Abstract. Gamma-ray bursts (GRBs) are a mixed class of sources consisting of, at least, the long duration and short-hard subclasses, the X-ray flashes, and the low-luminosity GRBs. In all cases, the release of enormous amounts of energy on a short timescale makes an energetic, relativistic or mildly relativistic fireball that expands until it reaches a coasting Lorentz factor determined by the amount of baryons mixed into the fireball. Radiation is produced when the blast wave interacts with the surrounding medium at an external shock, or when shell collisions dissipate kinetic energy at internal shocks. This series of notes is organized as follows: (1) The observational situation of GRBs is summarized; (2) Progenitor models of GRBs are described; (3) An overview of the the blast-wave physics used to model leptonic emissions is given; (4) GRB physics is applied to hadronic acceleration and ultra-high energy cosmic ray production; (5) Prospects for GRB physics and γ-ray astronomy with the Fermi Gamma-ray Space Telescope (FGST, formerly GLAST), and space-based and ground-based observatories are considered. Also included are exercises and problems.

0. Introduction

GRBs are brief flashes of radiation at hard X-ray and soft γ-ray energies that display a wide variety of time histories. GRBs were first detected with the Vela series of spacecraft at soft γ-ray energies with wide field-of-view instruments used to monitor terrestrial nuclear explosions. The Burst and Transient Source Experiment (BATSE) on the Compton Gamma Ray Observatory showed that GRBs are not a Galactic disk population. The discovery of X-ray afterglows with Beppo-SAX allowed for counterpart identification and redshift measurement, revealing the distance scale to long duration GRBs. HETE-II and Swift observations have revealed the counterparts to the short-hard class of GRBs, and Swift observations give us a crucial look at the early afterglow X-ray behavior of GRBs.

This series of five lectures is organized as follows:

1. Observations of GRBs. Introduction to GRB observations;
2. **GRB Progenitor Models.** A brief review of GRB progenitor models;

3. **Leptonic processes in GRBs—prompt and afterglow emissions.** A description of the blast wave physics used to model leptonic emissions, including nonthermal synchrotron and synchrotron self-Compton radiations;

4. **Hadronic processes and cosmic rays from GRBs.** Application of blast wave physics to hadronic emissions and the acceleration of cosmic rays;

5. **GRB and γ-ray studies with the Fermi Gamma-ray Space Telescope, formerly the Gamma-ray Large Area Space Telescope, GLAST.** The future of GRB studies and prospects for γ-ray astronomy in light of Fermi, ground-based γ-ray telescopes, and complementary multiwavelength and multimessenger observatories.

The term “gamma-ray bursts” is now understood to comprise several classes of these sources, including

1. Long-duration GRBs, the source class commonly meant by classical GRBs, which are associated with high-mass stars and star-forming galaxies;

2. The short hard class of GRBs, which are widely thought to originate from the coalescence of compact objects;

3. The X-ray flashes, which are distinguished from the long-duration GRBs by having the peaks of their energy output at X-ray rather than soft γ-ray energies; and

4. Low luminosity GRBs, which produce unusually low energy releases compared to the long-duration GRBs.

In addition to these subclasses of GRBs are the soft gamma repeaters (SGRs), which technically are not GRBs, but rather related to phenomena on highly magnetized neutron stars. Even without black holes they may have, like radio-loud subclasses of black-hole sources, relativistic outflows.

The physics developed here can be applied to all these classes of GRBs, and other important cosmic phenomena (e.g., blazars, microquasars), because all involve the release of a large quantity of energy during a catastrophic event, thought to be driven by matter accretion onto a black hole or, in the case of SGRs, a crustal anomaly on a highly magnetized neutron star.

### 1. Gamma-ray Bursts: Overview of the Observations

A GRB may flare up from any direction in space. The classical, long-duration GRB (LGRB) releases most of its energy in hard X-ray and soft γ-ray (X/γ) energies during (to the observer) a fraction of a second to tens of seconds. There is no compelling evidence that LGRBs are recurrent events. Therefore, a wide field-of-view instrument is necessary for serendipitous detection.
1.1. Discovery of Gamma Ray Bursts

GRBs were discovered in data returned between 1967 and 1973 by the Vela series of satellites used to monitor compliance with the nuclear test ban treaty. The Vela spacecraft carried non-imaging CsI detectors that were sensitive in the \(\approx 200 \text{ keV} - 1 \text{ MeV} \) range (Klebesadel, Strong, & Olson 1973). Above the large background, coincident events were identified in the light curves. Timing studies and triangulation were used to give an approximate direction to the GRBs, revealing a cosmic/non-terrestrial origin. [Exercise: Perform a simple timing analysis from synthetic satellite data to show how to reconstruct arrival direction information. Give uncertainty analysis.]

The basic observational data in GRB studies are the spectral photon fluxes \(\phi(\epsilon; t)\) measured at time \(t\) and at photon energy \(h\nu = m_e c^2 \epsilon\). From this quantity, one can derive, after subtracting backgound flux, the \(\nu F_\nu\) flux (cgs units of ergs \(\text{cm}^{-2} \text{s}^{-1}\))

\[
\nu F_\nu(\epsilon; t) \approx \frac{m_e c^2 \epsilon}{4\pi d^2} \phi(\epsilon; t),
\]

where \(\epsilon_d\) is the typical photon energy at which the detector is most sensitive. The fluence between times \(t_1\) and \(t_2\) and within the energy range \(\epsilon_1\) and \(\epsilon_2\) (cgs units of ergs \(\text{cm}^{-2}\)) is given by

\[
F(t_1, t_2, \epsilon_1, \epsilon_2) = \frac{m_e c^2}{4\pi} \int_{t_1}^{t_2} dt \int_{\epsilon_1}^{\epsilon_2} d\epsilon \phi(\epsilon; t).
\]

Flux and fluence distributions can be constructed from observations of many GRBs.

1.2. BATSE Observations: GRBs are Cosmological

The Burst and Transient Source Experiment BATSE on CGRO consisted of an array of large area detectors (LADs) most sensitive in the 50-300 keV band, in addition to smaller spectroscopy detectors. The BATSE has given the most extensive data base of GRB observations during the prompt phase. It searched for GRBs by examining strings of data for \(> 5.5 \sigma\) enhancements above background on the 64 ms, 256 ms, and 1024 ms time scales, and triggers on GRBs as faint as \(\approx 0.5 \text{ ph cm}^{-2} \text{s}^{-1}\), corresponding to energy flux sensitivities \(\lesssim 10^{-7}\) ergs \(\text{cm}^{-2} \text{s}^{-1}\). At hard X-ray and soft \(\gamma\)-ray energies, the peak flux may reach hundreds of photons \(\text{cm}^{-2} \text{s}^{-1}\) in rare cases. Empirical morphological studies of LGRBs give various phenomenological relations, including hardness-intensity correlation, generic hard-to-soft evolution of \(\epsilon_{pk}(t)\), and variability-distance correlation.

Expressing the sensitivity of a high-energy radiation detector in terms of a threshold energy flux \(\Phi_{\text{thr}}\) (same units as \(\nu F_\nu\)) imposes the condition that \(\Phi \geq \Phi_{\text{thr}}\). For unbeamed sources with luminosity \(L_\ast\) and distance \(d\), \(\Phi = L_\ast/4\pi d^2\), and the maximum source distance for a give source flux \(\Phi\) is

\[
d(\Phi) = \sqrt{\frac{L_\ast}{4\pi \Phi}}.
\]

(The luminosity distance which includes cosmological effects is defined by \(d_L = \sqrt{L_\ast/4\pi \Phi}\), and \(d \equiv d_L\) at low redshifts \(z \ll 1\). [Exercise. Relate energy to fluence, including redshift.]) Hence the well-known \(-3/2\) result for sources uniformly distributed with density \(n_0\) in Euclidean space, namely

\[
N(\Phi > \Phi) = N(\Phi < d) = 4\pi n_0 \int_0^{d(\Phi)} dx x^2 \propto \Phi^{-3/2}.
\]
The \( \langle V/V_{\text{max}} \rangle \) statistic

\[
\langle V/V_{\text{max}} \rangle = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{\Phi_i}{\Phi_{\text{thr}}} \right)^{-3/2}
\]  

expresses the deviation from 0.5 expected for a uniform Euclidean distribution of sources (Schmidt 1968). Here \( V \) stands for volume, and \( V_{\text{max}} \) is the maximum volume from which a source with flux \( \Phi \) could be detected. Values of \( \langle V/V_{\text{max}} \rangle > 0.5 \) represent positive evolution of sources, that is, either more sources and/or brighter sources at large distances or earlier times. Values of \( \langle V/V_{\text{max}} \rangle < 0.5 \) represent negative source evolution, i.e., fewer or dimmer sources in the past. Detailed treatments of the statistical properties of black hole sources must consider cosmological effects and evolution of source properties.

The integral size distribution of BATSE GRBs in terms of peak flux \( \phi_p \) is very flat below \( \sim 3 \) ph cm\(^{-2}\) s\(^{-1}\), and becomes steeper than the \(-3/2\) behavior expected from a Euclidean distribution of sources at \( \phi_p \gtrsim 10 \) ph cm\(^{-2}\) s\(^{-1}\). The directions to the BATSE GRBs are isotropically distributed in the sky and display no clustering toward the Galactic plane. When coupled with the flattening of the peak flux distribution, the implication is that we are at the center of an isotropic though bounded distribution of GRB sources. A cosmological distribution of sources is most compatible with these observations.

The duration of a GRB is defined by the time during which the middle 50\% \( (t_{50}) \), 90\% \( (t_{90}) \), or \( i\% \) \( (t_i) \) of the counts above background are measured. A bimodal duration distribution is measured, irrespective of whether the \( t_{50} \) or \( t_{90} \) durations are considered (Kouveliotou et al. 1993). About two-thirds of BATSE GRBs are long-duration GRBs with \( t_{90} \gtrsim 2 \) s, with the remainder comprising the short duration GRBs. The short duration GRBs tend to have harder spectra, so that they are referred to as the short, hard class of GRBs. They are also much weaker in average fluence in the BATSE range.

