# Gamma-Ray Bursts

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## 0.1 Historical Overview and Basic Concepts

Gamma-Ray Bursts (GRBs) were serendipitously discovered in the late 1960s by the military Vela satellites which were monitoring the Nuclear Test Ban Treaty between the US and the Soviet Union. The announcement was postponed for several years, after having ruled out a man-made origin and ascertained that they were outside the immediate solar system [1]. In a matter of a few years more than a hundred models had been proposed to explain their astrophysical origin [2], ranging from comet infalls, through stellar cataclysmic events, to events associated with supermassive black holes at the center of galaxies. The problem in making the first steps towards a theoretical understanding was that the gamma-ray instruments of the time had poor positional accuracy, transmitted to Earth only many hours after the trigger, so that only wide-field, insensitive telescopes could follow-up the bursts to look for counterparts at other wavelengths.

In the 1990s the Compton Gamma Ray Observatory (CGRO) was launched, one of whose main objectives was the detection of GRBs. The Burst and Transient Source Experiment (BATSE) onboard CGRO obtained, over a decade, the positions of $\sim$ 3000 GRBs. This showed that they were uniformly distributed over the sky [3], indicating either an extragalactic or a ‘galactic-halo origin. BATSE also found that GRBs can be classified into two duration classes, short and long GRBs, with a dividing line at $\sim 2$ s [4].

The search for GRB counterparts at other wavelengths remained unsuccessful for almost 25 years, until in 1997 the Beppo-SAX satellite localized with greater accuracy the first long lasting X-ray afterglows [5], which in turn enabled the first optical host galaxy identification and redshift measurement [6]. The long bursts were found to be associated with galaxies where active star formation was taking place, typically at redshifts $z \sim 1-2$, and in some cases a supernova of type Ic was detected associated with the bursts, confirming the stellar origin of this class. The power law time decay of the light curve was also observed, in a number of cases, to exhibit a steepening after $\sim 0.5 - 1$ day, suggesting (for reasons explained below) that the emission was collimated into a jet, of typical opening half-angle $\sim 5^o$, which eased the energy requirements. Even so, at cosmological distances this implied a total time-integrated energy output of $\sim 10^{50} - 10^{51}$ erg. This is roughly $10^{-3}$ of a solar rest mass, emitted over tens of seconds. This is more than our Sun emits over its ten billion year lifetime, and about as much as the entire Milky Way emits over a hundred years – and that is mainly concentrated into gamma rays.

Well before the CGRO and Beppo-SAX observations, early theoretical ideas about the origin of GRBs had converged towards an energy source provided by the gravitational potential of a compact stellar source, the latter being suggested by the short duration (tens of seconds) and fast variability $\gtrsim 10^{-3}$ s of the $\gamma$-ray emission, using a simple causality argument $R \lesssim c\Delta t \lesssim$ 10-100 Km. The large energies liberated in a small volume and in a short time, as well as the observed hard spectrum ($\gtrsim$ MeV) would then produce abundant electron-positron pairs via photon-photon interactions, creating a hot fireball which would expand, eventually reaching relativistic bulk velocities [7].

Among the first stellar sources discussed which could be responsible for GRBs were binary double neutron star (DNS) mergers, or black hole-neutron star (BH-NS) mergers, whose occurrence rate as well as the expected energy liberated $\sim GM^2/R$ appeared sufficient for powering even extragalactic GRBs [8, 9, 10, 11]. These are nowadays, the leading candidates for the short gamma-ray bursts, as shown by Swift and other observations e.g. [12]. Another candidate stellar source was the core collapse of massive stars and the accretion into the resulting black hole [13, 14]. Initially it was thought that this would result in a GRB and a failed supernova, but later observations, e.g. [15] and others, showed an unusually luminous core collapse supernova of type Ic associated with some GRBs; these supernovae have since been referred to as hypernovae. The core collapse model, referred to as a collapsar, is currently well established as the source of most long GRBs.

