GAMMA-RAY BURSTS

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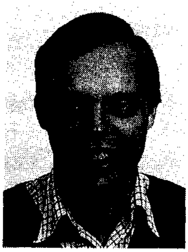

ABSTRACT

Gamma-ray Bursts are an exotic class of astronomical sources that are currently extremely topical within the astrophysical community and are also provoking considerable interest in a broader range of physics disciplines. This paper briefly reviews the generic properties of these transient sources, obtained from observations accumulated over the last two decades, and then discusses some of the latest observations, focusing on recent interpretations of the data, and theoretical approaches that may help unravel the mysteries of gamma-ray bursts.

AN INTRODUCTION TO GAMMA-RAY BURSTS

Gamma-ray Bursts (GRBs) have intrigued observers and confounded theorists ever since their discovery just over twenty years ago.[1] The results obtained by the Compton Gamma-Ray Observatory (CGRO) have perpetuated the confused picture we have of these enigmatic objects. Yet the GRB field is alive and more dynamic than ever, perhaps due to the exotic nature of these objects and the fascinating physics that may be needed to describe and understand them. The enigmatic nature of GRBs is largely because they are transient phenomena. They are bursts of gamma-rays, usually somewhere between about 10 keV and 10 MeV in energy (e.g. see ref. 2), and last for as little as milliseconds or as long as several minutes.[2-6] Typical burst time histories are displayed in the First BATSE GRB Catalogue[5] and an exceptionally good burst spectrum is presented in Fig. 1. While other transient astronomical sources exist, gamma-ray bursts are unique in that they are the only source population that emits only in the gamma-ray range of the spectrum; associated emission in

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other wavebands has never been observed. In fact, searches (e.g. see papers in ref. 7) for convincing transient or quiescent steady-state counterparts to classical GRBs in radio, optical and X-ray bands have proved negative. Note that such counterparts have been found for the soft-gamma repeaters, a separate class of objects that will not be considered here. This null result has prolonged and enhanced the mystery of GRBs, since the discovery of associated sources would provide distances to GRBs and thereby tell astronomers their origin.

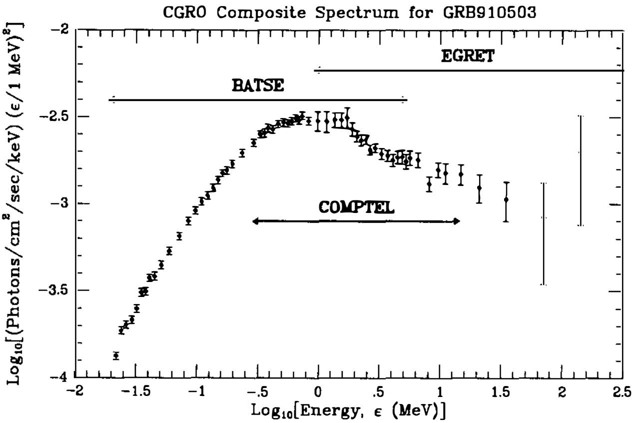

Fig. 1 The composite time-integrated spectrum[8] for the burst GRB910503 (detected May 3, 1991) as obtained by the BATSE, COMPTEL and EGRET instruments on the Compton Gamma-Ray Observatory (CGRO), multiplied by the square of the photon energy ε to depict the emitted power per logarithmic energy bandwidth. The various detector responses have been accounted for in producing this source spectrum, and the energy ranges over which the three instruments are sensitive are indicated.

Gamma-ray bursts have rapid time-variability with intensity fluctuations on timescales t_{var} sometimes less than a millisecond,[9] motivating the premise that they originate in compact environments of size $c t_{var} \sim 10^7$ cm. This naturally lead to the popularity of neutron stars as a site for GRBs, an idea that was bolstered by the realization that their extremely strong magnetic fields could contain the emitting plasma in the source for typical burst durations. The time-histories of GRBs, as illustrated in ref. 5, display a diversity of structure, with single or multiple peaks, subpeaks and lengthy gaps between peaks appearing in various sources. Typical burst spectra $f(\varepsilon)$ are such that the power $\varepsilon^2 f(\varepsilon)$ (e.g. see Fig. 1) peaks in the range 50 keV – 5 MeV, a rare feat for astronomical sources; even more remarkable is the fact that less than 2% of the GRB flux appears in the range[10] 2–10 keV. This paucity of X-rays renders bursts unique among classes of cosmic gamma-ray sources, and severely constrains theoretical GRB models. The observed GRB fluxes at earth imply source luminosities of $L \sim 10^{38}$ erg/sec if they are 1 kpc distant, suggesting a neutron star origin, or $L \sim 10^{50}$ erg/sec if 1 Gpc away, reminiscent of supernova events.