GRBs typically show a very hard spectrum in the hard X-ray to soft \( \gamma \)-ray regime, with a photon index breaking from \( \approx -1 \) at photon energies \( E_{\text{ph}} \gtrsim 50 \) keV to a \(-2\) to \(-3\) spectrum at \( E_{\text{ph}} \gtrsim \) several hundred keV. In BATSE studies, the distribution of the peak photon energies \( E_{\text{ph}} \) of the time-averaged \( \nu F_\nu \) spectra of BATSE GRBs are typically found in the 100 keV - several MeV range. The time-averaged or, for very bright GRBs, time-sliced GRB spectrum is usually well-described by the “Band function” \( N_B(\epsilon) \) (Band et al. 1993), a power-law times an exponential that smoothly connects to a steeper power-law, given by

\[
N_B(\epsilon) = k_B \epsilon^\alpha \exp[-\epsilon(\alpha - \beta)/\epsilon_{\text{br}}] H(\epsilon; \epsilon_{\text{min}}^B, \epsilon_{\text{br}}^B) + k_B \epsilon_{\text{br}}^{\alpha - \beta} \exp(\beta - \alpha) \epsilon^\beta H(\epsilon; \epsilon_{\text{br}}, \epsilon_{\text{max}}^B).  
\]  

(3)

Here \( \alpha \) and \( \beta \) are the low and high energy photon number indices, and \( E_{\text{br}} = m_e c^2 \epsilon_{\text{br}} \) is the “break energy.” The Heaviside function \( H(x; y, z) \) vanishes everywhere except at \( y \leq x < z \), where it equals unity. The term \( k_p \) is the constant normalizing the number fluence to the \( > 20 \) keV BATSE energy fluence \( \Phi_p (> 20 \) keV) of a particular GRB [Exercise: Derive the form of the Band function and normalizing constant, and convolve with nontrivial model detector response.] Typical values of Band alphas \( \alpha \approx -1 \) and Band betas \( \beta \approx -2.2 \) – \(-2.5\). Deviations of these values give valuable information about radiation processes and existence of separate radiative components.
1.3. Beppo-SAX and the Afterglow Revolution

Beppo-SAX GRB observations reveal that essentially all long-duration GRBs have fading X-ray afterglows. Beppo-SAX, launched April 30, 1996, carried three instruments. The Gamma Ray Burst Monitor was sensitive in the range 60 – 600 keV to GRBs brighter than \( \approx 10^{-6} \) ergs cm\(^{-2}\) s\(^{-1}\). The Wide Field Camera was sensitive in the range 2 – 30 keV down to \( \approx 10^{-10} \) ergs cm\(^{-2}\) s\(^{-1}\) and provided \( \approx 10^{0'} \) error boxes. The spacecraft was then slewed, requiring 6 – 8 hours, but was fast enough for the Narrow Field Instruments, sensitive to \( > 0.1 \) keV GRB emissions as faint as \( \approx 10^{-14} \) ergs cm\(^{-2}\) s\(^{-1}\), to give error boxes \( \lesssim 0.5' \). The first X-ray afterglow was obtained from GRB 970228 (Costa 1997), which revealed an X-ray source that decayed according to a power-law, \( \phi_{X}(t) \propto t^{\chi} \), with \( \chi \approx -1.33 \). Typically, \( \chi \approx -1.1 \) to \(-1.5 \) in Beppo-SAX \( \sim 2 - 10 \) keV X-ray studies.

The small X-ray error boxes allowed deep optical and radio follow-up studies. GRB 970228 was the first GRB from which an optical counterpart was observed (van Paradijs et al. 1997), and GRB 970508 was the first GRB for which a redshift was measured. Redshifts are provided by detection of optical emission lines from the host galaxy and absorption lines in the fading optical afterglow due to the presence of intervening gas. Host galaxies of long duration GRBs are bluish star-forming galaxies, primarily consisting of dwarf irregular and spiral galaxies. No optical counterparts were detected from approximately one-half of Beppo-Sax GRBs with well-localized X-ray afterglows, and are termed “dark” bursts. These sources may be undetected in the optical band because of dusty media, or intrinsically faint afterglows. These results give compelling evidence that LGRBs are associated with star-forming galaxies and the deaths of massive stars, especially given the detection of supernova emissions a few weeks after the GRB in a few, nearby faint GRBs which, however, may not be fully representative of the LGRBs (but rather the low luminosity GRBs, LLGRBs).

Apparent isotropic energy releases of LGRBs are enormous, exceeding \( 10^{54} \) ergs, and the redshift distribution of Beppo-SAX, BATSE, HETE-II and INTEGRAL (pre-Swift) GRBs is peaked near \( \langle z \rangle \approx 1 \). Achromatic breaks in the optical curves of GRB afterglows gives evidence for a beamed/jetted geometries, reducing the apparent energy release to a beaming-corrected energy release by a beaming factor \( F_{bm} \). Approximately 40% of GRBs have radio counterparts, and the transition from a scintillating to smooth behavior in the radio afterglow of GRB 980425 provides evidence for an expanding source. For BATSE/Beppo-SAX type GRBs, the lion’s share \( \sim 65\% \) of the energy is released in the form of \( > 25 \) keV X-rays and soft \( \gamma \) rays, \( \sim 7\% \) is softer X-rays, \( \sim 0.1\% \) in optical, during the prompt phase \( t \lesssim 2(t_{i}) \).

A class of X-ray rich GRBs, with durations on the order of seconds to minutes and X-ray fluxes in the range \( 10^{-8} - 10^{-7} \) ergs cm\(^{-2}\) s\(^{-1}\) in the 2-25 keV band, was detected with many X-ray satellites, including Ariel V, HEAO-1, ROSAT, and Ginga, but conclusively established with Beppo-SAX (Heise et al. 2001). These X-ray flashes (XRFs) are “\( \gamma \)-ray challenged,” as indicated by Band-function model fits to the prompt emission spectrum. Several phenomenological correlations of XRFs and LGRBs have been reported. One goal is to establish a pseudo-redshift indicator, another a “pulse” paradigm, and correlations between the duration of quiescent and subsequent pulse periods in separated pulses. A
quantitative relation between integrated fluence and $E_{pk}$ in well-defined pulses is reported. The Amati relation (Amati et al. 2002) correlates the $\nu F_{\nu}$ peak photon energy $E_{pk}$ with apparent isotropic energy release $E_{iso} = 10^{54} \mathcal{E}_{54}$ ergs according to

$$E_{pk} \propto E_{iso}^{1/2}.$$  \hfill (4)

The Ghirlanda relation (Ghirlanda et al. 2004) correlates $E_{pk}$ with the collimation-corrected absolute $X/\gamma$ energy release $E_{abs} = 10^{51} \mathcal{E}_{51}$ ergs according to

$$E_{pk} \propto E_{abs}^{0.7}.$$  \hfill (5)

The Amati and Ghirlanda relations are challenging to explain and potentially useful for cosmological studies.

### 1.4. Swift and Various Classes of Bursting Sources

The Swift Observatory is a NASA-ASI–supported MidEx launched November 20, 2004. Its main scientific payload consists of 3 instruments: the Burst Alert Telescope (BAT), triggering between 15 and 150 keV, and a very sensitive X-ray Telescope (XRT) operating between $\sim 0.3 – \text{few keV}$, and the Ultra-violet optical telescope (UVOT). The spacecraft slews autonomously in $20 – 75$ s in response to triggers from the BAT.

**Long duration GRBs (LGRB).** The redshift distribution of the GRBs detected with Swift, with average Swift GRB redshift $\langle z \rangle \approx 2$, differing markedly from $\langle z \rangle \approx 1$ for pre-Swift GRBs. This can be explained by the different triggering energy range of BAT vs. BATSE, and $E_{pk}$-flux correlations. Knowledge of the early X-ray afterglow phase, an important goal realized by the Swift mission, provided surprising unpredicted behavior, most notably rapid X-ray declines and X-ray flares to late times (Zhang et al. 2006; Nousek et al. 2006). The physical meaning of the rapid declines in the X-ray flux between $\sim 100 – 10^3$ s is in dispute, including multi-component jet models, refreshed jets, and hadronic signatures.

**Short Hard GRBs (SGRB).** As expected for an old population of host galaxy progenitors, as would be the case for coalescing neutron stars and black holes, SGRBs are expected to be associated with ellipticals as well as spirals. No evidence for supernova emissions has been found in SGRB afterglows, meaning that the progenitors are not associated with a young, massive stellar population. That this expectation received spectacular confirmation with Swift, and also HETE-II, only opens up the surprises, including delayed X-ray afterglow emissions, rapid X-ray declines, and X-ray flares.

The heterogeneous Swift/HETE sample has a redshift distribution broadly distributed around $\langle z \rangle \approx 0.4$, and differs in important ways from the LGRBs in terms of host galaxies, offsets from host galaxies, apparent energy releases, and lag-luminosity relation. Absolute energy determination for SGRBs is compromised by the difficulty of finding beaming breaks in light curves of SGRBs. (Exercise: Beppo-SAX was not sensitive to SGRBs. Why?)
Low Luminosity GRBs (LLGRBs). The LLGRB class is the long tail to the LGRBs to low apparent energy release (reviewed by Zhang 2007). LLGRBs could very well be a separate and distinct population from LGRBs, possibly associated with magnetar activity, as indicated by GRB 060218, or extended black-hole fueling activity. A possible new class of GRBs was found in relation to nearby GRB 060614 with no supernova emissions, though it could possibly be a nearby SGRB. Identification of LLGRBs as a separate class, known since GRB 980425/SN 1998bw, makes us rethink conclusions about the relation of LGRBs to supernovae (SNe), which mostly derived from nearby LLGRBs. (Exercise: Report on GRB 98025.)

Soft Gamma Repeaters (SGRs). The giant flare of December 27, 2004 was the most intense cosmic transient observed historically. It was detected by over 20 spacecraft from the Earth to Saturn, and apparently released $\approx 1000$ times more energy than all the Milky Way’s stars, $\gtrsim 1 \text{ erg cm}^{-2}$ in hard X-rays and $\gamma$ rays at Earth (Hurley et al. 2005). (Exercise. Estimate the bolometric radiation flux from the stars in the Milky Way. Estimate the total stellar energy flux of the universe.) The event, releasing $\sim 10^{47}$ ergs, lowered the level of the Earth’s ionosphere.

SGR 041227 began with an $\sim 0.2$ s long, hard spectrum spikes with $E \sim 10^{46} - 10^{47}$ erg. The spike is followed by a pulsating tail with $\approx 1/1000^{th}$ of the energy. Viewed from a large distance, only the initial spike would be visible, and would resemble a short GRB. It could be detected out to 100 Mpc GRB 050906 at $z = 0.03$ could be a magnetar flare. Giant flakes like this must occur in other galaxies, and could comprise $\sim 10\%$ of the the SGRB population.

1.5. Summary

1. Pioneering phase (1967 - 1991): era of confusion
2. BATSE/CGRO era (1991 –2000): GRBs are cosmological
3. Beppo-SAX afterglow era (1996 – 2006): distance and energy scale for classical LGRBs (HETE-II/INTEGRAL)
4. XRFs, first seen with Ginga, clarified with Beppo-SAX
5. Low luminosity GRBs class (first example in 1998: GRB 980425/SN 1998bw)
6. Swift era (2004 – ): early afterglows and the distance and energy scale for short-hard SGRBs (HETE-II)
7. Fermi GBM (GLAST Burst Monitor)/Fermi LAT (Large Area Telescope) era (2008 – )

2. GRB Progenitor Models

Summarizing the observations of LGRBs, we find that a “typical” long-duration GRB lasts $\approx 20$ s in hard X-ray/soft $\gamma$ ray emission from keV to MeV energies. It takes place in star-forming (spiral or dwarf irregular) galaxies, but not in ellipticals. It takes place in a galaxy at $\langle z \rangle \approx 1 – 2$, and releases $\sim 10^{51} - 10^{54}$
ergs of apparent isotropic energy in bursts of radiation with apparent isotropic luminosities of $\approx 10^{50} - 10^{52}$ ergs/s. It is followed by long-lived X-ray, optical, and radio afterglow emission. Variability times are as short as ms (though more typically 1 s). How to explain this phenomenology? The consensus of most GRB scientists is that a LGRB is the consequence of the collapse of a massive star $\approx 30M_\odot$ to a black hole fed by an accretion torus.

In this second Lecture, we present a description of

1. GRB Source Models: Core Collapse vs. Coalescence
2. Energy source: nuclear, gravitational, rotation
3. Jet formation: neutrinos vs. magnetic field energy
4. Pathways to progenitor formation of collapsars
5. Pathways to progenitor formation of merging compact objects

2.1. Beaming and the Fireball Model

A strongly collimated, jetted emission helps answer the question, “How is it possible for a source to produce $10^{54}$ ergs of energy?” The answer is, you produce only a fraction of this energy, in beams with $\partial E/\partial \Omega \approx E/4\pi$ in a small solid angle element $\Delta \Omega$. Beaming into a cone of opening half-angle $\theta_j \approx 5 - 10^\circ$ decreases the gamma-ray energies by $\sim 2$ orders of magnitude, to $\sim 10^{51}$ erg.