The predicted rate of occurrence of binary mergers and of hypernovae is sufficient to account for the number of bursts observed, even if the gamma-rays are beamed to the extent that only one event in 100-1000 is observed. (We expect less than one observable burst per million years from a typical galaxy, but the detection rate can nonetheless be of order one per day because that are so powerful that they can be detected out to the Hubble radius)

## 0.2 CGRO Results and Basic Models

The dynamics of the expected relativistic fireball expansion were investigated by [16, 17]. The fact that photons of over 100 MeV are detected provides compelling evidence for ultra-relativistic expansion. To avoid degradation of the spectrum via photon-photon interactions to energies below the electron-positron formation threshold $m_e c^2 = 0.511$ MeV the outward flow must have a bulk Lorentz factor $\Gamma$ high enough so that the relative angle at which the photons collide is less than $\Gamma^{-1}$, thus diminishing the pair production threshold [18, 19].

Since each baryon in the outflow must be given an energy exceeding 100 times its rest mass, a key requirement of the central engine is that it must concentrate a lot of its energy into a very small fraction of its total mass. This favours models were magnetic fields and Poynting flux are important.

The observed spectrum extends to high energies, generally in a broken power law shape, i.e., highly nonthermal. Two initial problems [9, 20] with the first expanding fireball models were that (a) they are initially optically thick and the photon spectrum escaping from the Thompson scattering photosphere would be expected to be an approximate blackbody, and (b) most of the initial fireball energy would be converted into kinetic energy of expansion, with a concomitantly reduced energy in the observed photons, i.e. a very low radiative efficiency.

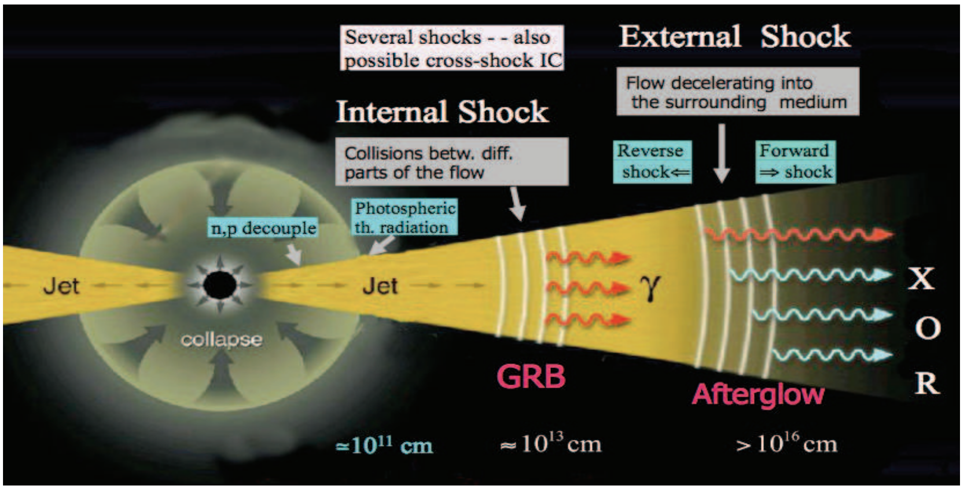

Figure 0.1 Schematic GRB jet from a collapsing star.

A simple way to achieve a high efficiency and a nonthermal spectrum, which is currently the most widely invoked explanation, is by reconverting the kinetic energy of the flow into random energy via shocks, after the flow has become optically thin [21]. Two different types of shocks may be expected. There will be an external shock, when the expanding fireball runs into the external interstellar medium or a pre-ejected stellar wind, and a reverse shock propagating back into the ejecta. As in supernova remnants, Fermi acceleration of electrons into a relativistic power distribution in the turbulent magnetic fields boosted in the shock leads to synchrotron emission [21, 22] resulting in a broken power law spectrum, where the high energy photon spectral slope fits easily the observations, and the single electron low energy photon slope -2/3 can, with a distribution of minimum energy electrons $\gamma_{min}$, reproduce the observed average low energy photon slope values of -1 (see also [23, 24]). The reverse shock would lead to optical photons, while inverse Compton emission in the forward blast wave would produce photons in the GeV-TeV range [25].

