Open Questions in GRB Physics

Bing Zhang

Abstract

Open questions in GRB physics are summarized as of 2011, including classification, progenitor, central engine, ejecta composition, energy dissipation and particle acceleration mechanism, radiation mechanism, long term engine activity, external shock afterglow physics, origin of high energy emission, and cosmological setting. Prospects of addressing some of these problems with the upcoming Chinese-French GRB mission, SVOM, are outlined.

Key words: gamma-rays: bursts; stars; black holes; neutron stars; shocks; magnetic fields; radiation mechanism

1. Introduction

The field of gamma-ray bursts (GRBs) has rapidly advanced in recent years, especially following the launches of NASA missions Swift (in 2004) and Fermi (in 2008) [1,2,3,4]. Due to their elusive nature, observing GRBs in all wavelengths at all epochs (including during and after the GRB) is still challenging with the current GRB detectors and follow up telescopes. As a result, every time when a new temporal or spectral window is unveiled, a rich trove of new phenomenology is uncovered. While solving some old problems, new observations usually raise more questions and challenges. This provides sustainable impetus to this still relatively young field. In any case, current observations gradually put together a sketch of the global picture of GRBs, although many details remain vague or uncertain.

This review summarizes the open questions in GRB physics as of 2011. Ten topics are discussed, including classification, progenitor, central engine, ejecta composition, energy dissipation and particle acceleration mechanism, radiation mechanism, long term engine activity, external shock afterglow physics, origin of high energy emission, and cosmological setting. In connection with the upcoming Chinese-French SVOM (Space-based multi-band astronomical Variable Object Monitor) mission, I also discuss some prospects of addressing some of these problems in 2015 and beyond. More detailed discussions on the SVOM mission [5] and multi-wavelength observational prospects in 2015 and beyond [6] can be found in this volume.
2. Open Questions

2.1. Classification

In astronomy, classification is traditionally solely based on distinct clusters in data based on well-defined criteria. Well known examples include stellar spectral classification and supernova classification, both having spectral line features as essential criteria. Since these criteria usually invoke “yes” or “no” judgments, the classification schemes of these objects are relatively unambiguous. As transient events without any credible spectral feature, the GRB classification was traditionally based on their durations in the temporal domain and hardness ratio (HR) in the spectral domain. An analysis of GRBs detected by BATSE (sensitive in 30 keV - 2 MeV) suggested that there are two classes of GRBs in the $T_{90} - HR$ space, i.e. the long/soft class that comprises roughly 3/4 of the population, and the short/hard class that comprises the other 1/4 [7]. A rough separation line in duration, i.e. $T_{90} \sim 2$ s in the observer frame, was suggested.

The main issue of applying the $T_{90}$ criterion to define the class of a GRB is that $T_{90}$ is detector dependent. GRB pulses are typically broader at lower energies. Also a more sensitive detector tends to detect weaker signals which would be otherwise buried in noises. It was therefore not surprising that observations carried out with softer detectors such as HETE-2 and Swift brought confusions to classification. For example, among a total 476 GRBs detected by Swift BAT (sensitive in 15 keV - 150 keV) from Dec. 19 2004 to Dec. 21 2009, only 8% have $T_{90} < 2$s [8], much less than the $\sim 1/4$ fraction of the BATSE sample. An additional 2% of Swift GRBs have a short/hard spike typically shorter than or around 2s, but with an extended emission lasting 10’s to $\sim 100$ seconds. These bursts, dubbed “short GRBs with E.E.” [9], have $T_{90} \gg 2$s as observed by Swift, but could be short GRBs if they were detected by BATSE. So the unfortunate consequence of the $T_{90}$ classification is that the membership to a certain category of the same GRB could change when the detector is changed. One possibility is to define a burst’s category based on its BATSE-band duration. Then two issues arise: First, what is special for the BATSE band? If other detectors such as Swift were launched earlier, what would be the criteria to define long vs. short GRBs? Second, it is difficult to precisely infer $T_{90}$ in the BATSE band using the data of other detectors (e.g. Swift/BAT). It requires accurate time-dependent spectral information of the entire burst, which is only available for few very bright GRBs. Even for these bursts, extrapolating the BAT band spectrum to the BATSE regime is risky and usually not correct, since the GRB spectrum is known to be curved. This has been evidenced in some Swift GRBs that were co-detected by other detectors with harder bandpass such as Konus/Wind. Fortunately, the confusion in $T_{90}$ classification only arises in the “grey” area between the two classes. For most GRBs, one can still tell whether they are “long” or “short”.

A further complication is that several groups argue that the best fit to the $T_{90}$ distribution histogram is three Gaussian functions in logarithmic space, e.g. [10]. This adds one more “intermediate-duration” class besides the traditional “short” and “long”. For the same GRB, the membership to this intermediate class is even more ambiguous and subject to the detector bandwidth and sensitivity.

The differentiation between long and short GRBs is established with a firmer footing thanks to the afterglow and host galaxy observations. Observations led by BeppoSAX, HETE2, and Swift suggest that at least some long GRBs are associated with supernova Type Ic [11,12,13,14,15]. Most long GRB host galaxies are found to be dwarf star-forming galaxies [16]. These facts establish the connection between long GRBs and deaths of massive stars [17,18]. The breakthrough led by Swift unveiled that some nearby short GRBs (or short GRBs with E.E.) have host galaxies that are elliptical or early type, with little star formation [19,20,21,22]. This points towards another type of progenitor. The top candidate model for this category is mergers of two compact objects, e.g. two neutron stars (NS-NS) or a neutron star and a black hole (NS-BH) [23,24,25]. This led to the common ansatz that “long GRB = massive star GRB, and short GRB = compact star GRB”.

Such a cozy picture was soon messed up by some observations. GRB 060614 and GRB 060505 are two long duration nearby GRBs that did not have bright SN associations and that share similar properties to short GRBs [26,27,28,29,30]. Two high-z GRBs 090423 and 080916 have rest-frame durations shorter than 1s, but are likely related to massive stars [31,32,33,34]. An observer-frame short GRB 090426 was found in many aspects similar to long GRBs [35,36,37]. This suggests that certain observation properties (e.g. long vs. short duration) do not always refer to certain types of progenitor.

While some appeal to modify the meaning of “long” and “short” to reflect “massive star origin” and “compact star origin” ^1, respectively, others started to “classify” GRBs physically [30,38,31], and appeal to multiple ob-

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1. The “long” and “short” notations become more and more confusing, since growing data demand to introduce more complicated
observational criteria to determine the “physical category” of a GRB [39,31]. The classification here is beyond the traditional definition of astronomical classifications (which are based on data). Rather, they are based on some well-motivated GRB progenitor models which are believed to be associated with GRBs (see more discussion below in § 2.2). For cosmological GRBs that mark catastrophic explosions, two general physical classes of GRBs (or two types of models that are associated with GRBs) are “massive star GRBs” (or “Type II GRBs”) and “compact star GRBs” (or “Type I GRBs”) [30,38,31,40,41]. Since duration alone is no longer necessarily a good indicator for the physical category of a GRB, one must appeal to multiple observational criteria to judge the correct physical category of the GRB progenitor model that is associated with a certain GRB [31,39].

One may also seek for other observational parameters to conduct GRB classification. For example, for GRBs with redshift measurements, a parameter $\varepsilon \equiv E_{\gamma,\text{iso},52}/E_{p,2}$ can be used to classify GRBs into two categories [42]. The high-$\varepsilon$ and low-$\varepsilon$ categories are found to be more closely related to Type II (massive star) GRBs and Type I (compact star) GRBs, respectively.

2.2. Progenitor

The progenitors of GRBs are not identified, and it will be very difficult to identify them. There are two ways to approach this goal. One is to use observational data to narrow down the allowed progenitor types. The other is to use theoretical insights to construct toy models (e.g. collapse of a massive star, merger of two NSs) and use analytical and numerical methods to investigate whether GRBs can be made.

For massive star GRBs (typically long), the following two observational facts have offered important clues for the progenitor type: (1) A handful of GRBs are found to be associated with supernovae Type Ic (no hydrogen lines and no or weak helium lines) [11,12,13,14,15,43]; (2) The hosts are dwarf galaxies with intense star formation, and the GRB locations track the brightest star formation regions in the hosts [16,44]. Theoretically, in order to produce a relativistic jet from a collapsing star to power the observed GRB, one requires that the stellar core must carry a high angular momentum [45]. The spin axis then provides a natural preferred direction for jet launch and propagation.

