EMISSION MODEL OF GAMMA-RAY BURSTS[#]

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ABSTRACT

This talk reviews the emission mechanisms of cosmic gamma-ray bursts. In particular, the thermal synchrotron model is discussed in detail as the most viable mechanism for the majority of the continuum emission. Within this framework various information about the source region can be extracted. The picture that emerges is that of a hot ($kT = .2 - 1.0\ mc^2$), thin sheet of dense pair-dominated plasma emitting via cyclo-synchrotron radiation in a strong magnetic field ($B \sim 10^{11}$ to 10^{12} gauss). Speculations on the origin and structure of this sheet are attempted. We also briefly discuss the problem of high-energy photons above pair production threshold escaping from the source.

INTRODUCTION

Despite numerous attempts by astrophysicists over the past decade, the origin and mechanisms of cosmic gamma-ray bursts remain a total mystery. Yet a number of significant observational developments over the last few years have greatly narrowed the field of viable speculations even by the most creative theorists. (See, e.g., Ruderman[1] and Katz[2] for reviews.) The discovery of the March 5, 1979, event (Cline[3]) and the optical predecessor of the November 19, 1978, event (Shafer[4]), plus the slightly more controversial discoveries by the Konus experiments (Mazets *et al.*[5]) of the presence of redshifted annihilation lines and low-energy spectral features, all help to reduce the number of viable candidates for the sites of these events. Currently, the most popular choice is the surface of strongly magnetized neutron stars. Theoretically, a strong magnetic field (> 10^{10} gauss) is also needed to confine such a hot plasma, especially if it is pair dominated. In this talk I shall try to review in some depth recent attempts along these lines to understand the emission mechanism for the continuum spectrum of most gamma-ray bursts.

THE THERMAL SYNCHROTRON MODEL

Ever since the early days of their discovery, it was recognized that most of the gamma-burst spectra assume a universal exponential

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shape with a characteristic $kT \sim mc^2$. Thus it was suggested that they were optically thin thermal bremsstrahlung (TB) emission by mildly relativistic thermal plasmas. Unfortunately, this interpretation immediately encountered difficulty because of the inefficiency of TB emission. Combined with the lack of detectable Comptonization ($\tau_{ec} < 1$), TB emission required unrealistically high aspect ratios for the emission geometry and nearby clustering of the source (e.g., Katz[6]). If we also believe in strong magnetic fields, then the cyclo-synchrotron emission of these hot plasmas would also greatly exceed the TB emission for all reasonable situations. Moreover, if the March 5, 1979, event is indeed at the distant of N49 (~ 55 kpc), then only the synchrotron emissivity of a hot plasma in a strong field has the remote chance of accounting for the high luminosity (Ramaty _et_ _al._[7], Liang[8]). This, therefore, motivated several authors to suggest that cyclo-synchrotron emission is the natural emission mechanism of most gamma-ray bursts (Lamb[9], Katz[6], and Liang[10]). Recently, using the semi-analytic results of Petrosian[11], Trubnikov[12] and the numerical results of Lamb and Masters[13], we have succeeded in fitting most gamma-burst spectra reported to date satisfactorily with the thermal synchrotron spectrum (TS) of mildly relativistic (.2 - 1.0 mc^2) plasmas in strong fields ($B \gtrsim 10^{12}$ gauss) (Liang[10], Liang _et_ _al._[14]). This is encouraging because it at least makes the strong field neutron star picture a self-consistent framework. In addition, various additional spectral features, when interpreted in this framework, provide us with valuable information about the source conditions.

Figure 1 illustrates the shape of the thermal cyclotron spectrum as the temperature is progressively increased. By the time the temperature gets up to hundreds of keV, all higher harmonics blend into a smooth continuum with only the first couple of harmonics barely visible. Their peaks time-dilated to energies below the Lamor frequency (ω_L = 11.6 keV $(B/10^{12}$ gauss$)$).

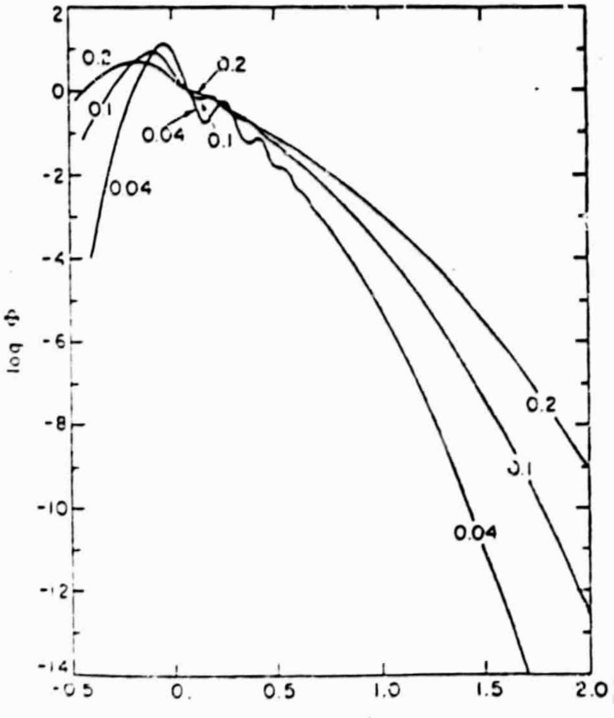


Fig. 1. Evolution of thermal cyclo-synchrotron spectra with increasing temperature (from Ref. 9). ($\Phi \propto j_\omega/\omega^2$; T is in units of $m_e c^2$.)