[Exercise: Work out the beaming factor for a two-sided top-hat jet, and for a non-trivial jet profile.] Optical beaming breaks are derived by equating the characteristic beaming angle of emission, $\approx 1/\Gamma$, with the jet opening angle, $\theta_j$. A softening of the power law takes place when $\theta_j \lesssim 1/\Gamma$ as deceleration of the blast wave reduces the $\Gamma$ factor. Beaming also increases the total burst rate by the same factor, but this does not contradict anything we know about star formation and evolution for $F_{\text{bm}} \sim 10^1 - 10^3$.

But how to obtain large energy releases, large luminosities, and short variability time scales?, and

How does the kinetic energy of the ejecta get converted to electromagnetic radiation?

These questions are answered by the fireball/blast wave model considered in the next lecture. In this lecture, we instead consider the question of the progenitor to the $\gamma$-ray burst.

Compared to SNe, which occur $\approx$ once per sec throughout the universe, LGRBs take place, depending on beaming factor, $\sim F_{\text{bm}}$ per day $\approx 10^2(F_{\text{bm}}/100)$ per day throughout the universe, representing as few as 0.1% of the SN population. GRB-hosted SNe, for example, SN 2002ap, tend to by hyper-energetic compared to “normal” SNe. Thus Paczynski (1998) coined the name “hypernovae,” which has proven to be a useful concept.

2.2. Classes of $\gamma$ Ray Transients

Short GRBs. What are the mechanisms for the SGRBs? Most GRB scientists support a picture involving the merger of a compact binary system, such as two neutron stars, or a neutron star and a black hole (Eichler et al. 1989).
Lack of optical and radio afterglows is explained by tenuous ISM, if the merger takes place outside the host galaxy. The class of GRBs involving merger events, namely the SGRBs, are different in significant ways, clearly revealing the two as having distinct origins. But there is also another distinct class.

**X-Ray Flashes**. [Exercise: Report on the properties of the XRFs.]

If XRFs are another manifestation of long GRBs, then are they

1. GRBs at high redshift?
2. GRBs observed away from the jet axis?
3. Explosions with less relativistic ejecta?

We have fairly complete data on one XRF (XRF020903, $z = 0.251$); in this case, the answer is compatible with 3 (Soderberg et al. 2004). The Amati relation gives evidence that XRFs and GRBs are part of the same family, consistent with a mass-loaded fireball model.

**Soft Gamma Repeaters**. What are the SGRs? Most GRB scientists think that the 3 or 4 SGRs in the Milky Way and the SGR in the LMC originate from a transient release of magnetic field energy in highly magnetized neutron stars ($B > B_{cr} = m^2 c^3 / e \hbar$). The energy could be released from global crustal fracture through B field annihilation, or when the magnetosphere fills with hot $e^-e^+$ plasma.

**Long duration GRBs**. LGRB progenitors generally involve black-hole/accretion-disk models. To answer the energy generation and release question, a number of problems must be solved, including the problems of the

- Black Hole/Accretion disk (BHAD) + Jets;
- Structure of a Relativistic Disk;
- Neutrino Driven Explosions from a BHAD system; and
- Magnetic Field Driven Explosions from a BHAD system.

To firmly resolve the astrophysical origins of GRBs, it is necessary to also understand the connections of the various classes of GRBs to their stellar evolutionary past.

### 2.3. Energy Sources and Energy Transport

Three main energy sources in astrophysics are

1. Nuclear Energy
2. Gravitational Potential Energy
3. Black Hole Rotational Energy
The proton-proton chain efficiency is 0.0067, too small to realistically power most GRB radiations. Gravitational energy will be released during core collapse or coalescence event, and such events could also trigger a rapid discharge of rotational energy from a rapidly spinning black hole. Which of the other two are most important for GRB energy release, or are they both?

Energy in the form of photons is transported very differently through stellar interiors than the energy of neutrinos, the former dominated by absorption and reemission, and the latter often following a rectilinear trajectory out from the stellar core. Simulations of core collapse give us ways to follow different modes of energy release, also including gravitational radiation.

2.4. Principal GRB Models

The majority GRB establishment has settled on a standard scenario for the production of LGRBs and SGRBs, both involving black-hole accretion disk (BHAD) models. The energy release in LGRBs is believed to result from the accretion of a massive torus onto a black hole following the collapse of the core of a massive star to a black hole. This is the collapsar scenario, pioneered by Stan Woosley (1993). Compact object mergers have a different family history, but also end up with the release of energy by jetted outflows from BHAD-type systems.

A variety of scenarios for catastrophic events involving compact stars can be imagined, for example,

1. Neutron Star - Neutron star mergers, e.g., the Hulse-Taylor binary pulsar system
2. Black Hole - Neutron star mergers
3. Black Hole - White dwarf mergers
4. Collapse of the core of a rotating massive star (binary or single star)
5. Neutron star – black hole merger with the helium core of an evolved primary, a He-star merger

The collapse of the core of a rotating massive star down to a black hole is the original scenario behind the collapsar model. MacFadyen & Woosley (1999) modeled the toy case of such a collapse, placing an artificial angular momentum profile onto a massive star whose core was assumed to immediately collapse to a black hole. They identified many of the key ingredients for a successful GRB outburst: high accretion rate and specific angular momentum. This simulation provided the first numerical confirmation of the collapsar model and showed that with artificial, but physically reasonable, energy drivers that the collapsar could explain the durations of LGRBs. It is worth noting that since this calculation, much more physically relevant models have been run including either magnetic fields (Proga et al. 2003) or modeling the collapse in 3-dimensions of a realistic star (Rockefeller et al. 2006).

One way to drive the energy is through neutrino annihilation above the black hole accretion disk. The usual assumed geometry of a torus accreting onto a black hole is given by a wedge, with prolific neutrino fluxes that forms a relativistic $e^+e^-$ pair wind from neutrino-antineutrino interactions. In extreme
cases for a large Shakura-Sunyaev accretion disk $\alpha(\approx 0.1)$ parameter and a maximally rotating black hole, efficiencies for $\nu \bar{\nu} \rightarrow e^+ e^-$ could reach a few percent. This channel for energy release is thought to be too inefficient to power LGRBs, though could be important for subclasses of SGRBs. Large $a$, rapidly rotating black holes, can release sufficient energy to power a GRB. Geometric beaming can be produced from energy deposition via neutrino annihilation. See Popham et al. (1999) for a review.

As far as neutrino-driven GRB engines go, the critical densities for most likely accretion disks are $\sim 10^4 - 10^8$ g/cm$^3$. For collapsars, this corresponds to black hole masses of $\approx 10 - 25M_\odot$, with delays between collapse and jet formation of 30 - 300 s. The neutrino-driven collapsar model probably does not work (Fryer & Mészáros 2003). The alternatives are magnetic fields and fast rotation (Narayan et al. 1992). Again, see Popham et al. (1999) for a review.

The magnetic field in the accretion-disk/black-hole/jet system is probably dominated in currents flowing in the accretion disk. Penrose energy extraction through the Blandford-Znajek (BZ) process can be as powerful as the accretion power. The literature on magnetically driven jets is extensive. The BZ power is insufficient except for rapidly rotating black holes. Magnetically driven jets probably produce much more energy than neutrino annihilation. Common physics should apply to GRBs and AGNs with collimated relativistic outflows, namely radio galaxies and $\gamma$-ray blazars.

Numerical simulations of collapsar jets through stellar envelopes of massive progenitor stars show the need for the envelope to have a width $\lesssim 10^{11}$ cm. Emerging jets, possibly protected by a cocoon formed at the interface of the hot light relativistic fluid, can maintain relativistic speeds. In the picture of Woosley, LLGRBs such as GRB 980425 is an off axis GRB, and XRFs could arise from angular effects in a mildly relativistic fireball, in contrast to a “dirty,” mass-loaded fireball scenario by Dermer, Böttcher and Chiang (1999). (Exercise: Tabulate similarities and differences, and contrast predictions of off-axis vs. mass-loaded XRF scenarios.) Constraints on the formation of collapsar GRBs include:

- The star must collapse to form black hole.
- Star must lose its hydrogen envelope so that it remains compact.
- Jet must travel through star roughly on the GRB duration timescale.
- Star must be rapidly rotating so disk forms around black hole.

An important mechanism in stellar evolution leading to GRBs is Roche-lobe overflow. When a star expands (in the giant or supergiant branch) in a binary, the outer layers of the star may feel greater gravitational attraction to the companion star, causing this material to “overflow” onto that companion. A second important mechanism is common envelope (CE) evolution. If Roche-lobe overflow proceeds faster than the companion star can accrete material, the expanding star envelops the companion, leading to two stellar cores within a single common envelope. The masses of primary (most massive) and secondary (least massive) stars in a binary are $M_p$ and $M_s$.

Some pathways to GRB formation include: (i) Massive Star which, if not affected by binary mass transfer, would undergo core-collapse ($M_{SN} \sim 8 - 10^2$ $M_\odot$).
Dermer & Fryer

$M_{\odot}$) to a black hole; (ii) He core - He core mergers during CE phase of binary systems with two massive stars (He core masses will also have transition masses for neutron star and black hole formation). The Black Hole Mass ($M_{BH} \approx 3M_{\odot}$) is the transition mass for black hole formation, and depends on angular momentum of core. See Fryer, Woosley, and Hartmann (1999).

In the isolated collapsar scenario, a massive single star with high metallicity loses its hydrogen envelope via winds. If it retains enough mass and rotation to form a BHAD system, a GRB is produced. Important related issues are the metallicity of the host environment, and whether the progenitor has the required rotation. Modeling the full collapse (first to a neutron star and then to a black hole) is required to understand some of these trends. Stellar collapse with nuclear equations of state are now being done in 3-dimensions (e.g. Fryer and Warren 2002) including rotation (Fryer and Warren 2004) and finally to the late times that approach black hole formation (Fryer and Young 2007). From these we can trace fluid flow and isopressure surfaces of outward moving bubbles. (*Exercise:* Use the concepts of mixing length in convection to write the one-dimensional stellar structure equations for a collapsing object. Discuss the equations’ deficiencies.)

The combined simulation and theory understanding of stellar collapse argues that different progenitor scenarios lead to remnant black holes with a mass distribution possibly reflected in systems with inferred black hole masses (Fryer & Kalogera 2001). Because large a black holes allow greater energy extraction per unit mass, GRB-hosted SNe are bound to be more asymmetric than normal SNe to have a spun-up black hole remnant, though all SNe should exhibit asymmetries. Note that those objects that do form GRBs eject the star, producing a lower mass black hole remnant than those SNe and failed SNe that form black holes with no subsequent explosion (presumably due to slow rotation speeds).

One of the observed properties of GRBs is that the associated supernovae do not show any hydrogen. Strong stellar winds can remove the outer hydrogen envelope, but these winds also carry away angular momentum. An alternative is to assume that the star is in a binary and a common envelope phase ejects the hydrogen envelope. This evolution can even increase the angular momentum. The mass and rotation constraints are easier to satisfy in binary systems (Fryer et al. 1999).

One alternative, proposed by Fryer et al. (1999) was the merger of two stars. Fryer & Heger (2005) merged two helium cores and found that they could indeed increase the core rotation rate while removing the hydrogen and some of the helium envelopes. For collapsars, this means that with magnetic fields (or with the current prescriptions of magnetic fields), single stars and even simple binaries have trouble working (Petrovic et al. 2005). Yoon & Langer (2005) have argued that single stars at low metallicity can go through extensive mixing, removing all of the hydrogen by burning it into helium instead of through a wind.