One then comes up with three requirements for a massive star GRB progenitor: (1) These stars must track the brightest regions in the star formation regions; (2) The hydrogen envelope is largely depleted so that the progenitor is likely a Wolf-Rayet star; (3) The core carries a high angular momentum. Within these general constraints, several candidate progenitor systems are possible [46]: collapse of a massive single star with a high angular momentum; collapse of a massive star in a close binary system; and merger of two He stars. For the single star scenario, achieving both a depleted hydrogen envelope (which requires a strong wind, and hence, high metallicity) and a rapidly rotating core (requires low metallicity) seem contradictory. It is argued that rapid mixing of H with He would result in burning H to He without the need of ejecting the H envelope (and hence without losing angular momentum) [47]. Alternatively, a binary progenitor can retain a high angular momentum core with the H envelope ejected [45].

An alternative idea to interpret massive star GRBs is to invoke two-step explosions. Such a “supranova” model [48] envisages a core collapse supernova explosion weeks to months before the GRB. This first explosion produces a rapidly rotating massive neutron star, which subsequently collapses to form a black hole and generates a GRB later when the centrifugal support is not enough to hold the neutron star. The observed GRB/SN associations suggest that the delay between the SN and GRB, if any, cannot be more than 1-2 days [12,13,14,15,43]. This model is therefore not favored for massive star GRBs.

One should keep in mind the following caveats regarding the massive star progenitors in general. (1) Among 5-6 robust cases of GRB/SN associations, only GRB 030329 is a typical GRB. The rest are nearby, low luminosity GRBs, which may form a typical population with a different progenitor or different central engine [49,50,51]. Strictly speaking, we may be relying on one case to speculate the progenitor of most GRBs. It is possible that all high luminosity GRBs are associated with SNe. Observationally the SN signature is however difficult to catch, since these GRBs are usually not at low redshifts, and since they typically have bright optical afterglows to outshine the SN signals. (2) A good fraction of long GRBs, namely “optically dark GRBs”, do not have a detectable optical afterglow. Their host galaxies are usually not identified. The predominant dwarf star-forming host galaxies in the published sample [16] may be due to a selection effect. In fact, a Chandra observation of the dark GRB 090417B shows that its host galaxy is a Milky-Way like galaxy with heavy dust extinction [52]. (3) The theoretical notations such as “long short GRBs” or “short long GRBs”.

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that peaks at low-$z$ luminosity function of short GRBs should be shallow [69]. Since most merger models predict a redshift-distribution expected in massive star core collapse scenarios) to help to collimate the jet [60,61]. Only BH-NS systems powered by BH spin may power these energetic events, but these mergers (with a massive BH and rapid BH spin) are very consistently reveals wide jets in merger systems due to the lack of a dense medium (e.g. the stellar envelope as rare. Second, in order to account for many high-$L$ events, but these mergers (with a massive BH and rapid BH spin) are very rare. Second, in order to account for many high-$L$ short GRBs and not-too-many low-$L$ nearby short GRBs, the luminosity function of short GRBs should be shallow [69]. Since most merger models predict a redshift-distribution that peaks at low-$z$, the shallow luminosity function is translated to a shallow peak flux distribution ($\log N - \log P$), which violates the BATSE short GRB sample constraint significantly [69]. The consistency between the merger models and the Swift z-known sample [70] or the BATSE sample [71] was claimed shortly after the discovery of short GRB afterglows. However, the Swift sample was too small and the two samples (Swift vs. BATSE) were not jointly considered in those analyses. A recent joint analysis shows a sharp inconsistency between various merger models and the observational constraints ($z - L$ distributions and $\log N - \log P$ distributions) [69]. This may suggest that either the merger models are not the correct model for short GRBs, or not all short GRBs are from compact star mergers. A recent modified compact star coalescence scenario is to invoke dynamical “collisions” of NS-NS or NS-BH systems in globular clusters [72,73]. If this population of coalescences dominates over mergers in the field galaxy due to gravitational wave radiation, the above conflict may be alleviated. In any case, since NS-NS and NS-BH merger models predict specific gravitational wave signals [74], a definite test to the merger models of short GRBs may be achieved in the future when gravitational wave detections become possible.

Besides mergers, several other types of progenitor have been proposed for short GRBs. One scenario is accretion-induced-collapses (AICs) of NSs (e.g. [75]), which is similar to the “supernova” model for long GRBs [48], but with a much longer delay between the SN and GRB. Cosmological short GRBs may be produced this way. Soft Gamma-ray Repeaters (SGRs) produce giant flares with a short, hard spike, which would be recognized as short/hard GRBs in nearby galaxies [76,77,78]. It is likely that the short/hard GRB population is contaminated by these events, but the fraction of contamination is believed to be small [79].

2.3. Central Engine

Different types of progenitor may result in a common central engine that powers the observed GRBs. Observations suggest that a GRB central engine should satisfy the following requirements: (1) It can drive an outflow with extremely high luminosity and energy. If the emission is isotropically distributed in all directions, the required jet luminosity ranges from $L_{\text{iso}} \sim 10^{47} - 10^{44}$ erg s$^{-1}$, and the total gamma-ray energy ranges from $E_{\text{iso}} \sim 10^{49} - 10^{52}$ erg [80,81]; (2) The ejecta need to be “clean” with small baryon contamination, so that they
can achieve a relativistic speed, with Lorentz factor $\Gamma$ typically greater than 100 [82,83,84], some even close to 1000 [85,86,87]; (3) The outflow needs to be collimated, with a beaming factor $f = \Delta \Omega / 4\pi \sim 1/500$ for bright GRBs [88,89,90,91], so that the real luminosity and energy of a GRB is reduced by this factor; (4) The engine needs to be intermittent, with a range of variability time scales [80,92]. In some GRBs, the engine can generate smooth (but varying) lightcurves [93,14]; (5) The engine can last long, with renewed, progressively less powerful late activities to power X-ray flares and other activities (see §2.7 for full discussion).

Several types of GRB central engine have been discussed in the literature. The leading candidate is a black hole (possibly rapidly spinning) + torus system. An alternative candidate is a rapidly spinning, highly magnetized NS (magnetar). A more exotic possibility is a compact star solely composed of quark matter, i.e. a quark star. There are three energy reservoirs involved in these engines: the accretion power, the spindown power of the central object, and the phase transition power.

The black hole - torus engine is widely discussed in both the collapsar scenario [17,94,95,96], and the compact star merger scenario [25]. The first energy source is the accretion power from the torus. Neutrino annihilation from the torus can drive a hot jet along the spin axis to power the GRB. The accretion powered jet luminosity is $L_{\text{acc}} = \zeta M c^2 \sim 1.8 \times 10^{51} \text{ erg s}^{-1} \zeta^{-3} (M/1 M_{\odot} \text{ s}^{-1})$. In order to achieve the observed GRB luminosity, the accretion rate should be close to (0.1-1) $M_{\odot}/s$ for a reasonable efficiency factor $\zeta$ to convert accretion power into jet power. The second energy source is the spin energy of the black hole. This energy can be tapped by magnetic fields threading the ergosphere of a Kerr black hole through the Blandford-Znajek (BZ) mechanism [98,99,100,101,102]. The jet luminosity $L_{\text{BZ}} \simeq 0.1 B^2 (\Omega_{\text{BH}} c) (GM_{\text{BH}} / c^2)^2 \simeq 3 \times 10^{50} \text{ erg s}^{-1} B_{51}^2 (M/3 M_{\odot})^2 a^2 (a)$, where $a$ is the dimensionless spin parameter of the black hole, and $f(a)$ is a increasing function of $a$. In order to power a GRB, the black hole should be rapidly spinning ($a \lesssim 1$), the accretion rate should be high so that magnetic fields near the horizon are strong enough (the radial magnetic field strength near the black hole is $B \gtrsim 10^{15} \text{ G}$). For a same $a$, a more massive BH (and hence, more spin energy to tap) would give a more luminous burst. Such a BZ-powered jet would carry a strong magnetic field, and is likely Poynting-flux-dominated. It is possible that both mechanisms (neutrino annihilation and BZ process) are acting in BH-torus systems. A variable outflow can be due to the interplay between the magnetic fields and the accreting materials [103,104]. For a jet emerging from a star, jet propagation instabilities in the envelope can give rise to further variabilities in the outflow [96,97].