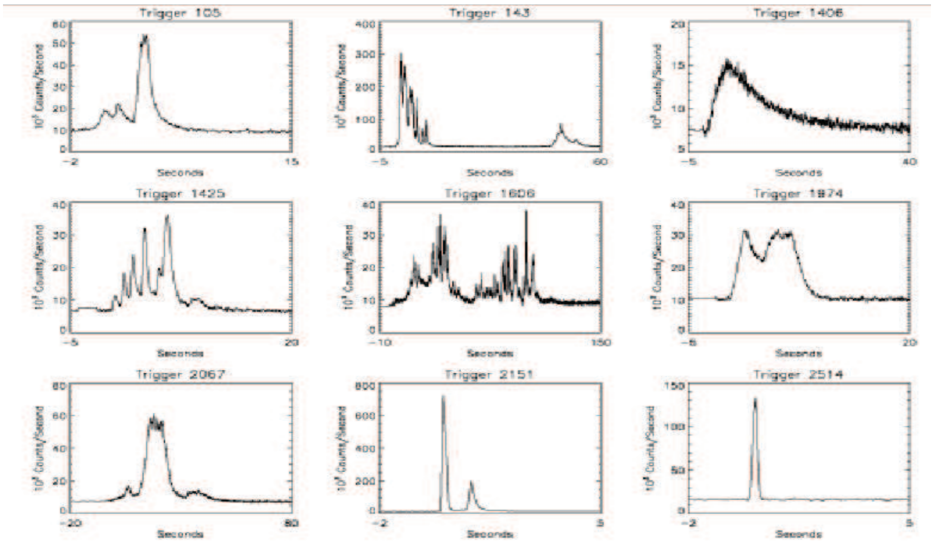

Figure 0.2 A diversity of gamma-ray light curves from the BATSE instrument on the Compton Gamma Ray Observatory.

There could, additionally, be dissipation and acceleration within the outflowing jet itself. If the jet is unsteady, internal shocks [26, 27] can form as faster portions of the flow catch up with slower portions. And if magnetic stresses are important within the jets (i.e. they are Poynting dominated outflows [28], instead of the usual baryonic inertia dominated outflows) then magnetic reconnection can provide efficient mechanical conversion of bulk into random energy [29] (see also [30, 31]) Any of these models provide a generic scenario for explaining the radiation spectrum, largely independent of the specific nature of the progenitor.

Internal shocks continue to be the model most widely used by observers to interpret the prompt MeV emission, while the external shock model is the favored interpretation for the long-term afterglows starting at high energies and phasing into gradually longer wavelengths over periods of days to months. Coincidentally, the detection of the afterglows was preceded, a few weeks earlier, by the publication of quantitative predictions of the power law spectral and time dependence of X-ray, optical and radio afterglows [32], in general agreement with observations. Prompt optical afterglows were first detected in 1999 [33], while multi-GeV emission was reported by CGRO-EGRET [34], and more recently and in greater detail by Fermi (see §0.5).

## 0.3 Beppo-SAX and HETE-2 Results and Issues

The evidence for a jet outflow is based on the observed steepening of the light curve after $\sim$ day [35], which is attributed to the transition between the afterglow early relativistic expansion, when the light-cone is narrower than the jet opening half-angle $\theta_j$ and the late expansion, when the light-cone has become wider than the jet, $\Gamma^{-1} \geq \theta_j$, leading to a drop in the effective flux [36, 37, 38]. A jet opening half-angle $\theta_j \sim$ 3-5 degrees is inferred, which reduces the total energy requirements to about $10^{51} - 10^{52}$ ergs. This, even allowing for substantial inefficiencies, is compatible with currently favored scenarios based on a stellar collapse or a compact merger, e.g. [12] and §0.1.

Observations with the Beppo-SAX and HETE-2 satellites indicated the existence of a sub-class of GRBs called X-ray flashes (XRFs), whose spectrum peaks at energies 30-80 keV instead of the 300 keV - 1 MeV of classical GRBs, and with wider jet opening angles, e.g. [39]. The relative frequencies of XRFs versus GRBs led to considerations about a possible continuum distribution of angles, as well as about the jet angular shape, including departures from simple top-hat (abrupt cut-off) including an inverse power law or a Gaussian dependence on the angle [40, 41, 42, 43].