But any binary may well not work. The issue is that we not only don’t see any hydrogen, but we don’t see helium in the supernovae associated with GRBs. So the models still have some work before they can fit all the data (see Fryer et al. 2007 for a review).
By comparison, compact object coalescence scenarios require a binary (or multiple star) system where the primaries and secondaries evolve to compact objects and merge within a Hubble time.

Double neutron star formation for SGRBs involve neutron star formation where the primary collapses after expanding off the main sequence, or being triggered by Roche lobe overflow of material onto the massive core. A likely scenario in close binaries involves CE evolution until the compact object settles to the center of the companion. The merger of the compact object with a He core forms a GRB. Alternately, in the absence of CE evolution, a compact binary can form with two progenitor high-mass stars. Accretion-induced collapse during the CE phase or during Roche lobe overflow introduces other evolutionary pathways to GRBs. (Exercise. Report on a GRB progenitor pathway in more detail.)

Optimistically, a neutrino mechanism could power a GRB, though would be associated with an old stellar population and large galactic offsets. Fryer et al. (1999) concluded that for collapsars, it is difficult to make isolated stars with enough angular momentum after removing envelope with winds. Binaries seem necessary (e.g. He-He or He-neutron star mergers). Compact object mergers (NS/NS or NS/BH) are rare, but sufficient for GRBs. Accretion rates are high ($\gtrsim 1 - 10 M_\odot/s$), but short-lived ($\lesssim 200$ ms).

GRB studies intersect many exciting fields of research, including

1. Jet and fireball physics;
2. Ultra-high energy cosmic ray acceleration and neutrinos;
3. Early universe, reionization;
4. Gravitational radiation; and
5. Mass extinctions, and geophysics.

Competing models include the

1. Supranova and two-step (SN $\rightarrow$ NS $\rightarrow$ BH) collapse processes for LGRBs, originally proposed by Vietri and Stella (1998,1999); see Dermer (2008); and
2. AIC of neutron stars to black holes in binary systems as a model for SGRBs (MacFadyen et al. 2005; Dermer and Atoyan 2006).

3. Leptonic processes in GRBs - prompt and afterglow emissions

This lecture gives an overview of the elementary leptonic blast wave physics developed to explain GRB prompt and afterglow emissions. The outline of this lecture is

1. Relativistic Kinematics
2. Blast-wave and Afterglow Theory
3. Relativistic Shock Hydrodynamics
4. Jetted Emission and Beaming Breaks

5. External Shocks

6. Colliding Shells

Reviews of GRB blast wave physics are given by Mészáros (2006), Piran (2005), and Dermer & Menon (2009).

To recap, we have associated

1. LGRBs ↔ Collapsars
2. SGRBs ↔ Mergers of compact objects
3. LLGRBs ↔ Probably a type of collapsar, perhaps magnetar-powered
4. SGRs ↔ Highly magnetized neutron stars

GRBs must be Galactic, as we now show based on discoveries made in the 1980s (and still valid). The typical energy flux of a GRB is \( \Phi \approx 10^{-6} \Phi_{-6} \) ergs cm\(^{-2}\), with significant factors-of-2 variations on timescales of seconds. Solar Maximum Mission observations of MeV photons (Matz et al. 1985) showed that the optical depth for attenuation of \( \gamma \) rays with energies \( \gtrsim 1 \text{ MeV} \) is

\[
\tau_{\gamma\gamma} \approx n_{\gamma} \sigma_{\gamma\gamma} R \approx n_{\gamma} \sigma_{T} R < 1
\]

for photons above threshold \( \epsilon \epsilon' \approx 2 \). The photon energy density

\[
n_{\gamma} \approx u_{\gamma}/E_{\gamma}, \ u_{\gamma} \sim L_{\gamma} t_{\text{esc}}/V \sim 3d^2 \Phi / R^2 c,
\]

with escape time \( t_{\text{esc}} \sim R/c \). Hence

\[
\tau_{\gamma\gamma} \approx \frac{u_{\gamma} \sigma_{T} R}{E_{\gamma}} \sim \frac{d^2 \sigma_{T} \Phi}{c^2 \Delta t E_{\gamma}} < 1,
\]

or \( d(10 \text{ kpc}) < \sqrt{\Delta t(s) / \Phi_{-6}} \). GRBs are known to be at cosmological distances. The flaw in this argument is the assumption that the emitting region is at rest. (The lesson here is not “Don’t believe theorists.”)

The conventional fireball/blast-wave model involves intermittent release of energy in a collimated relativistic jet, with variations of wind parameters leading to internal shocks and structure in the light curves. External shocks are responsible for the late Beppo-SAX afterglow, and could contribute to emission in the prompt and early afterglow phase.

The central problem in GRB astrophysics is to explain large apparent isotropic energies \( \gtrsim 10^{54} \) ergs, durations \( \lesssim 10^3 \) s, and short variability time scales \( \Delta t \lesssim 1 \text{ s} \). The widely accepted solution is the fireball/relativistic blast-wave model. The impulsive release of a huge amount of energy in a fireball with large entropy per baryon is described by an

1. Expansion phase; \( \Gamma(x) \approx x/\Delta_0, x < \Gamma_0 \Delta_0 \); a
2. Coasting phase; \( \Gamma(x) \approx \Gamma_0, x > \Gamma_0 \Delta_0 \); and a
3. Deceleration phase; \( \Gamma(x) = ? \)
3.1. Relativistic Kinematics

Important questions include

- How to calculate $\Gamma(x)$?
- How is $\Gamma(x)$ related to observer time $t$?
- How to calculate internal photon number and energy density for a relativistically moving source from measured energy flux?

We consider these problems for a simple blast-wave model with several simplifying assumptions: a spherical, uncollimated explosion, a uniform surrounding medium, the blast wave approximated by a uniform thin shell, and particle acceleration at the forward shock only. Three frames of reference are considered: the explosion (GRB, stationary, or starred) frame; the comoving fluid (primed) frame; and the observer (unstarred) frame.

Using the definition of the Doppler factor

$$\delta_D = [\Gamma(1 - \beta \mu)]^{-1}, \quad (6)$$

where $\mu = \cos \theta$ and $\theta$ is the angle between the direction of the radiating fluid and the observer, we have from elementary considerations

$$dt = (1 + z) \frac{dt'}{\delta_D}, \quad \text{and} \quad \epsilon = \frac{\delta_D \epsilon'}{1 + z}. \quad (7)$$

For well-defined pulses of radiation on a measured variability time scale $t_{\text{var}}$, the comoving emission-region size scale

$$r'_b \lesssim \frac{c \delta_D t_{\text{var}}}{1 + z}. \quad (8)$$

The variability timescale $t_{\text{var}}$ implies an engine size scale, with the comoving size scale a factor $\sim \delta_D$ larger, and the emission location $\sim \Gamma^2$ larger than values inferred for a stationary region. Rapid variability can be obtained from an external shock or internal shock by energizing regions within the Doppler cone, as defined by the Doppler factor of the shocked fluid.

The $\nu F_{\nu}$ spectrum at dimensionless photon energy $\epsilon = h\nu/m_e c^2$ from a source at redshift $z$ and luminosity distance $d_L(z) = 10^{28} d_{28}$ cm is denoted by $f_{\epsilon}$. Assuming that the blob radiates isotropically in the comoving frame,

$$f_{\epsilon}(t) \equiv \frac{\delta_D^4 V'_b}{4\pi d_L^2} \epsilon' j'(\epsilon'; t') \equiv \frac{\delta_D^4 \epsilon' L'(\epsilon'; t')}{4\pi d_L^2}. \quad (9)$$

where the comoving spectral luminosity $L'(\epsilon'; t') \equiv V'_b j'(\epsilon'; t')$, and $j'(\epsilon'; t')$ is the comoving spectral emissivity. The spectral energy density $u'(\epsilon') \equiv t'_{\text{lc}} j'(\epsilon')$.

Because $V'_b = 4\pi r'_b^3 / 3$,

$$u'_\epsilon = \epsilon' u'(\epsilon') = m_e c^2 \epsilon' u'(\epsilon') \equiv \frac{3 d_L^2 f_{\epsilon}}{\delta_D^4 r'_b^3} \gtrsim \frac{3 d_L^2 (1 + z)^2 f_{\epsilon}}{c^3 \delta_D^6 \Delta t_{\text{var}}}. \quad (10)$$
Consequently the relation between the total internal photon energy density $u'$ and the total measured energy flux $\Phi$ is

$$u' \gtrsim \frac{3d_L^2(1 + z)^2\Phi}{c^3\delta_Dt_{\text{var}}^2}.$$  \hfill (11)

Requiring that $\tau_{\gamma\gamma}(\epsilon_1) < 1$, so that the emission region is transparent to $\gamma$ rays gives, using a $\delta$-function result for the $\gamma\gamma$ attenuation cross section, the result

$$\tau_{\gamma\gamma}(\epsilon_1) \approx \frac{\sigma_T}{3}\left(\frac{2}{\epsilon_1}\right)n_{\text{ph}}'(\frac{2}{\epsilon_1})r_b'.$$  \hfill (12)

With eq. (8), the requirement of optical thinness to $\gamma\gamma$ attenuation gives for flat target photon SEDs in a $\nu F\nu$ representation the result

$$\delta_D \gtrsim 200 \left[(1 + z)d_{28}\right]^{1/3}\left[\frac{\Phi_{-6}E(\text{GeV})}{t_{\text{var}}(s)}\right]^{1/6}.$$  \hfill (13)

important for interpretation of Fermi Gamma ray Space Telescope (FGST) results.

3.2. Blast Wave and Afterglow Theory

The GRB explosion forms a radiation-dominated fireball with injection explosion entropy per baryon $\eta_b = L/Mc^2 \gg 1$, and $L$ is the wind power. The energy of the expanding relativistic wind is transformed into photospheric emission and the directed kinetic energy of a hadronic shell with coasting Lorentz factor

$$\Gamma_0 = E_0/M_0c^2.$$  \hfill (14)

Here $M_0$ is the amount of baryonic matter mixed into the initial explosion. For a uniform spherically symmetric CBM, the mass of swept-up material at radius $x$ is $M_{sw} = 4\pi m_pc^2 x^3/3$, where $n_0$ is the proton density, assumed to be made of H.

The blast wave will start to undergo significant deceleration when an amount of energy comparable to the initial baryon energy $E_0$ in the blast wave is swept up. Looked at from the comoving frame, each proton from the CBM carries with it an amount of energy $\Gamma_0 m_pc^2$ when captured by the blast wave. After capture and isotropization, the amount of energy carried by the blast wave from this swept-up proton is $\Gamma_0^2 m_pc^2$ as measured in the stationary frame. The condition $\Gamma_0^2M_{sw}c^2 = E_0$ gives the deceleration radius (Rees & Mészáros 1992; Mészáros & Rees 1993)

$$x_d \equiv \left(\frac{3E_0}{4\pi\Gamma_0^2 m_pc^2 n_0}\right)^{1/3} \approx 2.6 \times 10^{16} \left(\frac{E_{52}}{\Gamma_0^{52}n_0}\right)^{1/3} \text{cm},$$  \hfill (15)

where $E_0 = E_{52}/10^{52}$ ergs is the total explosion energy including rest mass energy, $\Gamma_{300} = \Gamma_0/300$, and $n_0$ is the CBM proton density in units of cm$^{-3}$.