The main power of a millisecond magnetar engine is its spindown power [105], which is $L_{\text{sd}} = B^2 \Omega^4 R^6 / 6 c^3 \sim 3.7 \times 10^{50} \text{ erg s}^{-1} B_{51}^2 \Omega_{15}^4 R_{15}^6$ for the dipole spindown model. In order to power a GRB, the magnetar must have a surface magnetic field $B \gtrsim 10^{15} \text{ G}$, and an angular frequency $\Omega \gtrsim 10^3 \text{ Hz}$ (which corresponds to a spin period $P \lesssim 0.6 \text{ ms}$). Notice that $\Omega \sim 10^4$ is already close to the upper limit of the angular frequency of a neutron star. The maximum total energy of a magnetar engine is defined by its spin energy $E_{\text{spin}} \sim (1/2) I \Omega^2 \sim 5 \times 10^{52} \text{ erg}$. Increasing $B$ would reduce the spindown time scale $\tau_{\text{sd}} = 3 c^3 I / (B^2 R^6 \Omega^2) \sim 800 s L_{15} B_{51}^{-2} R_{15}^{-6} \Omega_{15}^{-2}$. In principle, the engine cannot power an intrinsically luminous and long GRB. One may invoke a small beaming factor $f$ to accommodate a large isotropic luminosity. However, for millisecond rotators the open field lines have a large solid angle, so that $f$ cannot be too small unless another medium (e.g. envelope or supernova ejecta) serve to collimate the jet. It is possible that the accretion power also operates in a magnetar. The neutrino annihilation rate is enhanced with respect to the BH-torus system [106]. However, given the high accretion rate (e.g. 1$M_{\odot}/s$), the NS would quickly (e.g. in 2 seconds) turn into a BH. Another issue is that a neutrino-driven wind from a proto neutron star tends to be “dirty” [107,108], which cannot produce a clean fireball to power a GRB. A GRB may be generated after the proto neutron star cools and a Poynting flux dominated outflow is launched, typically several seconds later [109,110,111]. Scenarios to have a magnetic bubble penetrating through the stellar envelope without significant contamination have been discussed [112,113].

Strange quark matter could be more stable than neutron matter [114], so that strange quark stars could form in high pressure environments for a wide range of allowed parameters for QCD [115]. A quark star engine has been invoked to power a GRB in various contexts [116,117,118,119,120]. There are two advantages of introducing a quark star engine. First, extra energy sources due to phase transitions (from neutron matter to 2-flavor quark matter, from 2-flavor to 3-flavor strange quark matter, and quark matter condensation [116,118,120]) are introduced. Second, since the star is bound by strong interaction rather than gravity, neutrinos and photons can be released without launching materials to contaminate the fireball [116,118,119]. The time scale for phase transitions may be fast. In order to launch a highly variable jet, intermittent accretion is needed, and the engine power includes both the accretion power and the phase transition power [118].

Since all three types of engine are argued to satisfy most observational constraints, identifying the right one among them using observational data is not straightforward. Among the three possible engines, the BH - torus system is most naturally expected. For massive star GRBs, studies of Type Ic SNe associated with some GRBs suggest a large enough mass for the progenitor star to form a BH rather than a NS [121,122]. A BH-torus engine
is relevant for BH-NS mergers. For NS-NS mergers, the total mass of the two NSs ($\sim 2.8 M_\odot$) is believed to exceed the maximum NS mass for most NS equation of state, so that a BH - torus engine is also likely. Nonetheless, evidence of a NS (QS) engine in some GRBs is collected. First, spectral modeling of SN 2006aj associated with GRB 060218 suggests that this SN has much smaller ejecta mass and kinetic energy than other Type Ic SNe associated with GRBs, pointing towards a massive star progenitor that is not massive enough to produce a BH [50]. Second, the spin down luminosity of a NS (QS) should have a constant luminosity plateau followed by a $L \sim t^{-2}$ decay. This signature may show up in the early afterglow phase. The continuous injection of pulsar spindown energy onto the blastwave would result in a shallow decay phase in the early afterglow phase [123,124], which may account for the plateau feature in the early afterglows of some Swift GRBs [125,126,127]. If the pulsar wind has strong dissipation before landing on the blastwave and if the engine ceases suddenly (probably due to collapse into a black hole), an “internal plateau” would appear in the X-ray afterglow, characterized by a plateau phase followed by a very steep decay as observed in some Swift GRBs [128,129,130] (see §2.7 for more discussion). We therefore suggest that although BH - torus systems may be common in most bright, energetic GRBs, pulsar systems may exist in at least some GRBs. Unfortunately, besides theoretical arguments, there is essentially no “smoking-gun” observational criterion to differentiate a QS engine from a NS engine.

A dedicated review on numerical simulations of GRB central engines can be found in this volume [131].

2.4. Ejecta Composition

The composition of a GRB outflow includes three components: matter, magnetic fields, and photons. Photons are advected with matter and magnetic fields initially, and are decoupled from the ejecta at the photosphere radius, where Compton scattering optical depth drops below unity. Above the photosphere, the jet carries a matter flux and a magnetic flux, which is essentially a Poynting flux in the lab frame because of the existence of an induced electric field. More photons are generated from the regions where kinetic energy or magnetic energy is dissipated (i.e shocks or magnetic reconnection regions), which escape the ejecta without further coupling. The distribution of energy between matter and magnetic fields is denoted by the magnetization factor $\sigma \equiv B^2/4\pi \rho c^2$ (where the magnetic field $B$ and the matter density $\rho$ are measured in the lab frame), the ratio between Poynting flux and matter flux. Within the matter content, one has the baryonic and leptonic components. The relative distribution can be denoted by a parameter $Y = n_\pm/n_p$, the number ratio between leptons and protons. Usually the baryonic component dominates in mass unless $Y \gtrsim m_p/m_e$, the proton-to-electron mass ratio. Due to the extreme temperature (typically $kT \sim$ MeV) and density (typically nuclear density) at the central engine, heavy ions are less likely to survive in the jet, so the dominant charged baryons in the jet are protons. For both compact star merger and massive star core collapse central engines, it is likely that a noticeable fraction of free neutrons exist in the fireball, and initially are coupled with protons through strong interaction [132,133]. These neutrons decouple from the ion ejecta, decay with a comoving life time $\sim 900$ s, and would leave interesting observational features [132,134,135]. The abundance of free neutrons is usually denoted by the neutron-to-proton number ratio, $\xi \equiv n_n/n_p$.

The traditional GRB models are built in the matter-dominated regime ($\sigma \ll 1$). This is the standard “fireball” shock model [23,136,137,138,139,140]. Magnetic fields are likely to be entrained in the ejecta. In the matter-dominated models, they are believed not to play a kinematically dominant role. As $\sigma$ approaches and exceeds unity, magnetic fields become kinematically important. In such a magnetically-dominated jet, the ejecta would carry a globally ordered magnetic field. Notice that giving a same total outflow luminosity and at a same distance from the central engine, the absolute strength of magnetic fields does not vary significantly from $\sigma \lesssim 1$ to $\sigma \gg 1$. This is because the Poynting flux does not differ significantly, and different $\sigma$ is mostly caused by different mass flux of the flow. Another comment is that due to magnetic acceleration and dissipation, $\sigma$ is expected to drop with radius [141,142,143,144,145]. As a result, one needs to specify a radius (from the central engine) when judging whether the flow is matter-dominated or magnetically-dominated.

Diagnosing the composition of GRB ejecta has not been an easy task. Although the $\sigma \ll 1$ models have been widely discussed mostly because of their simplicity, evidence that magnetic fields are playing an important role at least in some GRBs is gradually accumulating. (1) If $\sigma \gtrsim 1$, an ordered magnetic field would give rise to strong linearly polarized synchrotron emission [146,147,148,149]. Strong linear polarization of gamma-ray emission has been claimed in some GRBs (e.g. [150,151]), although the results are subject to large uncertainty [152]. (2) Recent Fermi observations of GRB 080916C [85] revealed a series of nearly featureless Band-function spectra covering 6-7 orders of magnitude in energy throughout the entire burst. Such an observational fact brings challenge to the traditional fireball internal shock model. If the observed Band component is the non-thermal emission from
internal shocks, one would expect a bright quasi-thermal spectral component from the fireball photosphere which outshines the non-thermal component, making the observed spectrum significantly deviated from the simple Band form. This led to the suggestion that the ejecta has to be Poynting flux dominated in order to suppress the bright photosphere thermal emission [153,154]. Since most Fermi LAT GRBs have Band-only spectra similar to GRB 080916C [155], one may speculate that most GRBs may function similar to GRB 080916C. The $\gamma \ll 1$ dissipative photosphere model (e.g. [156,157]) could give rise to a Band-like spectrum, but the model predictions cannot reproduce the broad spectra of GRB 080916C (e.g. [145,155] for detailed discussion). The Fermi LAT GRB 090902B [158] is a special case that shows bright quasi-thermal emission in the time-resolved spectra [159,155], which can be well interpreted as the photosphere emission [160]. The magnetization parameter $\sigma$ is likely not very high, but the magnetic fields need to be strong in any case [160]. (3) As the ejecta is decelerated by the ambient medium, the existence and strength of the reverse shock depends on the GRB composition [161,162,163,164]. The general trend is the following [162]: when $\sigma \ll 1$, the reverse shock (RS) emission becomes progressively stronger as $\sigma$ increases, because the synchrotron emission becomes progressively stronger in a stronger magnetic field. The RS brightness reaches the peak around $\sigma \sim 0.1$. When $\sigma$ gets close and surpasses unity, the strong pressure from the magnetic field compensates part of the forward shock (FS) thermal pressure, so that the FS becomes progressively weaker until eventually disappears when the magnetic pressure can fully balance the FS pressure. Studying the strength of the RS can therefore diagnose ejecta composition. The bright optical flashes seen in several GRBs (e.g. GRBs 990123, 021211, 061126) require that the RS region is much more magnetized than the FS region, suggesting that the engine is carrying a strong magnetic field [165,166,167,168], with a $\sigma$ close to (but does not exceed) unity. An early optical polarimetry observation of GRB 090102 revealed a $10 \pm 1\%$ polarization degree of emission during the early steep decay phase believed to be of the RS origin [169]. This suggests that the central engine ejecta carried an ordered magnetic field.