The early observations of gamma-ray bursts yielded spectra that were mostly quasi-thermal in nature (e.g. see the KONUS data in ref. 11), however the results[12] obtained by instruments aboard the Solar Maximum Mission (SMM) suggested that many if not most continuum spectra were non-thermal and extended well above 1 MeV, with a quasi-power-law shape. This GRB property has been largely confirmed by the CGRO detectors, with COMPTEL and EGRET seeing several bursts with high energy emission,[13,14] specifically at about 1 GeV for the case of GRB930131.[14] This is a statistically significant detection rate that suggests that many (or most) GRBs emit at these energies. The earlier quasi-thermal observations may reflect intrinsic properties of those bursts, or that they may have been influenced by threshold effects at high energies in less sensitive detectors like KONUS.

Prior to the launch of CGRO, many observations of spectral lines from bursts were reported. About 20% of sources[11] showed single absorption dips in their spectra between 20 and 60 keV, which would yield magnetic field strengths of $2 - 5 \times 10^{12}$ Gauss in their emission regions if these broad features were interpreted as cyclotron absorption lines. Further, around 5% of bursts exhibited broad emission lines[11] at around 400 keV, which were naturally interpreted as electron-positron (pair) annihilation lines redshifted from 511 keV by the gravitational field of neutron stars. Therefore, around 1988, the weight of evidence in favour of a galactic neutron star association for bursts was substantial, and the stunning observation of double narrow absorption dips in two burst spectra by the GINGA X-ray satellite[15] (interpeted as cyclotron harmonics) all but clinched the case for proponents of galactic burst sources. Since then, the CGRO instruments, in particular BATSE, have observed no lines of either type in over 800 burst detections, spawning a controversy over the existence of GRB line features. The consistency of the apparently conflicting BATSE and GINGA results concerning absorption lines is hotly debated, and presently it is uncertain whether or not the discrepancy can be explained by the different instrumental line-detection capabilities.

RECENT POPULATION STUDIES

The launch of the Compton Gamma-Ray Observatory created an even bigger upheaval to the "conventional wisdom" of the galactic neutron star hypothesis when the BATSE experiment observed that the burst population was isotropic but inhomogeneous with a comparative deficiency of fainter sources.[16] Although this result was suggested by earlier experiments that observed significant numbers of GRBs, BATSE is a more sensitive detector and has been able to observe more bursts with a broader range of source fluxes. As such it was intended to observe to the edge of a galactic disk population and therefore detect an anisotropy in the spatial distribution of bursts; the contrary result has indicated that most (or all) bursts may in fact be cosmological in origin.[17] This is currently the new conventional wisdom, and while the observed isotropy and inhomogeneity may be explained by GRBs originating in a large spherical galactic halo, the expectation that halo bursts from M31, the nearest large galaxy (Andromeda), should be detected and upset the observed isotropy is now severely constraining[18] a possible halo population. A good review of the various population hypotheses is presented in ref. 19. In summation, it is now extremely unlikely that all bursts could be confined within the galaxy, though a significant minority disk population is still quite feasible.

Much discussion over the last year has concentrated on population studies with claims and counter-claims about evidence for two or more burst populations and repeating bursts. There is fairly strong evidence for a bimodality in the distribution of GRB durations,[6] which may not necessarily be an indication of two classes of bursts. Recent work[20] on average burst temporal profiles has suggested a time dilation effect that is consistent with, but not conclusively implying, a cosmological origin of bursts; the statistics on this result need to be improved in order to make more definitive deductions. There is even a hint of spectral reddening in fainter sources.