A problem with simple internal shock synchrotron models of the prompt MeV emission is that the low energy photon number spectral slope, which is expected to be -2/3, is found to be flatter in a fraction of BATSE bursts [44]. In addition, the synchrotron cooling time can be typically shorter than the dynamical time, which would lead to slopes -3/2 [45]. In either internal shock Fermi acceleration or in magnetic reconnection schemes, a number of effects can modify the simple synchrotron spectrum to satisfy these constraints. Another solution involves a photospheric component, discussed below.

A natural question is whether the clustering of spectral peak energies in the 0.1-0.5 MeV range is intrinsic or due to observational selection effects [46, 47]. A preferred peak energy may be attributed to a blackbody spectrum at the comoving pair recombination temperature in the fireball photosphere [48]. A photospheric component can address also the above low-energy spectral slope issue with its steep Rayleigh-Jeans part of the spectrum, at the expense of the high energy power law. This was generalized [49] to a photospheric blackbody spectrum at low energies with a comptonized photospheric component and possibly an internal shock or other dissipation region outside it producing Fermi accelerated electrons and synchrotron photons at high energies. Photospheric models with moderate scattering depth can in fact lead to a Compton equilibrium which gives spectral peaks in the right energy range [50] and positive low energy slopes as well as high energy power law slopes (the positive low energy slopes can always be flattened through a distribution of peak energies). A high radiative efficiency can be a problem if the photosphere occurs beyond the saturation radius $r_{sat} \sim r_0\eta$, where $r_0$ is the base of the outflow and $\eta = L/\dot{M}c^2$ is the asymptotic bulk Lorentz factor [49]. However, a high radiation efficiency with low and high energy slopes can be obtained in all cases if significant dissipation (either magnetic reconnection or shocks) is present in the photosphere [51, 52]. This can also address the phenomenological Amati [53] and Ghirlanda [54] relations between spectral peak energy and burst fluence [51, 55]

## 0.4 Bursts in the Swift Era

The launch of the Swift satellite in 2004 ushered in a new era of extensive data collection and analysis on GRBs, at wavelengths ranging from optical to MeV energies. This resulted in a number of interesting new discoveries, which have motivated various refinements and reappraisals as well as new work on theoretical models, as discussed at greater length in the next sections.

Swift is equipped with three instruments: the Burst Alert Telescope (BAT), the X-Ray Telescope (XRT) and the UV Optical Telescope (UVOT). The BAT detects bursts and locates them to about 2 arcminutes accuracy. This position is then used to automatically slew the spacecraft, typically within less than a minute, re-pointing the high angular resolution XRT and UVOT instruments towards the event. The positions are also rapidly sent to Earth so that ground telescopes can follow the afterglows.

A surprising new result achieved by Swift was that in a large fraction of the bursts the X-ray afterglow shows an initial very steep time decay, starting after the end of the prompt $\gamma$-ray emission. This then is generally followed by a much shallower time decay, often punctuated by abrupt, large amplitude X-ray flares, lasting sometimes for up to $\sim$ 1000 s, which then steepens into a power law time decay with the more usual (pre-Swift) slope of index of roughly -1.2 to -1.7 [56, 57]. A final further steepening is sometimes detected, ascribed to beaming due to a finite jet opening angle. The initial steep decay may be ascribed to the evanescent radiation from high latitudes $\theta > \Gamma^{-1}$ relative to the line of sight [58, 59], while the ensuing shallow decay phase may be due to continued outflow of material after the prompt emission has ended [60], which may undergo occasional internal shocks resulting in X-ray flares, e.g. [56, 61, 12]. The subsequent steepening can be ascribed to the previously known forward shock gradual deceleration and the beaming induced jet break. These structures in the X-ray afterglow light curves are present both in long and short bursts.