Besides the above observational diagnostics, claims about the GRB composition may be made using indirect theoretical modeling. For example, different models predict different radii of gamma-ray emission. The photosphere radius is typically $R_{\phi} \sim (10^{11} - 10^{12})$ cm from the central engine. Internal shocks, on the other hand, occur at distances $R_{\text{IS}} \sim \Gamma^2 c \delta t \sim 3 \times 10^{13}$ cm$^2 \delta t / \gamma$, where $\delta t$ is the typical variability time scale. Magnetic dissipation may occur in various radii. For models that invoke a striped-wind field geometry (relevant to pulsar-like central engines), significant magnetic dissipation can occur below the photosphere, so that the photosphere emission is enhanced. For models invoking helical magnetic geometry (relevant to black hole - torus engines), significant magnetic dissipation may not easy to occur at small radii, but rather occur at a large enough radius where the ordered field lines are distorted enough so that field lines with opposite orientations can approach each other and reconnect. Fast magnetic dissipation may be triggered either by collision-induced turbulent reconnection [145], by a switch from the collisional to the collisionless reconnection regimes [170], or by current instability [113]. In all these cases, the dissipation radius is usually larger than the photosphere radius, typically with $R_{\text{mag}} \geq 10^{14}$ cm. Finally, for a neutron rich outflow, neutrons decay in all radii, but with a characteristic decay radius $R_{n} \sim 900c\Gamma = 2.7 \times 10^{15}$ cm$^{2}$\,$\Gamma$. Measuring the location of the MeV GRB emission $R_{\text{GRB}}$ may shed light into the unknown composition of the GRB ejecta.

Observationally, it is not straightforward to measure $R_{\text{GRB}}$ using the MeV data. Nonetheless, there are three indirect ways to infer this radius using X-ray, optical and GeV emission data. (1) Swift GRBs typically show a rapidly decaying early X-ray afterglow, which is found to be connected to prompt gamma-ray emission [171,172,173]. The leading interpretation is that this is the high-latitude emission of a conical jet after the prompt emission ceases abruptly [174,175,176,177,178]. Within this interpretation, the duration of the steep decay phase is defined by $\Delta t_{\text{steep}} \sim (R_{\text{GRB}}/c)(1-\cos \theta_j)(1+z) \sim (R_{\text{GRB}}/c)(\theta_j^2/2)(1+z)$. For a typical jet angle $\theta_j \sim 0.1$, the data generally require that $R_{\text{GRB}} > 10^{15}$ cm [177,178]; (2) Some GRBs have prompt optical emission detected roughly tracking gamma-ray emission [179,180]. If this optical emission is from the same emission region as gamma-rays, the GRB emission site can be constrained by requiring that the synchrotron self-absorption frequency is below the optical band. For the naked-eye GRB 080319B, this gives $R_{\text{GRB}} \sim 10^{16}$ cm [180,181]. Constraints from other GRBs with prompt optical detections or upper limits give $R_{\text{GRB}} \geq \frac{10^1}{2}$ cm for typical GRB Lorentz factors [182]; (3) Fermi observations suggest that for a good fraction of GRBs, the MeV Band-function spectra extend to the GeV range, suggesting that GeV emission is from the same region as the MeV emission. For these bursts, the detected maximum GeV photon energy can be used to constrain $R_{\text{GRB}}$ along with $\Gamma$ [183]. For example, GRB 080916C gives a constraint $R_{\text{GRB}} \geq 10^{15}$ cm in general [153], and $R_{\text{GRB}} \sim 10^{16}$ cm if $R_{\text{GRB}} \sim \Gamma^2 c \delta t$ is assumed [85]. A general picture emerging from these indirect constraints is that $R_{\text{GRB}}$ is usually large, typically $10^{15}$ cm. This is also consistent with some model constraints based on GeV observations [184,185]. These large emission radii are consistent with the expectation of high-$\sigma$ models, although low-$\sigma$ models are not ruled out (but the parameter space is constrained). The caveat here is that the optical/GeV emission may not always be from the
same region as MeV emission. For example, various arguments suggest that the gamma-ray emission radius may be smaller than that of optical emission in GRB 080319B [186,187,188]. The distinct GeV component of GRBs 090902B and 090510 is very likely from a different radius from the MeV component [86,158,155].

To summarize, the case of GRB composition is inconclusive. Evidence of a strongly magnetized central engine is accumulating, although the \( \sigma \) value in the GRB emission region is not well constrained. It is possible that \( \sigma \) may vary from burst to burst. This may sound unnatural. However, as explained above, when \( \sigma \) is greater than, say, 0.3, the increase in \( \sigma \) does not correspond to a further increase of Poynting flux, but rather corresponds to a decrease in the associated matter flux. As a result, a slight change in matter flux may result in a significant change in the \( \sigma \) value in the outflow (e.g. from \( \sigma \lesssim 1 \) to \( \sigma \gg 1 \)). This is entirely possible. Since \( \sigma \) is a decreasing function of radius [141,142,143,144,145], one needs to specify a radius of reference for comparison in order to get a coherent picture of GRB magnetization. For example, it is possible that \( \sigma \gg 1 \) initially in the GRB emission region, \( \sigma \) is moderately high in the GRB emission region, and \( \sigma \lesssim 1 \) at the deceleration radius after the global magnetic dissipation process is over [145].

GRB composition is greatly tied to two interesting topics: whether GRBs are the dominant sources of ultra-high energy cosmic rays (UHECRs) [189,190] and high energy neutrinos [191,192,193]. These models all invoked a baryon-dominated outflow. If GRBs are on average Poynting-flux-dominated, the strengths of these signals would drop by a factor \((1 + \sigma)^{-1}\), rendering GRBs not necessarily the dominant contributors to UHECRs and the high energy neutrino background.

2.5. Energy Dissipation and Particle Acceleration Mechanism

The main energy sources of a GRB include the gravitational accretion energy \((E_{\text{grav}} \sim (1/2)GMm/R \sim 1.3 \times 10^{53} \text{ erg}(M/10M_{\odot})(m/1M_{\odot})/R_{7})\), where \( M \) is the mass of the accretor and \( m \) is the mass of accreted materials) and the rotation energy of the central BH \((E_{\text{rot,BH}} \sim M_{\text{BH}}c^2/(1 - \sqrt{1 - (1 + \sigma^2)^{-1}}) \lesssim 0.29M_{\text{BH}}c^2 \sim 5.2 \times 10^{54} \text{ erg}(M_{\text{BH}}/10M_{\odot}))\) or NS \((E_{\text{rot,NS}} \sim (1/2)I_{45} \Omega^2 \sim 5 \times 10^{32} \text{ erg}I_{45}\Omega_{29}^2)\). Besides, the central engine carries a magnetic field energy \(E_{\text{mag}} \sim (1/6)R_{7}^3B_{8}^2 \sim 1.7 \times 10^{50}B_{8}^2R_{7}^3\). For quark star scenarios, an extra phase transition energy (of the same order of the accretion energy) may be added to the energy budget.