Suggestions this last year[21] of evidence for repetition of bursts in the BATSE observations sparked a storm of controversy. It was argued that the first 260 bursts that BATSE detected had an improbably high clustering in the sky; specifically more bursts were correlated on four degree angular scales than expected, i.e. are near-neighbours in the sky. This lead to the provocative suggestion that BATSE was detecting repetitions of bursts, a naturally attractive idea to galactic GRB proponents since the enormous energies ($L \sim 10^{52}$ erg/sec) required to power GRBs at cosmological distances virtually precludes any chance of burst repetition. In fact an excess correlation on 176 degree scales[22] is also observed in the same population, which cannot indicate repetition; these two properties taken together might suggest the presence of a minority anisotropic (perhaps a galactic disk) population. Preliminary analysis[23] of the next 482 bursts indicates that these correlations may disappear with better statistics, though complete correction for instrumental systematic effects has yet to be included. Therefore, presently the evidence for repeaters is unconvincing.

SPECTRAL CONSIDERATIONS

Information about individual bursts is still best deduced from their spectra, which can provide much insight concerning the physical processes occurring in GRB emission regions. The natural example is the interpetation of low energy (20-60 keV) absorption features seen in spectra obtained by the KONUS[11] and GINGA,[15] referred to earlier, as being due to absorption of radiation at the cyclotron energy in the strong magnetic fields of neutron star magnetospheres. Since the BATSE instrument on CGRO has made no definitive observation of any spectral line features the GRB continuum must now provide the clues for theorists. Many such continuum spectra $f(\varepsilon)$ have a general appearance similar[24] to Fig. 1 [which depicts $\varepsilon^2 f(\varepsilon)$], with a very flat spectrum at the lower energies (i.e. below 50 keV) "turning over" or "breaking" to a steep spectrum above 1 MeV. The energy ε_B of the turnover varies from burst to burst[25], and a significant fraction of bright bursts[26] detected by BATSE have $\varepsilon_B > 100$ keV. The break energy ε_B and the spectral index $\alpha = -d[f(\varepsilon)]/d[\log_e \varepsilon]$ at energies above and below ε_B provide important constraints on theoretical models.

The most sophisticated model that generates turnovers in γ-ray continuum spectra is the $B = 0$ pair cascade model[27] that has been comprehensively developed for applications to active galactic nuclei (AGNs). This model used isotropic ultrarelativistic electrons, generated by some unspecified particle energization mechanism such as shock acceleration,[28] to produce a gamma-ray continuum by the inverse Compton scattering of UV photons, and then the two-photon pair production process $\gamma\gamma \to e^+e^-$ to absorb the γ-rays and initiate a cascade of several or many generations of pair production. The attenuation of the GRB continuum by $\gamma\gamma \to e^+e^-$ is an obvious candidate for a means to create the observed "MeV" turnovers. When this model is adapted[29] to try to fit the flatter hard X-ray continuum of GRBs, multiple inverse Compton scattering of the seed low energy photons occurs, spawning a peak at around 1 MeV where the Klein-Nishina decline of the Compton cross-section effectively shuts off the cascade. Refinements of the model[30] revealed that Coulomb scattering by the relativistic electrons heats the ambient cool thermal electron gas to relativistic temperatures, so that a broad quasi-thermal bump due to pair annihilation and thermal bremsstrahlung appeared around 1 MeV, contrary to observations. It now seems unlikely[31] that such field-free pair cascades can create the MeV breaks observed in bursts. Therefore it appears that the BATSE sources with breaks observed in the MeV energy range[26] require a mechanism other than $\gamma\gamma \to e^+e^-$ to generate their turnovers.[31]