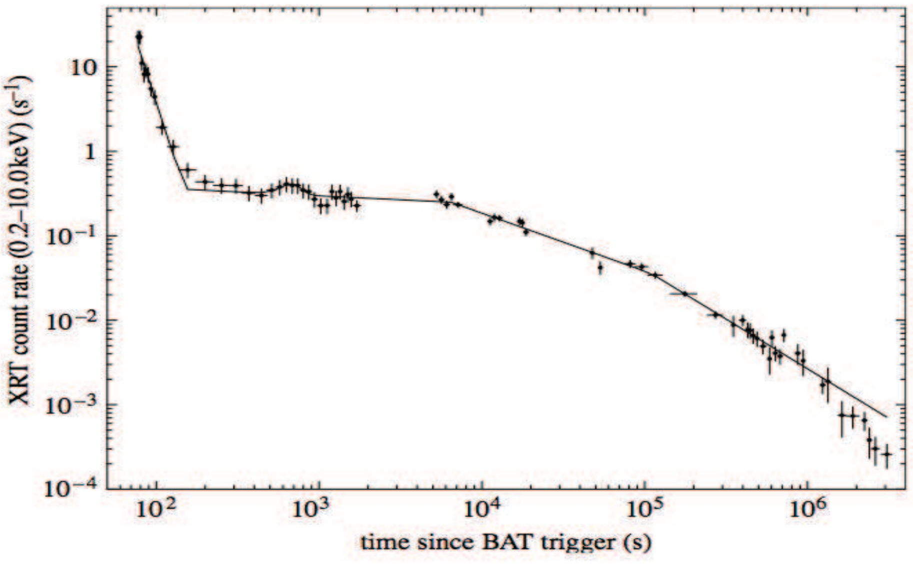

Figure 0.3 Light curves of GRB060428A from the Swift XRT [62].

Long GRBs (LGRBs) are found in galaxies where massive stars are forming, present over a large redshift range from $z = 0.0085$ to $z > 8$. Most LGRBs that occur near enough for supernova detection have an accompanying Type Ib or Ic supernovae, supporting the growing evidence that LGRBs are caused by “collapsars” where the central core of a massive star collapses to a compact object such as a black hole or possibly a magnetar.

The number of GRB redshifts obtained underwent a rapid expansion after the launch of Swift (currently in excess of 200), thanks to the rapid localization allowing large grounds-based telescopes to acquire high quality spectra while the afterglow was still bright. The most distant ones are intrinsically the brightest, typically $E_{iso} \gtrsim 10^{55}$ erg, the current record holder being GRB090423 at a spectroscopically confirmed redshift $z = 8.2$ [63], and GRB090429B, at a photometric redshift $z \sim 9.4$ [64].

With the increasing statistics, LGRBs are contributing to a better understanding of the high- redshift universe. They provide spectroscopic information about the chemical composition of the intervening intergalactic medium at epochs when the Universe was as low as 1/20th of its present age. Also, since LGRBs are the endpoints of the lives of massive stars, their rate is approximately proportional to the star formation rate. This gives information at high redshift where the rate is highly uncertain. There can be evolutionary biases, such as a dependence of LGRBs on the metalicity of host galaxies, which must be taken into account [65, 66].

Swift succeeded in finally localizing the host galaxies of a number of short GRBs (SGRBs). e.g. [67, 68]. Unlike long GRBs, the SGRBs typically originate in host galaxies with a wide range of star formation properties, including low formation rates. The host properties are substantially different than those of LGRBs [69, 70, 71], indicating a different origin. Furthermore, nearby SGRBs show no evidence for simultaneous supernovae [72], as do many long bursts. These results reinforce the interpretation that SGRBs arise from an old population of stars, probably due to mergers of compact binaries such as double neutron star or neutron star-black holes [72, 8, 9].