In a GRB, energy is transferred among various forms in different stages. A fraction of the gravitational potential energy is initially converted into thermal energy, forming a hot fireball of photons, electron/positron pairs and a small number of baryons. The fireball expands under its own thermal pressure, and converts thermal energy to the bulk kinetic energy of the ejecta. Torqued by magnetic fields, the spin energy of the central object can be converted into a Poynting flux, which is entrained in the ejecta. The ejecta can be also accelerated under the internal magnetic pressure of the ejecta.

At the photosphere radius, photons initially advected in the fireball are released, giving rise to a quasi-thermal spectrum (probably modified by Compton upscattering). This is the first location where photons are released. Above the photosphere, kinetic energy can be converted into particle energy and then into radiation in shocks. Alternatively, Poynting flux energy can be converted into particle energy and then into radiation in reconnection regions. These dissipation regions are additional sites to emit photons. The observed GRB emission is from one or more of these emission sites.

Shock dissipation is the widely discussed energy dissipation mechanism. The internal collisions within an unsteady matter-dominated wind injected from the central engine give rise to internal shocks [140,194]. The relative Lorentz factor between the two colliding shells can range from mildly relativistic \((\Gamma_{\text{rel}} \gtrsim 1)\) to relativistic \((\Gamma_{\text{rel}} \sim \text{a few to tens)}\).

After the collisions, it is assumed that shells merge. The leading fast shell interacts with the circumburst medium and drives an “external” forward shock into the medium [138,195]. A reverse shock propagates into the ejecta until crossing it [196,197,198]. The shocked materials between the forward and the reverse shocks form a “blastwave”. The forward shock is initially relativistic. The reverse shock is mildly relativistic if the central engine duration is not long (the thick shell regime), but could be highly relativistic if the central engine duration is long enough (the thick shell regime) [199]. During the self-similar deceleration phase [200], the blastwave may be refreshed by slow ejecta lagging behind [201] or a Poynting flux injected by a long-lasting central engine (e.g. a spinning down millisecond pulsar or magnetar) [123,124].

Particles (both baryons and leptons) are believed to be accelerated in shocks. The well known process is the first-order Fermi acceleration. The effect is well known in the non-relativistic regime. For relativistic shocks, particle-in-cell (PIC) simulations are starting to unveil the acceleration details [202,203,204]. A power law tail develops as simulation time grows. A relativistic Maxwellian component is still observed in the current simulation,
although it may be significantly eroded eventually [203]. Observationally there is no significant signature for such a relativistic Maxwellian component.

For a magnetized upstream, the shock jump condition is modified [205]. The energy that is available for dissipation is the matter part, which is $1/(1 + \sigma)$ of the total energy [162]. Without magnetic dissipation, the magnetic energy in the flow (a portion of $\sigma/(1 + \sigma)$) remains intact. For deceleration of a magnetized ejecta by an unmagnetized circumburst medium, the strength of the reverse shock progressively decreases [162,163] until completely disappears as $\sigma$ increases to 10s to ~ 100, when the forward shock internal pressure is no longer stronger than the magnetic pressure in the ejecta [162]. For collisions between two magnetized shells, a pair of shocks would propagate into both shells as long as the ram pressure exceeds the magnetic pressure of the shells. These shocks are weak, but in any case, would serve to distort the ordered magnetic field lines in the shell [162,145].

Whether and how particles are accelerated in magnetized shocks is subject to more investigations. PIC simulations [206] suggest that for a relativistic ($\Gamma \gtrsim 5$) magnetized ($\sigma > 0.03$) shock, particle acceleration is possible only within a narrow range of magnetic inclination angles ($\lesssim 34^\circ/\Gamma$). On the other hand, the reverse shock model to interpret early optical flashes require that the reverse shock is more magnetized than the forward shock (with $\sigma$ close to 0.1) [166,165,167]. A $\sim 10\%$ linear polarization degree was measured in the early optical afterglow for GRB 090102 [169], which is consistent with emission from a magnetized reverse shock. The inconsistency between data constraints and PIC simulations may be partially alleviated by the following two factors: First, for thin shells the reverse shock invoked in GRB modeling is usually transrelativistic (i.e. reaching mildly relativistic at the end of shock crossing) [199]. So the allowed magnetic inclination angle space is much larger. Second, If the outflow was initially Poynting flux dominated, it must have gone through significant magnetic dissipation during the GRB prompt emission phase so that $\sigma$ has dropped to around or below unity. Turbulence may have significantly distorted the ordered magnetic field configuration, so that during the deceleration phase, the magnetic field lines are no longer mostly perpendicular to the shock normal [145].

Besides shocks, magnetic dissipation is another effective way to accelerate relativistic particles. This is associated with reconnection of magnetic field lines with opposite polarity. The full details of reconnection is not well understood. The main difficulty has been that reconnection speed is slow in a steady state [207,208]. In the GRB context, continuous slow reconnection below and slightly above the photosphere may enhancephotosphere emission, and lead to an up-scattered non-thermal tail above the photosphere thermal peak [209,210,211,157]. In order to produce bursty emission above photosphere to power the observed GRBs, the traditional Sweet-Parker reconnection speed is too low. A possibility is that reconnection proceeds via turbulence, so that multiple sites reconnect simultaneously [212]. For a high-$\sigma$ flow, turbulence may be induced through multiple internal collisions which distort the ordered magnetic fields. A reconnection-turbulence cascade may result, which would discharge a significant fraction of magnetic energy to power a GRB with high radiative efficiency. This is the Internal Collision-induced MAgnetic Reconnection and Turbulence (ICMART) model of GRBs [145]. Particle acceleration in such turbulence-reconnection events is a difficult problem. Qualitatively, one can have three competing processes: direct electric field acceleration in current sheets, first-order Fermi acceleration between two approaching magnetic field lines, and the second-order Fermi acceleration in turbulence. Unfortunately, no currently available numerical tools can model the detailed particle acceleration processes in a relativistic, turbulent, dissipative, and strongly magnetized fluid. An alternative proposal for fast reconnection is the switch between collisional and collisionless regimes for a striped wind geometry [170]. It is interesting to further investigate how this proposal may account for the GRB prompt emission phenomenology.

Another particle acceleration mechanism in a strongly magnetized flow is the comoving Poynting flux acceleration [213], or inductive and electrostatic acceleration [214,215]. Particles “surf” on a wave of electric fields and gain energy. The applications of such a mechanism to GRBs have been discussed but are not explored in detail.

A dedicated review on particle acceleration in GRBs can be found in this volume [216].

2.6. Radiation Mechanism

GRB prompt emission is characterized by a smoothly-joint broken-power-law named “Band” function [217]. The “non-thermal” nature of the spectrum demands that the emission is produced by a population of particles (likely leptons) with a power law energy distribution. The leading radiation mechanisms include synchrotron (or jitter) radiation, synchrotron self-Compton (SSC), and Compton upscattering of a thermal seed photon source. GRB afterglow has a broad-band spectrum at any epoch. The main contributor to afterglow emission is the synchrotron and SSC emission of the electrons accelerated in the external shock.
While the origin of the external shock afterglow is relatively well modeled (see §2.8 for further discussion), the radiation mechanism of the prompt GRB emission is subject to debate.

The leading mechanism is synchrotron radiation [218,219]. This is because it is the most naturally expected non-thermal emission mechanism. The GRB central engine is likely magnetized. Internal shocks can also generate magnetic fields through plasma instabilities [220,204]. Shock accelerated electrons must gyrate in the magnetic fields and radiate synchrotron photons.

The most straightforward synchrotron model, however, suffers a list of criticisms. (1) The synchrotron cooling time scale is typically much shorter than the dynamical time scale, so that electrons are in the “fast cooling” regime. The expected photon spectrum below $E_p$ is supposed to have a photon index $\alpha = -1.5$, while the observations show a typical value of $\alpha \sim -1$. This is the fast cooling problem [221]. The possible solutions to this problem include introducing a rapidly decaying magnetic field in the internal shock region [222], introducing slow heating in the emission region (e.g. in an ICMART event) [145,223], and introducing Klein-Nishina cooling [224]. (2) The hardest low energy photon index is supposed to be $\alpha = -2/3$ in the synchrotron model (corresponding to the $F_\nu \propto \nu^{1/3}$ regime of synchrotron emission. However, a fraction of GRBs have $\alpha$ even harder than this “synchrotron line of death” [225]. Possible solutions include introducing contributions from the thermal photosphere [226], considering synchrotron self-absorption [227], and introducing “jitter” radiation [228]. (3) For typical parameters, the predicted $E_p$ from synchrotron emission is about 2 orders of magnitude smaller than the observed value. This requires that only a small fraction of electrons are accelerated in the internal shocks [229,230]. The same requirement is needed to correctly derive the synchrotron self-absorption frequency in internal shocks [182]. In a high-$\sigma$ flow, this problem is naturally solved [145]. (4) Within the internal shock model, it is argued that the allowed parameter regime for synchrotron model is greatly constrained [185]. Such a limitation applies to the internal shock model. For magnetic dissipation synchrotron models such as the ICMART model [145], the constraint is much weaker.