For neutron star models of GRBs, MeV breaks can be generated using synchrotron pair cascades, where magnetic pair production $\gamma \to e^+e^-$ acts to attenuate the continuum,[32,33] since in the strong fields of neutron stars ($B \gtrsim 10^{12}$ Gauss) this process dominates $\gamma\gamma \to e^+e^-$ as a means of absorbing gamma-rays. In these cascades, ultrarelativistic electrons are injected into the emission region with significant pitch angles θ so that a synchrotron continuum is radiated, with the radiation being beamed close to the direction of the electrons' momenta. The dramatic increase[2,32,34] in the pair production optical depth above the effective threshold of $\varepsilon = 2m_ec^2/\sin\theta$ efficiently truncates the continuum above this energy,[32] subsequently generating a pair cascade. Since this truncation energy is a function of pitch angle, spectra integrated over θ can generate broken power-laws given suitable angular distributions of electrons.[35] The spectral breaks in this scenario can be substantial or non-existent, an attractive versatility of this model, depending on how beamed the electrons are along the field lines. The drawback of the synchrotron cascades is that their spectrum below the break is never flatter than $\alpha = 3/2$, so that they cannot model many flat spectrum sources like GRB 910503 (see Fig. 1).

Another mechanism for generating MeV breaks in magnetized environments is resonant inverse Compton scattering. When $B \neq 0$, the Compton cross-section has a resonance at the cyclotron energy $\varepsilon_c \propto B$ in the electron rest frame, which dominates the scattering process and dramatically alters the shape of the spectrum. For ultrarelativistic electrons with a power-law distribution γ^{-p} of Lorentz factors γ, colliding with seed soft photons (presumably X-rays from the surface of a neutron star) of energy ε_s, this process yields broken power-law spectra, flat at low energies (i.e. $\alpha < 1$) with a break[36] at $\varepsilon_B = \varepsilon_c^2/\varepsilon_s$. Resonant scattering has no problem dealing with those GRB spectra that are flat below 100 keV, and can easily predict breaks at MeV energies. The introduction of e^- cooling to this model[37,38] steepens the spectrum somewhat and smooths the break; the observed spectra are strongly dependent on the angle of photon emission with respect to the field lines. The resonant scattering model has difficulty describing sources with small breaks such as GRB930131; possibly[31] a synchrotron self-Compton hybrid cascade model might succeed in eliminating the deficiencies of the two neutron star models discussed here. The few cosmological models for GRB spectra that exist, including the fireball scenarios discussed below and AGN-like models,[39] are considerably less sophisticated than the neutron star variety and need much more development for serious comparison with burst continuum observations.

RELATIVISTIC MOTION IN BURSTS

The indication earlier that $\gamma\gamma \to e^+e^-$ is not responsible for MeV turnovers in gamma-ray bursts implies that it is probably not operating to attenuate the gamma-ray continuum within the range of observed burst energies. An important consequence of this is that relativistic bulk motion may be common in burst sources. Two-photon pair production was first considered as a potential mechanism for attenuating GRB spectra by Schmidt,[40] who proposed that it could be used to provide upper limits to the distance to burst sources that revealed no spectral breaks above 1 MeV. Schmidt's application focussed on the case of isotropic photons, and concluded that the bursts seen before then (at energies less than a few MeV) must be galactic, since they had no breaks, in direct conflict with the recent BATSE results' implications for burst populations. If the majority of bursts are at cosmological distances (~ 1 Gpc), then the enormous luminosities expected ($L \sim 10^{50}$ erg/sec), combined with the compact source size implied by the observed rapid time variability, give photon densities high enough to make GRBs optically thick to $\gamma\gamma \rightarrow e^+e^-$ by many orders of magnitude; i.e. the free escape of gamma-rays from burst sources would be impossible. Such a situation is incompatible with the observed spectra of GRBs detected by EGRET, which show no attenuation at energies in some cases as high as 1 GeV (see refs. 13, 14).