Differential time elements in the stationary (starred), comoving (primed), and observer (unscripted) reference frames satisfy the relations

$$dx = \beta c dt_* = \beta \Gamma c dt' = \beta c \frac{dt}{(1 + z)(1 - \beta \mu)},$$

$$
\text{where } \beta c dt_* = \beta \Gamma c dt' = \beta c \frac{dt}{(1 + z)(1 - \beta \mu)},
$$

$$
\text{important for interpretation of Fermi Gamma ray Space Telescope (FGST) results.}
$$
where the last expression is obtained by noting that $dt/(1 + z) = dt’(1 - \beta \mu)$, and $\theta = \arccos \mu$ is the angle between the direction of outflow and the observer. Hence
\[
  dt = \frac{(1 + z)}{c} dx \left( \beta^{-1} - \mu \right) \approx \frac{(1 + z) dx}{\Gamma^2 c} .
\] (16)
The last expression applies to relativistic flows ($\Gamma \gg 1$) observed on-axis, assuming that the average emitting region is at $\mu \approx \beta$.

The deceleration time as measured by an observer is therefore
\[
  t_d \equiv (1 + z) \frac{x_d}{\Gamma_0^2 c} \approx \frac{9.6 (1 + z)}{\beta_0} \left( \frac{E_{52}}{\Gamma_8 \mu_{300} n_0} \right)^{1/3} s .
\] (17)

### 3.3. Blast-Wave Equation of Motion

The equation describing the speed of the relativistic blast wave, which changes as a consequence of the blast wave sweeping up material from the surrounding medium, is for an adiabatic blast wave,
\[
  \Gamma [M_0 + \Gamma m(x)] \approx \Gamma [M_0 + k x^3 (\Gamma - 1)] \approx \text{const} ,
\]
where $m(x)$ is the swept-up mass. For $\Gamma(x) \propto x^{-3/2}$, $t \approx c^{-1} \int dx \; \Gamma^{-2} \propto \int dx \; x^3$, so $x(t) \propto t^{1/4}$ and $\Gamma(t) \propto t^{-3/8}$. If the blast wave is partially or highly radiative, different behaviors follow. [Exercise: Derive the power-law behavior for adiabatic blast waves decelerating in an external medium with radial wind density profiles.]

The kinetic energy swept into the comoving fluid frame per unit proper time at the forward shock is given by
\[
  \left. \frac{dE'}{dt'} \right|_{FS} = A(x) n_0 m_e c^2 (\beta c) \Gamma (\Gamma - 1) \propto \Gamma^2 \quad \text{for } \Gamma \gg 1 .
\] (18)
where the area $A(x) = 4\pi x^2$ for an isotropic blast wave. The factor $\Gamma$ represents the increase of external medium density due to length contraction, the factor $(\Gamma - 1)m_p$ is the kinetic energy of the swept-up particles, and the factor $\beta c$ is proportional to the rate at which the particle energy is swept into by the blast wave. This process provides internal energy available to be dissipated in the blast wave. The original treatment of adiabatic and radiative relativistic blast waves using a fluid dynamical approach was given by Blandford and McKee (1976).

A fraction $e_e$ of the forward-shock power is assumed to be transferred to the electrons, so that
\[
  L_e' = e_e \frac{dE'}{dt'} .
\] (19)
If all the swept-up electrons are accelerated, then joint normalization to power and number gives
\[
  \gamma_{min} \approx e_e \left( \frac{p - 2}{p - 1} \right) \left( \frac{m_p}{m_e} \right) (\Gamma - 1) \approx e_e \left( \frac{p - 2}{p - 1} \right) \left( \frac{m_p}{m_e} \right) \Gamma , \quad \text{for } \Gamma \gg 1
\] (20)
and $2 < p < 3$. The magnetic-field energy density $u_B = B^2/8\pi$ is assumed to be a fixed fraction $\epsilon_B$ of the downstream energy density of the shocked fluid.
Thus $B^2/8\pi \approx 4\epsilon_B n_0 m_p c^2 \Gamma^2$. A break is formed in the electron spectrum at cooling electron Lorentz factor $\gamma_c$, which is found by balancing the synchrotron loss time scale $t_{\text{syn}}'$ with the adiabatic expansion time $t_{\text{adi}}' \approx x/\Gamma c \approx \Gamma t \approx t_{\text{syn}}' \approx (4\epsilon_B T B^2 \gamma_c/24\pi m_e c^2)^{-1}$, giving

$$\gamma_c \approx \frac{3m_e}{16\epsilon_B n_0 m_p c \sigma_T \Gamma^3 t}.$$  \hspace{1cm} (21)

For an adiabatic blast wave, $\Gamma \propto t^{-3/8}$, so that $\gamma_{\text{min}} \propto t^{-3/8}$ and $\gamma_c \propto t^{1/8}$.

The observed $\nu F_\nu$ synchrotron spectrum from a GRB depends on the geometry of the outflow. If $L_{\text{syn}}'(\epsilon') = \epsilon' (dN'/de' dt')$ is the spectral luminosity in the comoving frame, then $\epsilon' L_{\text{syn}}'(\epsilon') \approx \frac{1}{2} u_B c \sigma_T \gamma^3 N_{e}(\gamma)$, with $\gamma = \sqrt{\epsilon'/\epsilon_B}$ and $\epsilon_B = B/B_{cr} = B/(4.41 \times 10^{13} \text{ G})$. For a spherical blast-wave geometry, the spectral power is amplified by two powers of the Doppler factor $\delta$ for the transformed energy and time. The $\nu F_\nu$ synchrotron spectrum is therefore

$$f_{\nu}^{\text{syn}} \approx \frac{2\Gamma^2}{4\pi d^2_L} (u_B c \sigma_T) \gamma^3 N_{e}(\gamma), \quad \gamma \approx \sqrt{\frac{(1+z)\epsilon}{2\Gamma \epsilon_B}}.$$ \hspace{1cm} (22)

For a power-law injection spectrum, the cooling comoving nonthermal electron spectrum can be approximated by

$$N_{e}'(\gamma) \approx \frac{N_0}{s-1} \gamma_0^{s-1} \begin{cases} \gamma^{-s}, & \gamma_0 \lesssim \gamma \lesssim \gamma_1 \\ \gamma_1^{p+1-s} \gamma^{-(p+1)}, & \gamma_1 \lesssim \gamma \lesssim \gamma_2. \end{cases} \hspace{1cm} (23)$$

In the slow cooling regime, $s = p$, $\gamma_0 = \gamma_{\text{min}}$ and $\gamma_1 = \gamma_c$, whereas in the strong cooling regime, $s = 2$, $\gamma_0 = \gamma_c$ and $\gamma_1 = \gamma_{\text{min}}$. This method for deriving the behaviors of the breaks in the electron and synchrotron spectrum for the simple synchrotron blast-wave model were originally given by Sari, Piran, and Narayan (1998). [Exercise. Derive the temporal and spectral behaviors for the elementary blast-wave model consisting of an impulsive adiabatic blast wave with a strong forward shock sweeping a uniform surrounding medium.]

The synchrotron shock blast-wave model has been used to fit afterglow data and deduce microphysical and environmental parameters. Detailed leptonic models include a synchrotron self-Compton (SSC) component, which is highly sensitive to the baryon-loading parameter $\Gamma_0$.

### 3.4. Beaming Breaks and Jets

An observer will receive most emission from those portions of a GRB blast wave that are within the Doppler angle $\theta_D \sim 1/\Gamma$ to the direction to the observer. As the blast wave decelerates by sweeping up material from the external medium, a break in the light curve will occur when the jet opening half-angle $\theta_j < 1/\Gamma$. This is due to a change from a spherical blast wave geometry to a geometry defined by a localized emission region. Assuming that the blast wave decelerates adiabatically in a uniform surrounding medium, the condition $\theta_j \approx \Gamma_0^{-1} = \Gamma_0^{-1} (x_{br} / x_d)^{3/2} = \Gamma_0^{-1} (t_{br} / t_d)^{3/8}$ implies

$$t_{br} \approx 45(1+z) \left( \frac{E_{52}}{n_0} \right)^{1/3} \theta_j^{8/3} \text{ days}, \hspace{1cm} (24)$$
from which the jet angle

$$\theta_j \approx 0.1[\frac{t_{br}(d)}{1+z}]^{3/8} \left( \frac{n_0}{E_{52}} \right)^{1/8}$$

(25)
can be derived. Note that the beaming angle is only weakly dependent on $n_0$ and $E_0$.

Numerical models show X-ray beaming breaks hidden by the effects of the SSC component. The important discovery (Frail et al. 2001) of a clustering, beaming-corrected energy for LGRBs opens the possibility to perform cosmological studies with GRB data.

### 3.5. Relativistic Shock Physics

The structure of a shock is determined by continuity of the particle number, energy and momentum fluxes across the shock front. The pressure $p = (\gamma - 1)e_{ke}$, where $e_{ke}$ is the kinetic energy density of the fluid, and $\gamma$ corresponds to the ratio of specific heats. For a nonrelativistic monatomic ideal gas, $\gamma = 5/3$, whereas $\gamma = 4/3$ for a relativistic gas. For strong shocks, $n' \approx n_0 \Gamma$.

The equality of kinetic-energy densities at the contact discontinuity implies, for fluids made primarily of proton-electron plasma, that

$$\frac{e_{ke}}{m_p c^2} \approx n_f (\Gamma - 1) \approx n_r (\bar{\Gamma} - 1) \approx 4n_0 \Gamma^2 \approx 4n(x)(\bar{\Gamma}^2 - \bar{\Gamma}),$$

(26)

where the reverse shock Lorentz factor is $\bar{\Gamma} = \sqrt{1 - \beta^2}$. The relativistic shock jump conditions for an isotropic explosion in a uniform surrounding medium imply (Sari & Piran 1995)

$$\frac{n(x)}{n_0} = \frac{E_0}{4\pi x^2 \Gamma_0^2 n_0 m_p c^2 \Delta} \approx \frac{E_0^3}{x^2 \Gamma_0^4 \Delta} = \frac{\Gamma^2}{\Gamma^2 - \bar{\Gamma}} \rightarrow \begin{cases} 2\Gamma^2 / \bar{\Gamma}^2, & \text{NRS} \\ \Gamma^2 / \bar{\Gamma}^2, & \text{RRS} \end{cases}$$

(27)

The relations between the forward shock (FS) and reverse shock (RS) Lorentz factors can be derived in the limit of a nonrelativistic reverse shock (NRS) and strong forward shock, and in the limit of a relativistic reverse shock (RRS) and relativistic forward shock. The RS power is $dE'/dt'|_{RS} = A(x)n(x)m_p c^2 \beta(\Gamma^2 - \bar{\Gamma})$. With the shock jump condition, one finds that $(dE'/dt'|_{RS})/(dE'/dt'|_{FS}) = \beta$, so that roughly equal power is dissipated as internal energy in the forward and reverse shock during the RRS phase.