A variant of the synchrotron radiation mechanism is the jitter radiation mechanism [228]. Within this scenario, magnetic fields have too small a coherence length $\lambda_B$ so that electrons cannot make a complete gyration. The typical jitter emission frequency no longer depends on the strength of the magnetic field, but is related to $\lambda_B$. The low energy photon index below $E_p$ can range from 0 to -1 [231]. One issue of this scenario is that the assumed small coherence scale is not revealed from PIC numerical simulations of relativistic shocks [232]. On the other hand, such a small coherence scale may be realized in magnetic reconnection regions [233], so that the radiation mechanism may be relevant in models that invoke magnetic dissipation as the origin of GRB emission.

The second radiation mechanism candidate to interpret prompt GRBs is SSC. Within this scenario, the synchrotron radiation peaks in the IR/optical/UV range, and the observed GRBs are dominated by the SSC emission [234]. It was found that within the internal shock model, the allowed parameter space of SSC is much larger than that of synchrotron if all the electrons are accelerated [185]. Introducing an assumption that only a small fraction of electrons are accelerated would largely alleviate this problem [235]. The SSC mechanism attracted serious attention following the discovery of the “naked-eye” GRB 080319B [180]. Bright optical pulses are found associated with gamma-ray pulses, with flux greatly exceeding the extrapolation of gamma-ray emission into the optical band. An immediate possibility is that optical is due to synchrotron radiation, while gamma-rays are due to SSC [181,180,236]. Counterarguments against the simplest SSC mechanism for GRB 080319B include the energy crisis (since $Y \sim 10$, the 2nd order IC component would be even more energetic) [237,187,238], $\sim 1$ s lag of the optical emission with respect to the gamma-ray emission [239], and the difficulty of interpreting the more variable gamma-ray lightcurve (than optical) [188]. More complicated SSC models invoking turbulence in the emission region may overcome some of these criticisms [236].

The third radiation mechanism commonly discussed in the literature is Compton upscattering of thermal photons. The leading scenario is upscattering off thermal photons from the jet photosphere [209,210,240,241,211,242,156,157,243]. This requires energy dissipation below and slightly above the photosphere. Within this scenario, the observed $E_p$ is essentially the temperature of the photosphere. Upscattering naturally gives rise to a power law spectrum above $E_p$. The spectral index below $E_p$, however difficult to alter from the Rayleigh-Jeans slope (corresponding to $\alpha = +1$ rather than $\alpha = -1$ as typically observed). Considering sub-photosphere heating and equal-arrival-time effect in a relativistic ejecta, one gets $\alpha \sim 0.4$ [156], still much harder than the observed spectrum. The equal arrival time effect would modify $\alpha$ to approach $-1$ at late times when the flux already drops significantly [243]. This may be relevant when the central engine activity is over, but is not applicable during the prompt emission phase when a continuous wind is ejected from the central engine. In general, the dissipative photosphere models have the difficulty to interpret the low energy photon spectral index of GRBs.

Besides the photosphere, other thermal sources can give rise to seed photons for relativistic electrons to upscatter. These photon sources include the thermal photons released from the exploding star [244], the thermal photon “glory” from the progenitor star that is trapped by the environment [245], as well as thermal photons...
from shock breakout [246].

Finally, hadronic mechanisms (proton synchrotron and proton-photon interaction to produce charged and/or neutral pions) have been also suggested to interpret prompt GRB emission (e.g. [247,248,249]). Since protons are radiatively inefficient as compared with leptons, these models require that protons carry most of the total energy (i.e. proton dominated).

It is difficult to identify the correct radiation mechanism with the current available data. The “smoking gun” would be the gamma-ray polarization data. Although both synchrotron radiation in an ordered magnetic fields [113,148] and IC viewed at certain angles [250,251] can give high degree of polarization, systematically studying the statistical polarization properties of a sample of GRBs can differentiate the competing models and may lead to identification of the radiation mechanism of GRB prompt emission [149].

A dedicated review on multiwavelength GRB prompt emission observations can be found in this volume [252].

2.7. Long Term Central Engine Activity

One of the major discoveries of Swift is that the so-called “afterglow” is not only the emission from the external shock (as generally believed in the pre-Swift era), but also includes emission from a long-lasting central engine. The arguments for a long lasting central engine lie in the following three pieces of evidence.

The most convincing evidence is the existence of X-ray flares following nearly half of Swift GRBs [253,254,255]. These flares have sharp rise and sharp decay. The morphology is essentially impossible to be interpreted within the framework of the external shock model [256]. One therefore needs to appeal to late central engine activities to interpret them [253,255,257,258,259]. The most convincing evidence of such an interpretation is the reset of the clock for each episode of engine activity, as is suggested from the data: in order to interpret the decay following an X-ray flare as the high latitude emission effect, the required \(T_0\) is usually right before the rise of the flare [175]. Such a property cannot be naturally interpreted within other X-ray flare models that do not invoke late central engine activities (e.g. [260]).

Next, a small fraction of GRB X-ray afterglows show an extended plateau followed by a sudden drop of flux with a decay index steeper than 3 (sometimes even as steep as 9) [128,129,130]. Such a rapid fall cannot be interpreted within the external shock models, and needs to invoke internal dissipation of a long lasting central engine wind. Such a plateau is therefore sometimes also called an “internal plateau” [129,130]. For comparison, most X-ray afterglow lightcurves show a plateau followed by a “normal” decay with slope \(\sim -1\) [125,126]. Within the external shock interpretation, the X-ray plateaus are due to adding energy into the blastwave. Before observing the internal plateaus, there have been two possibilities to account for such a refreshed shock: a long lasting central engine [123,124] or piling up slow materials ejected promptly [201,261]. With the discovery of internal plateaus, it is now clear that some GRBs indeed have a long-lasting central engine activity, so that the former scenario can operate at least in some GRBs.

Last, some authors even interpret the most common X-ray plateaus (those followed by a \(t^{-1}\) normal decay phase) as emission from the central engine [262,263,264,265]. The main reason is that in more than half cases, no optical break was discovered at the transition time from the plateau to the normal decay phase [266,129], and that there is essentially no spectral evolution across the temporal break [267]. Such a chromatic behavior is very difficult to interpret within the framework of the external shock models. Invoking two-component external shock jets [268] would require contrived shock parameters and unnatural assumptions. Invoking a long lasting reverse shock [269,270] would require that the forward shock emission is suppressed by many orders of magnitude. Another possibility, i.e. dust scattering effect [271]), can interpret the lightcurve but not the spectral evolution as observed for most GRBs [272]. One therefore is left with the possibility that the X-ray emission is dominated by the internal emission of a long-lasting central engine. Indeed, a quantitative X-ray afterglow model attributing X-ray emission to the dissipative photosphere of a long lasting central engine wind can reproduce the shallow, normal, and late break of X-ray lightcurve with chromatic features as observed [273].

To conclude, the observational data demand the following two aspects related to the GRB central engine. First, the engine is usually still active after the prompt emission phase is over, and can last up to \(> 10^4\) s after the trigger. Second, there can be two types of central engine activities, an erratic component that can power X-ray flares, and a smooth component that can power the plateaus (those followed by a steep decay segment or even those followed by a normal decay segment).

There is no well accepted mechanism yet to account for the erratic behavior of the late central engine activities. Nonetheless, some ideas have been proposed. These include fragmentation of the collapsing star [274], fragmentation of the accretion disk of both massive star and compact star GRBs [275], intermittent accretion behavior
caused by a time variable magnetic barrier [276], magnetic bubbles launched in a post-merger differentially rotat-
ing, proto-neutron star [277], helium synthesis in the post-merger debris of a compact star GRB [278], and quakes in solid quark stars [120]. In any case, since the neutrino-driven jet luminosity drops steeply when the accretion rate becomes small [279], the existence of low-luminosity X-ray flares at late times demand that the late jets that power X-ray flares are driven and collimated by magnetic mechanisms [281]. Another caveat is that an intermittent jet may not always correspond to intermittent accretion. It may be possible that accretion is continuous, but another mechanism (e.g. magnetic activity) is responsible for the observed intermittent jet emission (e.g. [280]).