Short GRBs are found to have generally a lower isotropic-equivalent luminosity and total energy output $E_{iso}$ than LGRBs, typically $E_{iso} \sim 10^{50}$ ergs, with a weak afterglow, and in the few cases where a jet break has been measured, the jet opening angle appears to be wider than in LGRBs, $\theta_j \sim 5^o - 25^o$ [73, 74]. Another new result was the discovery, in about 25% of SGRBs, of a longer ($\sim$ 100 s) light curve tail with a spectrum softer than the initial episode [75, 76]. This is puzzling in the context of double neutron star or neutron star-black hole mergers, since numerical simulations suggest that the disk of disrupted matter is accreted in at most a few seconds, e.g. [72]. A longer accretion timescale, however, may occur if the disk is highly magnetized [77], or if the compact merger results in a temporary magnetar whose magnetic field holds back the accretions disk until the central object collapses to a black hole [78].

### *0.4.1 Other types of bursts*

The demarcation into two classes of bursts is however too simplistic to be the whole story. Some bursts fit neither category. For example, some bursts detected by Swift are extreme magnetar flares caused by the sudden readjustment (and release of stored energy) in the magnetosphere of a highly magnetized ($\gtrsim 10^{14}$ G) neutron star. These are of interest for phenomenologists but are a confusing complication for those seeking correlations between the observable parameters of bursts.

But the Swift spacecraft has revealed another type of object that is of great interest, and which was a surprise: bursts characterized by unusually persistent and prolonged emission, and located at the centre of the host galaxy. These are interesting both to astrophysicists and to relativists, as they may be triggered by a long-predicted effect that has not before been conclusively detected: the tidal disruption of a star by a massive hole.

Tidal capture and disruption of stars attracted interest back in the 1970s, when theorists started to address the dynamics of stars concentrated in a high-density 'cusp' surrounding the kind of black hole expected to exist in the centres of galaxies (and perhaps in some globular star clusters as well). It was recognized that stars could be captured and swallowed by the central hole if they were in a 'loss cone' of near-radial orbits.

If the central hole is sufficiently massive, tidal forces at the horizon may be too gentle to disrupt to star while it is still in view, in which case it is captured without any conspicuous display. For a solar-type star, this requires $\sim 10^8 M_\odot$; for white dwarfs the corresponding mass is $\sim 10^4 M_\odot$. (And neutron stars are swallowed whole by black holes with masses above about $10 M_\odot$ - this is important for the gravitational wave signal in coalescing binary stars, as discussed elsewhere in this volume). For a spinning hole, the cross-section for capture, and the tidal radius for disruption, depend on the relative orientation of the orbital and spin angular momenta. (Stars on orbits counter-rotating with respect to the hole are preferentially captured: this is a process that would reduce the spin of a hole in a galactic nucleus.)

When stars are swallowed before disruption, they can be treated as point mass particles moving in the gravitational field of the hole; their interactions among themselves can be treated the same way, except insofar as star-star collisions are important. But the physics is much messier in the cases when the tidal radius is outside the hole and the star is disrupted rather than swallowed whole. This phenomenon has been studied since the 1970s, first via analytic models (e.g. [79, 80]) and subsequently by progressively more powerful numerical simulations (e.g. [81, 82], etc.). In the Newtonian approximation the tidal radius is $R_t \sim R_* \left(M_{BH}/M_*\right)^{1/3}$. There are several key parameters: the type of star; the pericentre of the star's orbit relative to the tidal radius, and the orientation of the orbit relative to the hole's spin axis. In most astrophysical contexts, the captured stars would be on highly eccentric orbits (i.e the orbital binding energy would be small compared to that of a circular orbit at the tidal radius). If the pericentre is of order $R_t$, the star will be disrupted, and the debris will be continue on eccentric orbits, but with a spread of energies of order the binding energy of the original star. Indeed nearly half the debris will escape from the holes gravitational field completely; the rest will be on more tightly bound (but still eccentric ) orbits, and would be fated to dissipate further, forming a disc much of which would then be accreted into the hole. A pericentre passage at (say) 2 or 3 times $R_t$ would not disrupt a star completely, but would remove its envelope, and induce internal oscillations, thereby extracting orbital energy and leaving the star vulnerable on further passages. On the other hand, as first discussed by [79], a star that penetrates far inside the tidal radius (but not so close to the hole that it spirals in) will be drastically distorted and compressed by the tidal forces, perhaps to the extent that a nuclear explosion occurs, leading to a greater spread in the energy of the debris than would result from straight gas dynamics.