### 3.6. External Shock Model

This is sufficient blast-wave physics that evolving forward and reverse shock emissions can be calculated for comparison with data. Synthetic light curves in the external-shock model can be derived and used to make predictions for the generic behavior of GRBs with smooth light curves. Spikiness of the light curve could originate from inhomogeneities in the external medium, before the blast wave has entered the adiabatic deceleration regime. Consider a blast wave intercepting a cloud with size $r \ll R/\Gamma_0$ that is located at an angle $\theta$ with respect to the line of sight to the observer. The duration of the received pulse
of radiation depends on the light travel-time delays from different portions of the blast wave as it interacts with the cloud. Photons emitted when the blast wave passes through the near and far sides of the cloud are received over a radial timescale

$$t_r = \frac{2r}{\beta_0 \Gamma_0 \theta_D c} \approx \frac{r}{\Gamma_0^2 c}. \quad (28)$$

Photons emitted from points defining the greatest angular extent of the cloud are received over an angular timescale

$$t_{ang} \approx \frac{r \theta}{c}. \quad (29)$$

Note that if $r \to R/\Gamma_0$ and $\theta \to 1/\Gamma_0$, then $t_{ang} \to R/\Gamma_0^2 c$, as expected. When $\theta \approx 1/\Gamma_0$, $t_{ang} \approx \Gamma_0 t_r \gg t_r$. Except for those few clouds with $\theta < \approx 1/\Gamma_0$, $t_{ang} \gg t_r$. Highly variable light curves with reasonable ($\approx 10\%$) efficiency can be produced in an external shock model (Dermer & Mitman 1999).

In the external shock model, a single relativistic wave of particles interacts with inhomogeneities in the surrounding medium to accelerate particles that radiate the prompt $\gamma$ rays. A central requirement for strong radiative efficiency in an external shock model for the prompt phase is that a strong forward shock is formed; otherwise the Lorentz factor $\Gamma \ll \Gamma_0$ and the radiation is strongly beamed. A strong forward shock is formed when the comoving shell density $n(x) \gg \Gamma_0^2 n_0$.

### 3.7. Internal Shock/Colliding Shell Model

In the internal shock model, an active central engine eject waves of relativistic plasma that overtake and collide to form shocks. The shocks accelerate nonthermal particles that radiate high-energy photons. The relative Lorentz factor of the two shells with Lorentz factors $\Gamma_1$ and $\Gamma_2$, with $\Gamma_2 = \zeta \Gamma_1$, $\zeta \geq 1$, is

$$\Gamma_{rel} = \frac{\Gamma_1 \Gamma_2 (1 - \beta_1 \beta_2)}{\Gamma_1^{1/2} + \Gamma_2^{1/2}} \left(\frac{1}{2} (\zeta - \zeta^{-1})\right). \quad (30)$$

For mildly relativistic internal shocks with a range of relative Lorentz factors $1 \lesssim \Gamma_{rel}, \zeta \lesssim 10$, the Lorentz factor $\tilde{\Gamma}$ of the shocked fluid with adiabatic index $\tilde{\gamma} = 5/3$ in the explosion frame is

$$\Gamma_{sf} \approx 2\Gamma_1 - \frac{\Gamma_{rel} F^{1/4}}{\sqrt{2 \Gamma_{rel} F^{1/2}}} \approx \sqrt{2 \Gamma_{rel} \Gamma_1} \approx \sqrt{\Gamma_1 \Gamma_2},$$

where $F = n_2/n_1$ is the ratio of proper frame densities of shell 2 to shell 1 when they intercept each other (eq. [27]), and the final expression assumes that $n_2 \approx n_1$ and $\Gamma_{rel} \gg 1$. The proper shocked fluid number and energy densities are

$$n_{sf} = (4\Gamma_{rel} + 3)n_1 \approx 4\Gamma_{rel} n_1, \text{ and } e_{sf} = \Gamma_{rel} n_{sf} m_p c^2.$$

Now consider the elastic collisions of shell 2 with mass $m_2$ intercepting shell 1 with mass $m_1$. In an elastic collision, the Lorentz factor of the merged shell is

$$\Gamma_m \approx \sqrt{\frac{m_1 \Gamma_1 + m_2 \Gamma_2}{m_2 / \Gamma_2 + m_1 / \Gamma_1}}. \quad (31)$$
The efficiency to convert the directed kinetic energy of the shells into internal energy is
\[ \eta = 1 - \frac{(m_1 + m_2)\Gamma_m}{m_1\Gamma_1 + m_2\Gamma_2}. \] (32)

The efficiency is greatest when the shells have comparable mass and \( \Gamma_2 \gg \Gamma_1 \); otherwise \( \eta \sim \text{few} \% \). When the contrast between the \( \Gamma \) factors of the shells is large, \( \eta \sim 10 - 20\% \) is possible.

The rapid X-ray decline can be explained by high-latitude emission after the central engine has been turned off. Writing the flux density \( F_\nu \propto \nu^\alpha t^\beta \) gives the curvature relation, which assumes that the spectral shape of the radiated flux is constant within the Doppler cone. The curvature relation is \( \alpha = 2 - \beta \).

In the standard model for LGRBs with relativistic winds and colliding shells, X-ray flares are made when the GRB engine is restarted. Long-lasting GRB central engines can also involve continual injection scenarios with pulsars. The generic long-duration GRB light curve at \( \sim 1 \) keV, from Swift observations (Zhang et al. 2006; Nousek et al. 2006), can be divided into a prompt phase (0), a decay phase (I), a plateau phase (II), an afterglow phase (III), and a jet break phase (IV), in addition to X-ray flares (V). Kinematic shapes of GRB pulses can be calculated for illuminated shells when the thickness and duration of illumination of the shell are varied.

3.8. Leptonic GRB Physics: Summary

The success of the fireball/relativistic blast wave model arises from its ability to explain

1. Large energy releases in short times;
2. Escape of \( \gamma \) rays;
3. Afterglows at various wavelengths from radio through \( \gamma \) rays.

The physics is widely applicable to many nonthermal systems, including blazars, microquasars, pulsar winds, . . .

This hardly exhausts leptonic blast-wave physics. Other interesting physics involves thermal photospheres, the “line of death” and synchrotron jitter radiation, and the origin of the Amati and Ghirlanda relations.

4. Hadronic Processes and Cosmic Rays in GRBs

Acceleration of ultra-relativistic protons and ions is favored in a blast wave physics scenario at least as much energetic ions, insofar as \((1 - \epsilon_e)\) of the power in the dissipation region emerges in the form of magnetic field energy or ions and, if ions, with energy \( \gtrsim \Gamma_0^2 \) GeV. The outline for this lecture is

1. Ultra-high Energy Cosmic Rays (UHECRs)
2. Photohadronic Processes, Energetics, and Power
3. Hadronic Blast Wave Theory
4. Cosmic Rays from GRBs

5. Neutrinos from GRBs

6. GRBs in the Milky Way

4.1. Ultra-High Energy Cosmic Rays

The year 1912 is a landmark date in space science when the cosmic radiation, a “penetrating radiation from above,” was discovered by Victor Hess by flying electroscopes on a balloon. The cosmic-ray energy density at GeV/nucleon energies is \( u_{CR} \approx 10^{-12} \text{ ergs/cm}^3 \), with the total cosmic-ray kinetic energy density modulated by the outflowing Solar wind on 22-yr Solar cycle. The knee of the spectrum is at \( \approx 3 \text{ PeV} \), the second knee is at particle energy \( E \approx 10^{17.4} \text{ eV} \), the ankle (or dip) at \( E \approx 10^{17.6} \text{ eV} \), and the GZK cutoff is at \( E_{GZK} \approx 10^{19.5} \text{ eV} \). The value of \( u_{CR} \approx 10^{-21} \text{ ergs/cm}^3 \) at \( E > \sim 10^{19} \text{ eV} \).

The Pierre Auger Observatory (PAO), located in the Mendoza Province in Argentina at \( \approx 36^\circ \text{ S latitude} \) determines the arrival directions and energies of UHECRs using a hybrid technique consisting of four telescope arrays to measure Ni air fluorescence and 1600 surface detectors spaced 1.5 km apart to measure muons formed in cosmic-ray induced showers. Event reconstruction using the hybrid technique gives arrival directions better than \( 1^\circ \), and energy uncertainties better than \( \approx 20\% \). Two important discoveries were made in 2007, namely

- GZK cutoff with the HiRes Observatory (Abbasi et al. 2008) and the PAO (2008).
- Clustering of arrival directions toward AGN in the supergalactic plane, with the PAO (2007).
- Interesting though ambiguous results on composition were also announced by the PAO in 2007 (Unger et al. 2007).

The GZK cutoff, now seen clearly with HiRes and the PAO, contrary to earlier AGASA results, is a consequence of exponentially increasing energy losses of UHECR protons due to photopion-producing reactions with photons of the CMBR. For UHECR Fe, strong photo-dissociation though, primarily, one and two-nucleon losses in giant dipole resonance reactions, also produce a GZK cutoff. There is no strong evidence for a lighter composition at \( E \gtrsim 10^{19} \text{ eV} \) inferred from data taken with the PAO to energies \( E \lesssim 4 \times 10^{19} \text{ eV} \), contrary to pre-Auger suggestions (Watson 2006). Extrapolation of particle physics uncertainties to large values of total CM energy make deductions about composition from shower data uncertain.

A major result announced by the PAO collaboration in 2007 was the correlation of arrival directions of \( E \gtrsim 60 \text{ EeV} \) UHECRs with nearby, \( d \lesssim 75 - 100 \text{ Mpc} \), AGNs in the Véron-Cetty & Véron (2006) catalog. A marked excess in the direction of Cen A has generated much interest in the possibility that Cen A is an UHECR source. Both radio-loud AGN and GRBs remain plausible candidates, but the absence of strong radio galaxies within \( \approx 100 \text{ Mpc} \) of a number of UHECR arrival directions is puzzling for a radio-galaxy origin of the UHECRs.
4.2. Photohadronic Processes, Energetics, and Power
Like filling a bathtub, filling the Galaxy with cosmic rays, or the universe with UHECRs, is a balance between injection and escape (loss). Symbolically,

$$u_{CR}(E) \simeq t_{\text{loss}}(E) \dot{\varepsilon}_{CR}(E). \quad (33)$$

The emissivity $\dot{\varepsilon}_{CR}(E)$ is source dependent, and expected to favor strong non-thermal sources. Relevant photohadronic processes are photomeson and photopair production, and photodisintegration for ions. The photomeson or photopion cross section resembles a threshold step-function due to the onset of various resonant and nonresonant channels above threshold. Photopion losses due to interactions with photons of the extragalactic background light (EBL), importantly consisting of the CMBR, and Bethe-Heitler ($N \gamma \rightarrow Ne^+e^-$) photopair losses on nucleon $N$. In addition, one must consider ion-synchrotron and universal expansion losses. (*Exercise:* Derive the ion-synchrotron energy loss rate in a tangled magnetic field, and the maximum synchrotron photon energy and particle energy in Fermi acceleration scenarios.) For photopion losses, we use a step-function approximation, from which the energy loss mean-free-path for particles of energy $E$ can be derived.

The UHECR emissivity (or luminosity density), from eq. (33), is $\dot{\varepsilon}_{CR}(E) \simeq u_{CR}(E)/t_{\text{loss}}(E)$. Using PAO measurements and results of energy-loss mean-free-paths, then $\dot{\varepsilon}_{CR}(E) \simeq 10^{44}$ ergs/Mpc$^3$-yr for $E \gtrsim 10^{18}$ eV. This is within an order of magnitude of the electromagnetic emissivity of GRBs, as noted in 1995 by Vietri and Waxman. If the baryon-loading factor $f_b \gg 1$, as implied when $\epsilon_e \ll 1$, then LGRBs could power the UHECRs; SGRBs do not seem to have the required emissivity.

LLGRBs, which take place at low redshifts (GRB 980425/SN 1998bw was at $d \approx 40$ Mpc), can also, in principle have the requisite emissivity. Estimates show emissivities of the outflowing kinetic energy in LLGRBs of $\approx 250 \times 10^{44}$ ergs/Mpc$^3$-yr (Wang et al. 2007); however only a small fraction of this luminosity density can be expected to emerge in the form of hard X-rays and soft $\gamma$ rays.