The mechanisms to account for a long-lasting continuous late central engine activity include fall-back accretion onto the black hole engine [282,283,284], or tapping the spin energy of a strongly magnetized millisecond pulsar [123,124]. For the latter possibility, one needs to interpret the energetic prompt gamma-ray emission without introducing a black hole - torus central engine. Possible mechanisms include hyperaccretion onto a neutron star [106] or phase transition into a quark star [116,117,118,119].

To firmly test the long-lasting central engine scenarios, additional observational channels are needed. For example, X-ray polarization measurements for X-ray flares would be essential to test the magnetic nature of the late jet [281]. Gravitational wave observations during the plateau phase would shed light onto the nature of the millisecond pulsar central engine [285].

2.8. External Shock Afterglow Physics

Among all the topics discussed in this review, the external shock afterglow physics is the most definite one. Even though the forward shock afterglow model has some free parameters ², the dynamics of the blastwave, the radiation spectrum at any instant, as well as the lightcurve at any wavelength can be uniquely predicted once these input parameters are specified [196,286,287,288]. As a result, using multi-band (radio, optical and X-rays) data, one can constrain these unknown parameters based on the model [289,290,291,292]. More complicated factors, such as jet break [293,294], energy injection into the blastwave [201,123,124,295], angular structure of the jet [296,297,298,167,180], as well as transition to the non-relativistic phase [299,300] can be added into the model to interpret more complicated observational behaviors.

Modeling afterglow using the external shock model has been the main topic before Swift. Swift observations of early afterglows on the other hand revealed a more complicated picture. The X-ray afterglows show a canonical lightcurve with 5 distinct components [125,126]. The early steep decay component connecting the prompt emission [171,172,173] (Component I of [125]) and the erratic X-ray flares (Component V of [125]) are believed to be of the internal origin. The rest three segments: shallow decay (II), normal decay (III) and the late steep decay (IV) are well interpreted within the external shock model: II is the external shock during the continuous energy injection phase, III is the external shock emission after injection is over, and IV is the external shock emission after the jet break phase [125,126,301]. According to such an interpretation, the two breaks are hydrodynamical breaks and should also appear in other wavelengths as well (i.e. achromatic). This was indeed seen in some GRBs (e.g. GRB 060729 and GRB 060614 [302,303]). However, chromatic behaviors were discovered around both breaks in a good fraction of GRBs [266,129,90]. This suggests that the X-ray afterglow might not be always of the external shock origin. Therefore, in the Swift era, the afterglow modeling made one step backwards: instead of constraining the afterglow model parameters using the data, one needs first to identify which emission component is from the external forward shock, and which is not.

An important result from the pre-Swift era was that massive star (Type II) GRBs are collimated, and the jet opening angles are such distributed that the jet corrected energy is roughly constant [88,89,304]. Swift observations raise cautions to accept this conclusion readily. There is no platinum jet breaks identified (i.e. those clearly show achromatic feature in all wavelengths) [90]. Some bursts have chromatic breaks at the so-called “jet break” epoch, while some bursts do not have a break at much late epochs [90,91]. More late time optical observations (e.g. [305]) are needed to reveal jet breaks and GRB collimation and energetics.

Another important aspect of the external shock afterglow physics is the emission of the reverse shock that propagates into the ejecta. Traditionally the ejecta is approximated as a finite width shell with uniform density. The reverse shock therefore gives a short-live emission signature. Since the density of the shell is approximately \( \Gamma \) times of that of the medium, and since the FS and RS regions share roughly the same pressure and internal energy,

² For the standard model, five parameters are needed: the total energy of the blastwave \( E_{\text{iso}} \), one parameter to describe the circumburst medium - the number density \( n \) for a constant ISM model, or the \( A_\star \), parameter for the stellar wind model, one parameter for electron energy distribution \( p \), and two parameters for shock energy partition - the electron equipartition parameter \( \epsilon_e \) and the magnetic field equipartition parameter \( \epsilon_B \).
each electron in the RS region has less energy than those in the FS, so that the peak synchrotron frequency is smaller by roughly $\Gamma^2$. As a result, while the FS emission initially peaks in X-rays and above, RS emission peaks in IR/optical/UV [196,197,198]. At the shock crossing time, the synchrotron emission peak fluxes, typical frequencies between RS and FS are connected through some simple relations [306,166]. For typical shock parameters for both the FS and the RS, the RS emission is not expected to be very bright. The optical lightcurve is characterized by double peaks, the first RS peak marking fireball deceleration, and the second FS peak related to crossing of the typical synchrotron frequency in the optical band [166]. The bright optical flashes characterized by a $F_\nu \propto t^{-2}$ decay followed by a normal $F_\nu \propto t^{-1}$ decay (e.g. [307]) requires that the RS is more magnetized than the FS [166,168]. There is also a regime where the typical RS synchrotron frequency is way below the optical band, so that there is essentially no RS signature in the optical lightcurve [308]. Considering ejecta magnetization, the RS flux increases initially as $\sigma$ increases from below, but would start to decrease as $\sigma$ approaches unity and gradually diminishes when $\sigma \gg 1$ [162,163]. A group of GRBs are found to have a smooth afterglow onset bump dominated by the emission from the FS (e.g. [84]). These either have a low RS typical frequency [308] or have a highly magnetized ejecta at the deceleration time [162,163].

For a wind medium, the RS is usually relativistic, which is accompanied by a prominent optical emission signature [309,310]. SSC in the RS region [311] or cross IC between the electrons and photons from FS and RS [312,313] could be important when the RS emission is prominent, which may contribute to early X-ray and gamma-ray afterglow emission.

It is possible that the ejecta do not have a uniform Lorentz factor, luminosity and density. Considering an ejecta with a more complicated stratification profile, the RS emission lightcurve can be made to have rich features, including reproducing the canonical X-ray lightcurve as observed by Swift [269,270]. However, for nominal parameters, the FS emission is brighter by several orders of magnitude. In order to interpret the data with the RS model, one has to argue that the FS emission is suppressed [269,270].

A dedicated review on GRB afterglow can be also found in this volume [314].
are usually found to track the MeV photons in time. This not only is valid for the Band-only GRBs such as GRB 080916C, but also applies to GRBs showing a distinct spectral component at high energy (e.g. GRB 090902B) [155]. This hints that during the prompt emission phase, the high energy photons are likely of an internal origin. (7) Puzzlingly, the > 100 MeV photons decay more slowly than the MeV photons. After the GBM-band burst is over, LAT-band photons are usually observed to decay with a single power law with a slope $\sim -1.4$ [319,155]. This suggests either that the entire high energy emission has a different origin from the MeV emission (which is in contrast with the points 2 and 6 above) [322,323,319], or that the high energy lightcurve is the superposition of two components with a second (external shock) component setting in as the prompt emission fades [155,320].

Even though the origin of high energy emission is still subject to debate, these new data shed light into several open questions in GRB prompt emission physics (e.g. topics discussed in §2.4, §2.5 and §2.6). (1) The featureless Band-only GRBs such as GRB 080916C are difficult to interpret within the simplest baryonic fireball picture. If the entire non-thermal spectrum is from the internal shocks, then the photosphere emission of the hot fireball is expected to be bright enough to show up above the detected Band spectrum [153,154]. This led to the suggestion that GRB 080916C and most LAT GRBs have $\sigma \gg 1$ at the central engine, and probably also in the emission region as well [153]. The bright thermal emission of GRB 090902B, on the other hand, points towards a fireball picture [160], with $\sigma \lesssim 1$. This would suggest a diverse composition among GRBs. The possibility that the Band spectrum is from a dissipative photosphere has been discussed (e.g. [321,156,157]). These models have specific predictions that are not consistent with the data. For example, the predicted spectrum cannot extend to energies higher than $\sim 1$ GeV, while the Band spectra extend all the way to rest-frame $\sim 70$ GeV for GRB 080916C. The assumption that this prompt GeV emission is from the external shock is not supported by detailed data analysis [155]. Also the low energy photon index of a dissipative photosphere is predicted to be $\alpha \sim 0.4$, which is much harder than the observed $\alpha \sim -1$. (2) The long-term GeV emission may be originated from the external shock. This requires some extreme parameters for the external shock [322,323], a radiative blastwave [319] or a Klein-Nishina cooling dominated shock [325,326]. GeV emission during the prompt emission phase, however, is not easy to interpret within the external shock model [327,328,329], and is likely of an internal origin, as suggested by the data [155]. (3) The delayed onset of GeV emission has been interpreted as emergence of the upscattered cocoon emission [324], synchrotron emission from shock accelerated protons [249], delayed residual internal shock emission [329], as well as the delayed fireball acceleration to an extremely high Lorentz factor [330]. Alternatively, it can be simply due to change of particle acceleration condition or pair production opacity during the early stage of a GRB [145,155].