There have in recent years been detailed computations of these processes, and also of the complicated and dissipative gas dynamics that leads to the accretion of the debris, and the decline of the associated luminosity as the dregs eventually drain away. There are two generic predictions: the debris enveloping the hole should initially have a thermal emission with a power comparable to the Eddington luminosity of the hole; and at late times, when the emission comes from the infall of debris from orbits with large apocentre, the luminosity falls as $L \propto t^{-5/3}$.

There has been much debate about the role of tidal capture in the growth of supermassive holes, and the fueling of AGN emission, and many calculations of the expected rate, taking account of what has been learnt about the masses of holes, and the properties of the stellar populations surrounding them. Some flares in otherwise quiescent galactic nuclei, where the X-ray luminosity surges by a factor $\gtrsim 100$, have been attributed to tidal disruptions.

But tidal disruption is included in this chapter mainly because of a remarkable burst detected by Swift, Sw J164449.3 [83], located at the centre of its host galaxy, and which was exceptionally prolonged in its emission. This is perhaps the best candidate so far for an event triggered by tidal capture of a star. The high energy radiation, were this model correct, would come from a jet generated near the hole. Modeling is still tentative, and is difficult because there is no reason to expect alignment between the angular momentum vectors of the hole and of the infalling material. But the inner disc (and therefore the inner jet) would be expected to align with the hole, though it is possible that the jet is deflected further out by material with different alignment (c.f. [84]).

Be that as it may, this exceptional burst offers model-builders an instructive 'missing link' between the typical long ('Type 1') burst, involving a massive star, and the jets in AGNs which are generated by processes around supermassive holes.

## 0.5 Bursts at Energies above GeV: Fermi and beyond

The Fermi satellite, launched in 2008, has two instruments: the Gamma-ray Burst Monitor (GBM, [85]) and the Large Area Telescope (LAT, [86]). The GBM measures the spectra of GRB in the energy range from 8 keV to 40 MeV, determining their position to $\sim 5^o$ accuracy. The LAT measures the spectra in the energy range from 20 MeV to 300 GeV, locating the source positions to an accuracy of $< 1^o$. The GBM detects GRBs at a rate of $\sim 250$ per year, of which on average 20% are short bursts, while the LAT detects bursts at a rate of $\sim 8$ per year. The great strength of this combination is to provide the large field of view and high detection rate of the GBM extending to energies as low as the BAT in Swift, with the very high energy window of the LAT, which opens up a whole new vista into the previously almost unexplored GeV to sub-TeV range of GRBs.

Two unexpected features of the GeV emission of bursts were soon discovered by the Fermi-LAT. One is that the onset of the GeV emission is invariable delayed relative to the onset of the MeV emission (by a few seconds in LGRBs, and fractions of a second in SGRBs), e.g. [87, 88, 89, 90]. The other is that the GeV emission generally lasts for much longer then the MeV emission, decaying as a power law in time and lasting up to a 1000 s in some cases, i.e. well into the afterglow phase, including both LGRBs and SGRBs. The fact that GeV emission has been detected from a number of SGRBs is, in itself, also new. Remarkably, the GeV behavior of LGRBs and SGRBs is quite similar. This is not unexpected, since most of the GeV emission is produced in the afterglow phase, which is essentially a self-similar process. What is more unexpected is that the ratio of the total energy in the GeV range to MeV range is $\sim 0.1 - 0.5$ for LGRBs, while it is $\gtrsim 1$ for SGRBs.