4.3. Hadronic Blast Wave Theory
The elements of blast-wave theory applied to leptons is, with appropriate changes, directly applied to hadrons. In the simplest model, cosmic-ray protons are injected downstream of the shock with spectrum

$$\dot{N}'(\gamma') \propto \gamma'^{-p} H(\gamma'; \gamma'_{\text{min}}, \gamma'_{\text{max}}), \quad (34)$$

normalized to the number of swept-up protons $N_0 = 4\pi x^3/3$, the swept-up power, and the magnetic field $B$ defined in terms of shocked fluid energy density (Lecture 3). The minimum comoving proton Lorentz factor $\gamma'_{\text{min}} \approx \Gamma'(x)$, and the maximum is set by equating size scale with Larmor radius. For equipartition magnetic fields, cosmic-ray protons reach ultra-high, $\gtrsim$ EeV energies after freely escaping from the blast wave into interstellar space. (*Exercise:* work out these relations.)

The emission spectrum from a GRB includes in addition to a leptonic component a photohadronic component. The three dominant collision processes are
(i) secondary nuclear production; (ii) photomeson production; and (iii) photopair production. Energetics arguments favor photohadronic processes over the nuclear collision processes. Proton and ion synchrotron radiation must also be considered. The cascade \( \gamma \)-ray spectrum is initiated by decay of secondary mesons, attenuation of high-energy photons, and synchrotron radiation. Hadronic emission decays more slowly than leptonic emissions in standard blast-wave model calculations (Böttcher & Dermer 1998).  

**Problem:** Analytically examine correlations in variability behavior for proton synchrotron \( \gamma \) rays and leptonic synchrotron emission. Do the same for photohadronic processes.

### 4.4. UHECRs from GRBs

The astrophysics to calculate the UHECR energy spectrum measured here at Earth can be extensive (Berezinskii & Grigor’eva 1988). Assuming a homogeneous source type that explodes and releases the same UHECR spectrum into intergalactic space throughout cosmic time enormously simplifies the problem. The star formation rate factor for GRB progenitors could follow the classical SFR (Hopkins & Beacom 2006), or have a different dependence due, e.g., metallicity effects. For very active SFRs at \( z \approx 1 \) compared to now, the pair-production trough becomes more pronounced to explain the ankle feature through photopair losses. The model of Wick, Dermer, and Atoyan (2003) for the UHECR spectrum from GRB sources predicts a very sharp GZK cutoff but requires a large baryon load, \( f_b \approx 30 – 100 \). (Note that the lower normalization of Auger vs. HiRes brings the value of \( f_b \) down.)

Different choices for the GRB star formation rate, which normalizes the luminosity density (emissivity) at different \( z \), can be normalized to various SFR factors. Very active star formation rates can be ruled out by comparing Swift and pre-Swift statistical GRB data (Le & Dermer 2007). The UH ECR spectrum is also quite sensitive to the maximum energy of accelerated ions or protons.

### 4.5. Neutrinos from GRBs

The opening of the high-energy (> TeV) neutrino window is anxiously awaited, when statistically significant detection of a cosmic point or extended source of high-energy neutrinos with a deep ice-based or water-based Cherenkov light sensitive detectors happens. Charged-current interactions of a neutrino with a nucleon induce muon, electron, or tau production (Gaisser et al. 1995). These particles cascade and shower to make Cherenkov light. Detector optical modules (DOMs) in the IceCube detector at the South Pole detect upward-going tracks to screen out the intense background from downward-going showers induced by cosmic-ray muons.

Significant extraction of UHECR energy via photohadronic processes can be made in a collapsar-model GRB, with a significant fraction going into neutrinos. The efficiency for neutrino production depends importantly on the baryon loading and Doppler factor. A spectrum with index \( -2 \) minimizes energy requirements and gives detectable neutrino production for the large GRB baryon loading required to fit the UHECR spectrum. Interesting anti-correlations between neutrino and \( \gamma \)-ray brightness arise because of the underlying physics. Photomeson cascade calculations consist of many generations of Compton-upsattered and lepton synchrotron radiation. A \( \gamma \)-ray spectral model of a GRB must in-
clude, at least, a photohadronically induced $\gamma$-ray component from UHECRs in GRB blast waves, in addition to the lepton synchrotron and SSC radiation. The high-energy neutrinos are formed between $\approx 100$ TeV and 100 PeV.

Photomeson production in a GRB blast wave, for parameters used to fit the UHECR spectrum, leads inevitably to a neutral beam of neutrons, $\gamma$ rays, and neutrinos. Many interesting implications of the neutral beam model (Atoyan & Dermer 2003) follow, first being detectability of GRBs in high-energy neutrinos for reasonable collapsar model GRB parameters, though with Doppler factors $\lesssim 100$. Subsequent photopion interactions from UHECR neutrons or neutron-decay UHECR protons induce beam of $\gamma$ rays and leptons that cascade, making hyper-relativistic, highly polarized synchrotron radiation. A classical LGRB model for UHECRs allows fairly definite predictions to be made involving only a few parameters for the cosmogenic GZK neutrino spectrum. This gives the “guaranteed” UHECR $\nu$ spectrum for a given astrophysical/cosmological model of UHECR origin.

4.6. GRBs in the Galaxy

Cosmic Rays from GRBs in the Galaxy. Depending on the beaming factor $\varphi_{bm}$, the rate of GRBs in Milky Way is estimated to be $\sim 1$ per $(0.1 - 1)$ Myrs. The rate of GRBs producing astrobiological effects at Earth is $\sim 1$/Gyr.

For a beaming factor $\sim 1/50 - 1/500$ (Frail et al. 2001) the mean $\gamma$-ray energy in X/$\gamma$-rays is $\approx 5 \times 10^{50}$ ergs. The likelihood of a recent ( $\lesssim$ Myr) GRB in our Galaxy is scaled from BATSE rate of $\approx 2$ GRB/day. From these estimates, $\approx 0.3 - 1\%$ of SNe collapse into black holes, implying $\sim 1$ GRB every $\sim 3 - 100$ kyrs in the Galaxy The expected number of recent GRBs within $r$(kpc) of Earth over a period of duration $t$ is, roughly,

$$\langle N_{GRB} \rangle \approx r^2(kpc) t(\text{Myr}).$$

(Exercise: Verify, correct, or improve these estimates.)

Upon injection by a GRB, high-energy cosmic rays diffuse throughout the disk into the halo of the Milky Way. For isotropic turbulence and a diffusion coefficient $D(E)$, a particle cloud diffuses according to the relation

$$N(E, r, t) \propto r_{diff}^3 \exp\left(-r^2/r_{diff}^2\right), \quad r_{diff}(E) = \sqrt{2D(E)t}.$$

A two-component turbulence spectrum, corresponding to turbulent energy injection at the pc and 100 pc scales following Kolmogorov and Kraichnan behaviors, was used to model (Wick et al. 2004) propagation of cosmic rays and ions between $\approx 100$ TeV and $\approx 10^{17}$ eV. The diffusion coefficient is limited by the relation $r_{diff}(E)/t < c$ and, in general, is anisotropic.

In its simplest form, such a model is sufficiently quantitative to fit the energy spectra of UHECR ions, as measured with the Karlsruhe observatory, KASCADE (Antoni et al. 2004). The injection spectrum of the ion component is fixed, with composition varied to improve the fit. The propagation characteristics depends of the rigidity coefficient, essentially energy per charge at these energies. A crucial issue is anisotropy. The combined Galactic GRB model for cosmic rays through the knee, combined with the extragalactic/cosmological UHECRs make a complete model for high-energy cosmic rays. Propagation of
high-energy cosmic rays in the Galaxy exhibit surprising but easily understood effects.

**Astrobiological Effects from GRBs in the Galaxy.** The rate of intense events from GRBs in the Galaxy can be estimated from the previous results (Dermer & Holmes 2005). Define the bolometric photon fluence \( \varphi = S\varphi_\odot \) with reference to the Solar energy fluence \( \varphi_\odot = 1.4 \times 10^6 \) ergs cm\(^{-2}\) received at Earth in one second. Significant effects on atmospheric chemistry through formation of nitrous oxide compounds and depletion of the ozone layer is found when \( S > 10^2 - 10^3 \) because of the very hard incident radiation spectrum of GRBs that is reprocessed into biologically effective 200 – 320 nm UV radiation.

Using the standard energy reservoir for LGRBs to establish apparent energy release for a jet with opening half-angle \( \theta_j \), one finds that the maximum sampling distance \( R_s \) of a GRB with apparent isotropic \( \gamma \)-ray energy release \( E_{\gamma,\text{iso}} \) to be detected at the fluence level \( \varphi > \varphi_{\text{th}} = S\varphi_\odot \) is

\[
R_s = \sqrt{\frac{E_{\gamma,\text{iso}}}{4\pi\varphi_{\text{th}}}} \simeq 1.1 \text{kpc} \left(\frac{\theta_j/0.1}{S/10^3}\right)^{\frac{1}{2}}. \tag{37}
\]

If one GRB occurs every \( 10^5 t_5 \) years in the Milky Way, the rate of biologically significant events is

\[
\dot{N}(> S) \simeq 0.3 \frac{\mathcal{E}_{51}}{R_{15}^2 (S/10^3) t_5} \text{Gyr}^{-1}. \tag{38}
\]

Thus a GRB at a distance \( \approx 1 \) kpc with \( S > 10^2 \) takes place about once every Gyr, and more frequently if \( t_5 \approx 0.1 \).

A GRB pointed towards Earth produced a lethal flux of high-energy photons and muons that destroyed the ozone layer, killed plankton, and led to trilobite extinction in the Ordovician Epoch (Melott et al. 2004). Geological evidence points toward two pulses: a prompt extinction and an extended ice age. A muon dose and intense flux of ionizing photons from a GRB could have produced the prompt extinction. Delayed cosmic rays could have produced the later ice age. (*Exercise:* Calculate muon dose at Earth’s surface from UHECR neutron impacts on the upper atmosphere made by a GRB in the Galaxy. Describe effects.)

The issue of metallicity-dependence of LGRB progenitors introduces a large additional uncertainty into these estimates (Stanek et al. 2006). Local LLGRBs are found in low-metallicity host galaxies. This may also be the case for LGRBs. Recent work has also considered the role of LLGRBs as sources of UHECRs.

A complete model for cosmic rays developed by Wick, Dermer, and Atoyan (2004) has

1. Cosmic Rays below \( \lesssim 10^{14} \) eV from SNe that collapse to neutron stars
2. Cosmic Rays above \( \gtrsim 10^{14} \) eV from SNe that collapse to black holes
3. CRs between knee and ankle/second knee from GRBs in Galaxy
The highest energy cosmic rays originate from outside our galaxy, because their Larmor radii exceed the size scale of the Galaxy. *(Problem: Derive the transition energy from galactic to cosmological dominance of cosmic rays for a realistic galactic magnetic field model. Fit to data using simplifying assumptions.)*

### 4.7. Hadronic GRBs: Summary

The acceleration of ultrarelativistic hadrons in GRB blast waves introduces many new aspects to the GRB problem. Specializing to LGRBs and UHECR protons, we find that

- LGRBs are a viable source of UHECRs;
- Hard $\gamma$-ray emission components are formed by hadronic cascade radiation inside GRB blast wave;
- A second emission component is formed by outflowing high-energy neutral beam of neutrons, $\gamma$-rays and neutrinos;
- GRBs can be detectable high-energy neutrino sources, which would confirm UHECR acceleration;
- Cosmic rays can be accelerated by GRBs in the Galaxy; and
- GRBs could be responsible for ionizing or extinction events on Earth.