Bright GRBs co-detected by Fermi/LAT and Swift would be highly valuable to understand the nature of high energy emission. This is because a Swift BAT trigger would lead to early XRT and UVOT observations. Some GeV models (e.g. the external shock model) have specific predictions in the X-ray and UV/optical band. The detections of early afterglows by Swift would prove or disprove these predictions, so that one can narrow down the allowed models for GRB high energy emission. Unfortunately, the chance of LAT/Swift joint trigger is low. The only case so far (GRB 090510) was a short GRB [331]. More cases, especially for long GRBs, are highly desirable.

2.10. Cosmological Setting

GRBs are cosmological events. The redshift distribution of GRBs spans from $z = 0.0085$ (for GRB 980425 [11]) to $z = 8.2$ (for GRB 090423 [32,33]). Several open questions of GRBs within the cosmological context include the following:

Are massive star GRBs good tracers of star formation history of the universe? Do these GRBs favor a low metallicity environment? Does the GRB luminosity function evolve with time? These questions are related to each other. In order to account for the detections of GRB 080916 at $z = 6.7$ [34] and GRB 090423 at $z = 8.2$ [32,33], the GRB event rate at high-$z$ should be higher than the simple extrapolation of the known star formation history (e.g. [332]) to higher redshifts [333,33]. One possibility is that GRBs still follow the star formation history of the universe, but there is a rise of SFR at high $z$ due to the contribution from the population III stars [334]. Although the high-$z$ GRB excess may be interpreted this way, the fact that the observed high-$z$ GRBs are not different from their nearby sisters [32,33] suggest that this factor is not adequate to interpret the current data. One therefore needs to argue that GRBs favor low metallicity environment [54,335,336,337] or their luminosity function evolves with redshift so that luminosity is higher at higher-$z$. These two effects are coupled with each other, and may not be differentiated with the $L - z$ and log $N - \log P$ data [337,336]. On the other hand, the low metallicity possibility is favored by the host galaxy modeling as well (e.g. [53,338,55]).
Can high-$z$ GRBs probe the reionization history of the universe? The universe is known to be re-ionized around $z \sim 6$. The details of the reionization history is not well constrained (e.g. [339]). GRBs are believed to exist at as early as $z \sim 20$. As bright beacons in the “dark ages”, these high-$z$ GRBs can probe the cosmic reionization history in their near IR afterglow spectrum. In particular, the damping wing bluewards of the Lyman-$\alpha$ “Gunn-Peterson” trough carries the information of the neutral hydrogen column density along the line of sight. This can in principle extend the intergalactic medium (IGM) ionization state mapping (previously by quasars [340]) to higher $z$’s. One issue is that the GRB host damped Lyman-$\alpha$ (DLA) system would contribute to the observed neutral column, so that the IGM absorption feature is not clean (e.g. [341]). Numerical simulations suggest that the GRB host DLA column decreases with redshift [342,343]. Such a feature makes it more promising to use GRBs to probe reionization at $z > 8$. Since afterglow is rapidly fading, very early IR observations for high-$z$ GRBs are needed to make breakthrough in this direction.

Do high-$z$ GRBs have a different progenitor from the low-$z$ ones? The first generation stars may be more massive than the nearby massive stars [344]. If these massive stars produce GRBs, they should be powered by supermassive black holes through the Blandford-Znajek mechanism [345,346]. These GRBs should be more powerful than normal GRBs. No such energetic high-$z$ GRBs have been detected so far. On the other hand, recent numerical simulations revealed that the halo to form first generation stars may fragment, so that the first generation stars may be in binary systems with smaller masses [347]. The GRBs in such systems may be then not much different from the normal GRBs.

Observationally, the two highest-$z$ GRBs (080916 and 090423) both have a rest-frame duration shorter than 2 s. One possibility is that this is due to a selection effect (i.e. the fainter pulses are buried below the noises). However, if the effect is intrinsic, one would wonder whether they are massive star (Type II) GRBs or compact star (Type I) GRBs (e.g. [31] and references therein). Applying the multiple criteria besides the duration and hardness information, it is highly likely that these bursts are Type II GRBs [31]. Under certain conditions (e.g. slow rotators), it is possible that a massive star only has a small torus after prompt collapse, so that a short duration GRB can be powered [348,349]. If future high-$z$ GRBs prefer short durations, one then needs to seriously address why the conditions for a short accretion time are preferred for high-$z$ massive stars.

A dedicated discussion on GRBs as cosmological probes can be also found in this volume [350].

3. The SVOM connection

The Chinese-French mission SVOM is a multi-wavelength GRB observatory scheduled to launch in 2014-2015 [5]. It carries four space-flown instruments: a wide field X-ray/soft $\gamma$-ray (4-250 keV) detector ECLAIRs, a hard gamma-ray (50 keV - 5 MeV) detector GRM, a visible telescope VT, and an X-ray telescope MXT. A set of three ground based dedicated instruments, including two robotic telescopes (GFTs) and one wide angle optical monitor (GWAC), will complement the space borne instruments. Its operation window overlaps with that of $\text{Fermi}$ and $\text{Swift}$ and probably overlaps with other planned GRB missions (such as JANUS, EXIST) as well. After 2014-2015, several multi-messenger detectors (e.g. neutrino detector Icecube and gravitational wave detector Advanced LIGO) will be fully operating. It is foreseen that an exciting era of GRB study will be ushered in.

It is unrealistic to solve all the open questions discussed in this review, but some aspects of the problems will be better addressed for sure in the SVOM era. Here I discuss some prospects.

- **Classification & Progenitor**: ECLAIRs and GRM can give independent $T_{90}$ measurements for many GRBs. This will give a large sample to study energy-dependent $T_{90}$ classification. Similar to $\text{Swift}$, SVOM will lead broad-band follow-up observations for many GRBs. This will allow collection of multi-criteria needed to diagnose the physical origin of the GRBs (e.g. [31]). SVOM will continue to study massive star (Type II) GRBs and compact star (Type I) GRBs to allow better understanding of their progenitors. SVOM is not ideal to detect standard short GRBs, but the sensitivity of ECLAIRs to soft $\gamma$-rays would help to detect more cases of “extended emission” of short GRBs. This would offer a chance to study the condition of extended emission, as well as whether short GRBs with extended emission are different from the canonical short GRBs. SVOM will also be powerful to study nearby low-luminosity long GRBs, allowing a better statistics for these events, addressing their supernova associations, event rate, luminosity function, as well as whether they indeed form a distinct population from canonical GRBs.

- **GRB Prompt Emission Physics**: ECLAIRs and GRM cover a different spectral window from $\text{Fermi}$ GBM and LAT. The joint spectral analysis between the two instruments would allow diagnose of the prompt GRB emission spectral components (e.g. [155]). In particular, it allows a systematic analysis of the X-ray excess in
the spectrum, addressing the existence/strength of the photosphere thermal emission component, shedding light into jet composition, energy dissipation, particle acceleration and radiation mechanisms. GWAC will also regularly monitor prompt optical emission. Detections or upper limits of optical emission during the prompt phase would lead to the constraint on the broad-band prompt spectrum, and therefore nail down the radiation mechanism (e.g. synchrotron vs. SSC) of the prompt GRB emission.

- **Afterglow and “foreglow” physics:** VT will regularly record early optical afterglow emission from GRBs. Being redder and deeper than *Swift* UVOT, VT is ideal to address the early optical emission physics, including categorizing the early afterglow behavior and addressing the origin of optically dark GRBs. Together with MXT, VT can address chromatic/achromatic behaviors (for temporal breaks and flares) between the two energy bands. This would allow a systematic study of the long-term central engine activity of GRBs. GWAC will be monitoring the SVOM field of view during and even before the GRB trigger. This provides a chance of studying prompt optical emission and leading to detection of upper limits of optical emission before the prompt emission. In view of the recent motivation of discussing GRB “prior emission” (e.g. [351,352]), both positive and negative detections of these “foreglows” would shed light onto the function of the GRB central engine.

- **Cosmological setting:** Having a softer bandpass than *Swift* BAT, ECLAIRs may be able to detect more soft high-z GRBs. Deep upper limits of VT below 0.95µm would promptly provide good GRB candidates with z > 6. So ideally SVOM would lead to more detections and identifications of high-z GRBs, offering the opportunity to better address high-z star formation history, metallicity effect, GRB evolution, cosmic reionization, as well as whether population III stars could give rise to GRBs.

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