly from the sun.

15.3.9.2 Other worlds

It is of interest to speculate upon the total effect of GRBs on the Avogadros number of planets throughout the universe. Each GRB is likely to deliver a human fatal dose of radiation to $\sim 10^4$ stars or 10^5 planets. The probability of this occurring per planet is of order one percent and so even here the impact of stellar evolution is of more consequence.

15.4 Conclusion

The last two decades of research on GRBs have provided a thrilling ride for drivers, passengers and spectators. They have appealed to the impatient and rewarded the enterprising. They have taught us that the observable Universe is still capable of surprising us. They have demonstrated, once again, the high connectivity of modern astrophysics, where specific source types can literally illuminate other questions while posing astronomical and astrophysical puzzles in their own right. The next twenty years ought to be as exciting so long as we can keep observing these remarkable sources.

Two strong themes run through the preceding analysis of how the historical rate of discovery about GRBs can be resumed. The first is that fluid dynamical (including magnetic field and general relativity) simulations are now becoming reliable enough to put a large variety of analytical models to the test. This is not quite the same as directly trying to simulate a physical GRB. However, it should be good enough to decide between several competing descriptions of what happens during the initiation, propagation, $\gamma-$ray emission and afterglow phases and this, in itself, will constitute a considerable advance. These simulations should also help elucidate the physics of AGN, X-ray binaries and protostars. It seems entirely reasonable that they will be as influential and as good for framing debates as the corresponding Dark Matter simulations have been for observational cosmology. There have been great strides as well in plasma simulations that should also be put in a much larger context as we are still getting major surprises as to how fundamental plasma constructs such as collisionless shocks, reconnection and MHD turbulence, operate in practice. Integrating this sort of local description with a global model will be a big challenge but well worth pursuing if we can constrain the source properties. We are already getting many strong clues from simulations of quite different high energy sources like the Crab Nebula.

The second theme is observational. GRBs are observed daily on average and it is very tempting to rely upon statistical discussions to learn what is actually happening. However, I suspect that progress here will now be slower than it has been. This is partly because the bursts we observe are so heterogeneous and partly because increasing the number substantially over what we have will be a large challenge. Instead I believe that it will be the rare bursts that are extreme in some way that will point the way forward. It will be necessary to quantify what is meant by “extreme” fluence, timescale, redshift *etc* - and to build upon the great organizational exercises that have already been executed and exploit the coming capabilities involving neutrinos, gravitational radiation, TeV astronomy, omni-directional radio arrays, *LSST*, Giant Segmented Mirror Telescopes and so on to follow up special bursts as soon as possible. Protocols will have to be simulated and agreed to optimize the scientific return for reasonable application of telescope resources. It will be hard, of course, to draw conclusions about the whole population on the basis of the behavior of a few members but this is a common enough problem in astronomy and there should be enough multi-dimensional information to proceed with confidence.

However, although I have mostly discussed ways to consolidate what we think we know, I must conclude as I started, by emphasizing that GRBs still have the capacity to surprise us by overturning major components of their current interpretation. I hope they do so.

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