A Northern hemisphere Auger, like its Argentine counterpart, will produce the first full-sky map of the universe not in the electromagnetic window, but in the particle window.

### 5. GRB and $\gamma$-ray studies with Fermi/GLAST

Each major advance in GRB science is a result of new instrumentation. The next GRB epoch has already began with the launch of GLAST on June 11, 2008, renamed the Fermi Gamma-ray Space Telescope (FGST) on August 26, 2008. Besides GRBs, the FGST will vastly increase our knowledge of astronomical $\gamma$-ray sources. The historical perspective presented here will soon be superseded by the FGST, but gives us the opportunity to guess what it might see.

Besides the steady diffuse glow of the Milky Way at 100 MeV – GeV energies from the decay of pions formed as secondaries in cosmic-ray collisions with dust and gas, the $\gamma$-ray sky is pulsing from pulsars, flarings from the Sun and blazars, burstings from GRBs, and revealing $\gamma$-ray enhancements from sources in the Solar system, Galaxy, and beyond the Galaxy at sites of cosmic-ray production or dark-matter annihilation.

The FGST will join an ongoing revolution in high-energy astronomy, including ground-based air and water Cherenkov telescopes VERITAS, HESS, Cangaroo III, MAGIC-2, and Milagro and its successor HAWC. At GeV energies, AGILE (with its super-AGILE X-ray detector), will be joined by the FGST with its GBM and LAT. This is in addition to multimessenger observatories (including Auger, KM3NeT, HiRes, LIGO, LISA, ANITA) and X-ray telescopes (e.g., Chandra, XMM, RXTE, Suzaku . . .) *(Exercise: Report on various observatories.)*
5.1. EGRET and Fermi/GLAST

The Energetic Gamma Ray Experiment Telescope (EGRET) on CGRO was most sensitive between \( \approx 100 \text{ MeV} - 5 \text{ GeV} \) with a field-of-view equal to about \( \frac{1}{24} \)th of the full sky. Its maximum effective area between 100 MeV and 1 GeV was about 1200 cm\(^2\), and its point-spread function was \( \approx 5.7^\circ \) at 100 MeV, improving \( \propto E^{-1/2} \) at higher energies. For a nominal two-week observing period, EGRET reached integral fluxes \( \gtrsim 15 \times 10^{-8} \text{ ph}(>100 \text{ MeV}) \text{ cm}^{-2} \text{ s}^{-1} \) for high-latitude point sources. The FOV is defined as the subtended solid angle swept from the zenith to the angle where the effective area is one-half of on-axis effective area.

EGRET provided tantalizing clues to \( \gamma \)-ray emission from GRBs, including GRB 940217 with a tail of 100 MeV – GeV emission to \( \sim 93 \) minutes after the GRB trigger (Hurley et al. 1994). A 20 GeV photon appeared after the end of Earth occultation. Forming crude spectra during prompt phase and afterglow phase shows clear evidence for a second, high energy emission component. Moreover, \( \sim 100 \text{ MeV} \) \( \gamma \) rays are found during peak pulses.

Not only GRB 940217, but the superbowl GRB 930131, which could be a SGRB, displayed hard emission after the end of the prompt phase. The prototype Milagro experiment presented evidence for multi-TeV emission from GRB 9704171A, which can best be confirmed if new members of this class were detected.

Most important for expectations with the FGST is to consider results for five GRBs from the EGRET Spark Chamber. The average spectrum of high energy GRB emission within 200 seconds of BATSE trigger for GRB 940301, GRB 940217, GRB 930131, GRB 910601, GRB 940503 is well fit with a differential power law photon spectrum with index \( 1.95^{+0.25}_{-0.4} \) (Dingus et al. 1998). Seven GRBs were detected with EGRET either during the prompt sub-MeV burst, or after sub-MeV emission has decayed away. The ratios of the 100 MeV – 5 GeV EGRET fluence to \( >20 \) keV BATSE fluence are typically a few percent to a few tens of percent. (Note that these GRBs were all observed early in the EGRET mission before the spark chamber gas was degraded. Silicon strip detector technology in the FGST avoids the use of consumables.)

The Total Absorption Calorimeter on EGRET scintillated in response to very bright GRB events, even for off-axis GRBs. Joint BATSE/EGRET TASC analysis discovered anomalous \( \gamma \)-ray emission components in GRB 941017 not easily explained with the leptonic blast-wave model (González et al. 2003).

The FGST, as already noted, consists of two telescopes, the Large Area Telescope, the LAT, and the Fermi GLAST Burst Monitor, GBM. The sensitive energy range of the LAT is between 50 MeV and 100 GeV (self-vetoing backsplash limited the highest energies of EGRET to 5 GeV), with a FOV of \( \frac{1}{5^5} \)th of the full sky, and a PSF of \( \approx 3.5^\circ (0.55^\circ) \) at 100 MeV (1 GeV). Its on-axis effective area for GeV photons is \( \approx 9000 \text{ cm}^{-2} \), and the nominal observing strategy is to scan the sky every three hours. The combined effective area and smaller FOV means that the FGST can reproduce EGRET’s one-year capabilities within about 4 days, and will reach one-year detection thresholds of \( \approx 0.4 \times 10^{-8} \text{ ph}(>100 \text{ MeV})/\text{cm}^{2}\cdot\text{s} \). The GBM can, to first order, be considered comparable to a slightly smaller BATSE, detecting \( \approx 200 \) GRBs per year,
but with better sensitivity between $\approx 1 - 30$ MeV due to the BGO (Bismuth Germanate) scintillator, as well as sensitive down to $\approx 8$ keV.

The effective area for the FGST telescope depends on the observing mode, but naive comparison of effective areas and point spread functions reveals how superior the FGST will be with respect to EGRET. (For the latest Fermi LAT instrument performance, google “GLAST LAT Performance.”) Thin and thick sections refer to different thicknesses of conversion layers in the LAT tracker to optimize for effective area (thick layers) or direction (thin layers). Different predictions about FGST LAT detection of GRBs can be made by scaling from the relative ratios of fluences in BATSE to EGRET for the 5 spark chamber GRBs. About 20 GRBs full sky per year with more than 10 ($> 100$ MeV) $\gamma$ rays, or about four per year in the LAT FOV with more than 5 ($> 100$ MeV) $\gamma$ rays (excluding autonomous slewing maneuvers), are predicted (Le & Dermer 2008). Only about 1 GRB with more than 100 ($> 100$ MeV) $\gamma$ rays is predicted through the five-year nominal Fermi/GLAST lifetime, but presence of second components or new classes of GRBs should improve detection rate.

FGST data is proprietary until one year after the start of Phase I, the first year of science operations. Even during the first year, the GLAST team is obligated to release light curves and spectral data as soon as practical for $\gamma$-ray transients that exceed a flux of $\approx 200 \times 10^{-8}$ ph($> 100$ MeV)/cm$^2$-s, which should occur at the rate of once every week or so. On top of that, the light curves and spectral behavior of some 24 sources of interest will be released to the community.

Analysis of EGRET data to search for point and extended points of radiation requires, especially at low ($|b| < 10^\circ$) Galactic latitudes, a diffuse model for cosmic-ray interactions in the Galaxy. The third EGRET catalog (Hartman et al. 1999) lists 271 $\gamma$-ray sources, including the single 1991 solar flare bright enough to be detected as a $\gamma$-ray source, the Large Magellanic Cloud, five pulsars, one probable radio galaxy detection (Cen A), and 66 high-confidence identifications of blazars (BL Lac objects, flat-spectrum radio quasars, or unidentified flat-spectrum radio sources). In addition, 27 lower confidence potential blazar identifications are noted. Finally, the catalog contains 170 sources not yet identified firmly with known objects.

Surprises and important results are expected from FGST regarding

1. $\gamma$ rays from associations of high mass stars with strong stellar winds;

2. Spectra of $\gamma$-ray emission from supernova remnants, allowing $\gamma$-ray astronomy a final chance to answer the question of Galactic cosmic-ray origin;

3. Origin of microquasar $\gamma$-ray emissions, whether due to a scaled-down microquasar jet or to particles accelerated the shocks formed at the interface of a binary system consisting of a young pulsar and a high-mass star;

4. Galactic astronomy, using other data bases (e.g., WMAP) to search for gaseous components in the Galaxy that are illuminated by cosmic-ray interactions;

5. Search for $\gamma$ rays from normal, starburst, and IR luminous galaxies;
6. γ-rays from cosmic rays energized by structure formation shocks in clusters of galaxies;

7. γ-rays from dark matter annihilation;

8. Blazars and their misaligned radio galaxy counterparts.

5.2. AGN Studies with the Fermi Gamma-ray Space Telescope

The standard blazar model features collimated ejection of relativistic plasma from supermassive black holes. The relativistic motion accounts for lack of γγ attenuation, as in the case of GRBs. Other evidence for relativistic outflows include superluminal motion, super-Eddington luminosities, high-energy beamed γ-rays made in Compton or photo-hadronic processes. There is a considerable difference in the environments of GRBs and blazars, for example, the intense external radiation field from broad line-region gas in FSRQs.

The redshift distribution of EGRET blazars leads to model predictions for the FGST. Connections between different types of supermassive black holes with jets of radio and γ-ray emitting plasma can be made based on data with the FGST, including tests of the blazar main sequence, and studies of black-hole engine and jet physics. FGST observations with correlated multiwavelength campaigns will provide important data for modeling studies, and for searching for anomalous blazar γ-ray emission components, including orphan flares and hadronic γ-ray signatures. Long straight radio and X-ray jets, like in the FR2 radio galaxy Pictor A, could reveal UHECR acceleration in blazars through neutral beam processes. Acceleration of UHECRs in blazars, like in GRBs, will be most decisively demonstrated with neutrino detection. The detection of one or two ~PeV neutrinos from a blazar during flaring conditions will overturn our thinking about how radio lobes are formed, because a decaying neutrons and attenuated UHE γ-rays can power the knots, hot spots, and lobes of a radio galaxy. Detection of pair halos from nearby radio galaxies would give evidence in favor of the UHECRs made in GRBs.

The superposition of γ-rays formed by various sources throughout cosmic time produce an unresolved γ-ray background intensity. Only about ~10 – 20% of the diffuse background can be made by FSRQ and BL Lac blazars, based on analysis of the EGRET results (Dermer 2007). Other source classes that can make up the diffuse extragalactic γ-ray background include

1. Star-forming galaxies;

2. Starburst galaxies;

3. Pulsars;

4. Galaxy cluster shocks; and

5. Dark matter annihilation.

Although GRBs are momentarily very bright, they are so rare that their contribution to the diffuse background is small. (Problem: Construct fully analytic or semi-analytic [solution in quadrature, i.e., single integral] models of various source classes.)
5.3. Concluding Remarks

Some important problems in GeV $\gamma$-ray astronomy that will soon be opened for study in view of anticipated FGST discoveries include

1. Particle acceleration theory;
2. Origin of the galactic cosmic rays;
3. Jet physics, and the differences between radio/$\gamma$-ray black-hole sources;
4. Blazar demographics;
5. Search for hadronic $\gamma$-ray emission components and the sources of UHE-CRs; and the
6. Origin of the diffuse/unresolved $\gamma$-ray background.

In view of the Fermi Gamma ray Space Telescope for GRB studies, we can expect a new golden era.

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