One way around this problem is to assume beaming of the radiation, which raises the pair production turnover to energies above those observed. Relativistic motion of the source is a natural way to achieve beaming of the emission and avoid attenuation in GRBs. The radiation from a source that is emitting isotropically in a reference frame that moves relativistically with respect to an observer on earth will be beamed roughly within an angle $1/\Gamma$ in the observer's frame,[31,41] where Γ is the bulk Lorentz factor. Such *relativistic beaming* of radiation naturally suppresses the pair production rate, since the $\gamma\gamma \rightarrow e^+e^-$ mechanism has a threshold energy $2(m_ec^2)^2/[\varepsilon(1-\cos\Theta)]$ for photons of energy ε; this is strongly dependent[31,41] on the angle Θ between the photon directions. This implies that relativistic beaming of radiation in bursts with declining spectra ($\alpha = -d[f(\varepsilon)]/d[\log_e \varepsilon] > 0$: true for all EGRET sources) will "blueshift" the $\gamma\gamma \rightarrow e^+e^-$ turnover up in energy by a factor of Γ (since then $\Theta \sim 1/\Gamma$); that this moves above the EGRET energy range therefore provides a determination of a lower bound to Γ.

When the source opening angle is of order $1/\Gamma$, the pair production optical depth $\tau_{\gamma\gamma}$ is reduced by a factor $\Gamma^{-(1+2\alpha)}$ below the optical depth for isotropic radiation.[31,41] The condition that no spectral attenuation occurs is that $\tau_{\gamma\gamma} < 1$ up to the highest energies observed (the optical depth is effectively the probability that $\gamma\gamma \rightarrow e^+e^-$ occurs in the source). The bulk Lorentz factors Γ consequently required for the bright "superbowl" burst GRB930131, detected by EGRET[14] up to an energy of 1 GeV, are $\Gamma \gtrsim 10^3$ if it is 1 Gpc distant and $\Gamma \gtrsim 10$ at 30 kpc (ref. 42). Similar estimates of bulk relativistic motion are obtained for the other EGRET sources,[43] indicating that this phenomenon is common in bursts. An advantage of relativistic beaming is that a smaller source luminosity is required because the observed flux is enhanced by a solid angle factor Γ^2 (ref. 41). However, then the number of sources must really be a factor Γ^2 higher than detected in order to account for the observed rate of gamma-ray bursts. In the case of cosmological GRBs, this factor could be as high as 10^6 for the typical Lorentz factors $\Gamma \sim 10^3$, which is unacceptably large for many models. Source geometry therefore has significant impact on the viability of models. Expanding the opening angle to become much larger than $1/\Gamma$ could ease this problem[44] if the high energy photons were able to escape; in fact estimates of the minimum Γ for completely spherical expanding sources are qualitatively similar to the highly beamed case.[44]

FIREBALL MODELS

While relativistic motion in GRBs that have $\tau_{\gamma\gamma} < 1$ may be common, it is also probable in bursts of high optical depth to $\gamma\gamma \to e^+e^-$. Such situations lead to many generations of pair production and naturally arise out of several cosmological models for bursts. Among these is the so-called merger scenario, where two neutron stars or a neutron star and a solar mass black hole coalesce[45–47] due to the loss of their orbital energy via the radiation of gravitational waves. Such mergers, which are envisaged as forming a cosmological population of GRBs, may occur at the rate of about one per galaxy per million years since there are four binary neutron star systems observed in our own galaxy,[48] and can release a large fraction of a solar mass of energy (about 10^{54} ergs) in an extremely small volume, typically about $R \sim 10^8$ cm in radius. The energy density is therefore enormous, as is $\gamma\gamma \to e^+e^-$, and thermal equilibrium is established rapidly, generating a pair plasma at relativistic temperatures[45] $[\, kT/(m_e c^2) \sim (k/m_e c^2)[M_{\odot} c^3/(4\sigma R^3)]^{1/4} \sim 20\,]$. This energy naturally must dissipate adiabatically,[45,49] and the resulting expansion of pairs is called[50] a *fireball*. The early stages of such a dynamic fireball may involve rapid neutrino production (and $\nu\bar{\nu}$ annihilation to produce pairs with 0.1% efficiency) so that enormous numbers of neutrinos are emitted[46] $(E/c^2 \sim M_{\odot} \Rightarrow 10^{60}\nu)$; unfortunately this leads to about 10^3 neutrinos per square cm on earth, a signal that is many orders of magnitude too small for detection.