Bursts detected with the LAT have spanned a range of redshifts extending

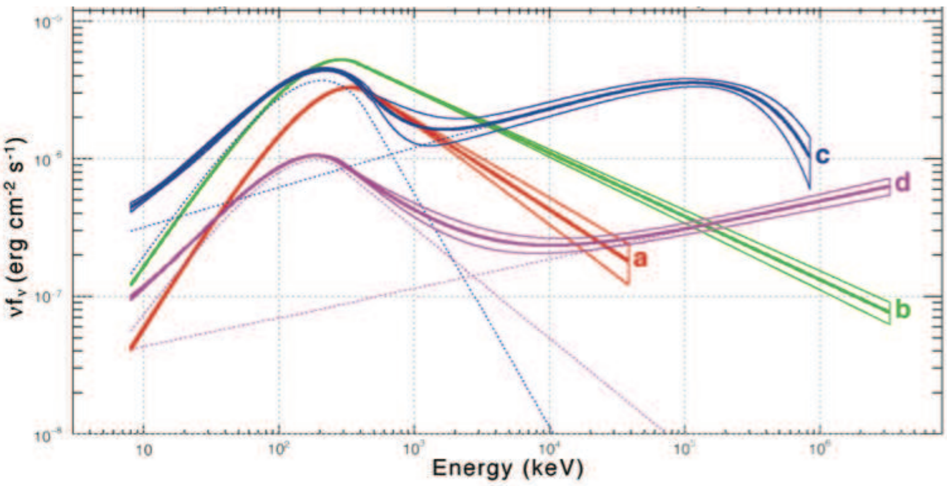

Figure 0.4 Spectra of GRB090926A from *Fermi* at four different time intervals, a= [0.0-3.3s], b= [3.3-9.7s], c= [9.7-10.5s], d= [10.5-21.6s] [91].

up to $z = 4.3$, with photon energies (in the burst rest frame) up to $10-130$ GeV, the highest value so far being being that found for GRB 130427A [92], at a redshift $z \sim 0.33$. This is encouraging for the planned large Cherenkov Telescope Array (CTA) [93, 94], whose energy threshold may be as low as 50 GeV and whose detection rate of GRBs is estimated in the range $0.7-1.6$ per year, based on the rate of Swift triggers. A roughly similar rate of detection is also expected for the High Altitude Water Cherenkov (HAWC) detector [95, 96], whose threshold is expected to be 10-20 GeV.

## 0.6 GRBs in Non-photonic Channels?

Two types of non-photonic signals that may be expected from GRBs are gravitational waves (GWs) and high energy neutrinos (HENUs). The most likely GW emitters are short GRBs [97], if these indeed arise from merging compact objects [12]. The Swift and Fermi localization of a short GRB would help to narrow the search window for gravitational waves from that object [98]. The detection of gravitational waves from a well-localized GRB would lead to a great scientific payoff for understanding the merger physics, the progenitor types, and the neutrons star equations of state. The rates of compact merger GW events in the advanced LIGO and VIRGO detectors may be at least several per year [99]. However, even if these events all give rise to gamma ray bursts, only a small fraction would be beamed towards us. Long GRBs, more speculatively, might be detectable in GWs if they go through a magnetar phase [100], or if the core collapse breaks up into substantial blobs [101]; more detailed numerical calculations of collapsar (long) GRBs lead to GW prospects which range from pessimistic [102] to modest [103].

High energy neutrinos may also be expected from baryon-loaded GRBs, if sufficient protons are co-accelerated in the shocks. The most widely considered paradigm involves proton acceleration and $p\gamma$ interactions in internal shocks, resulting in prompt $\sim 100$ TeV HENUs [104, 105]. Other interaction regions considered are external shocks, with $p\gamma$ interactions on reverse shock UV photons leading to EeV HENUs [106]; and pre-emerging or choked jets in collapsars resulting in HENU precursors [107]. An EeV neutrino flux is also expected from external shocks in very massive Pop. III magnetically dominated GRBs [108]. Current IceCube observations [109] are putting significant constraints on the simplest internal shock neutrino emission model. More careful modeling of internal shocks [110] reveal that several years of observations will be needed for reliably testing such models, while other types of models, such as photospheric models [111] or modified internal shock models [112] are yet to be tested. However, the excitement in this field is palpable, especially since the announcement of the detection by IceCube of PeV neutrinos [113] whose origin is almost certainly astrophysical.

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