Other models where fireballs arise include failed type 1b supernovae,[51] in which a star with a massive iron core fails to expel its outer layers as a supernova, allowing the would-be ejecta to form a transient accretion disk and then collapse onto the condensed core (a newly-formed neutron star) and explosively depositing energy to form a fireball. Copious production of neutrinos would be expected in this model. It has also been suggested[52] that rapidly spinning neutron stars in distant galaxies could form with extremely high magnetic fields, 10^{15} Gauss, much stronger than conventional pulsar fields. These so-called *magnetars* would result from the collapse of accreting white dwarfs with unusually high magnetic fields (about 10^9 Gauss), and would rapidly lose angular momentum through gravitational and magnetic-dipole radiation. A predominantly electromagnetic fireball would then be initiated, comprised mostly of electron-positron pairs and photons. Both models are envisaged as defining cosmological burst populations.

Non-relativistic temperatures (typically around 20 keV) are usually achieved[45,49] in the adiabatic cooling of fireballs, which naturally imply that the bulk velocities attained by the expansions when they become optically thin to $\gamma\gamma \to e^+e^-$ are ultrarelativistic (typically $\Gamma \sim 10^3$); this is required in order to satisfy energy conservation. These properties are confirmed by hydrodynamic analyses of fireball evolution.[53] Rudimentary calculations[49] of the output spectrum of this fireball is a cool (narrow) Planck continuum blueshifted to MeV energies and distorted by bulk motion of the plasma. This is unlike the observed non-thermal spectra of bursts, leading immediately to a problem with pure fireball models. More detailed computations[54] of radiative transfer effects in late stages of fireball evolution indicate that high energy power-law tails may be possible, though refinement of these calculations is needed.

The fireball phenomenon is not as simple as an adiabatically expanding plasma of pairs and photons; realistic models must include some form of baryonic pollution swept up from the environment of the progenitor. This contamination depends strongly on the geometry in the progenitor. It was realized[55] that the presence of baryonic matter in the fireball must rob it of its radiative efficiency since the baryons can dominate the kinetic energy of the expansion. Effectively the initial energy of the fireball is deposited as kinetic energy of the baryons rather than emitted as radiation. Simple computations[55] reveal that the final bulk Lorentz factor Γ attained by the fireball is less than the ratio of pair to baryon energy in its initial stages, and that the fraction of the available energy that appears as radiation is generally much less than unity, posing a severe problem for fireball models. A natural way of avoiding these problems is to allow the fireball to impact on the surrounding interstellar medium,[56] generate one or several shocks (much like the propagation of supernova ejecta), and accelerate particles in the shock environs i.e. convert the kinetic energy of the expansion to non-thermal energy. The resulting ultrarelativistic particles radiate efficiently via synchrotron radiation or inverse Compton scattering[57] guaranteeing that a large fraction of the initial fireball energy is extracted in the form of radiation. The clumpiness of the interstellar medium provides the GRB time variability as the fireball sweeps up matter on a timescale of order seconds.[56] The resulting spectra[57] can have spectral breaks in the GRB energy range, however there is no preferred energy for the breaks, so a broad range of ϵ_B would be anticipated in this scenario. In addition, it is presently unclear that the model can fit the variety of spectral slopes α present in GRB data.

CONCLUSION

This more or less summarizes one theorist's view of the gamma-ray burst dilemma and some recent observations and interesting theoretical work. Clearly the dilemma continues, and gamma-ray bursts remain as enigmatic as ever. It appears unlikely that any stunning new observations may appear on the scene from CGRO, which will largely be devoted to refinement of existing results by increasing the database. However, positive results from searches[58] for gravitationally-lensed GRBs (by distant galaxies) would provide the smoking gun for cosmological pundits, and any observation of 20–60 keV absorption features by BATSE would excite proponents of the galactic neutron star hypothesis. Neither discovery would conclusively prove that *all* bursts belonged to either population. In fact, searches for photoelectric absorption effects[59] in the very low energy X-ray spectra of bursts would have the potential to flip the cosmological/galactic coin either way. For theorists, who depend on the observations, the GRB question will almost certainly be resolved by the observations; however development of various cosmological (and galactic) models, particularly in regard to spectral issues, will aid in reducing the plethora of viable models.

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