Above the third or fourth harmonic, the continuum emissivity is well approximated by the analytic formula (cf. Ref. 14):

$$j_\nu(\theta) = \frac{\pi e^2}{\sqrt{2}\cdot 3\ c} n_e\ \nu K_2^{-1}\ (1/T)\ \exp\left(-(4.5\nu/\nu_c \sin\theta)^{1/3}\right)\quad \nu_c \equiv \nu_L T^2\ , \quad (1)$$

where $T \equiv kT/m_e c^2$ and K_2 is a modified Bessel function.

Figure 2 shows how well this shape fits the typical gamma-ray burst spectra.

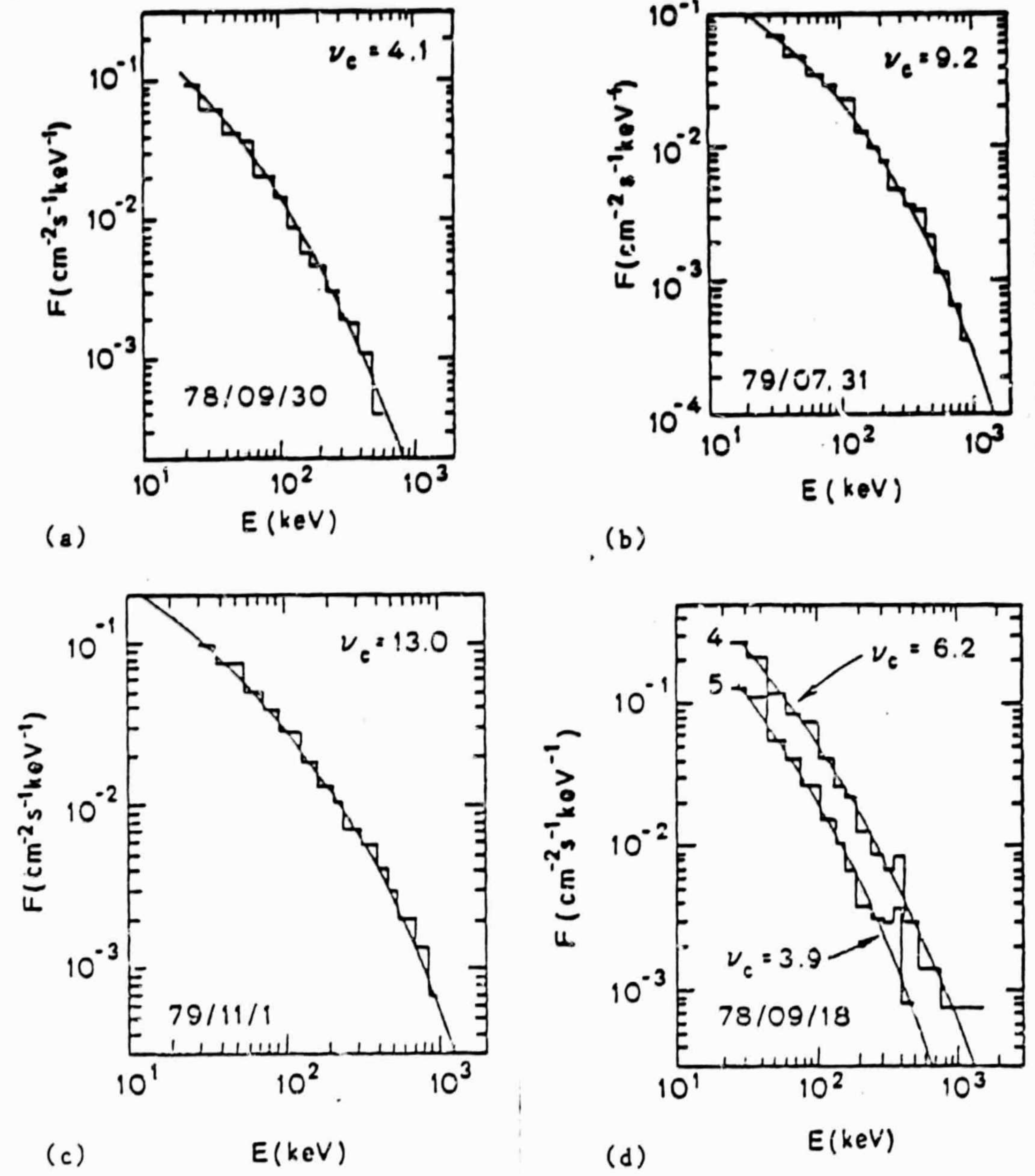


Fig. 2. TS fits to some typical gamma-bursts spectra. Value of ν_c is in keV (from Ref. 14).

When the emission column density is too large, the low-energy part of the spectrum becomes self-absorbed and turns over into a Rayleigh Jeans spectrum. The location of the turnover, $_m$, determines (cf. Bekefi[15]) the emission column density and therefore the optically thin flux. These are given by the formulas:

$$n_e h = 3.8 \times 10^{19}\ \nu_m T\ K_2(T^{-1}) e^{x_m}\ \mathrm{cm}^{-2}\quad x_m \cong (4.5\ \nu_m/\nu_c)^{1/3} \tag{2}$$

$$F_{syn} = 3.6 \times 10^{26}\ T\ \nu_{m\ keV}\ \nu_{c\ keV}^{\ 2} \sum_{i=0}^{5} x_m^i/i!\ \mathrm{erg} \cdot \mathrm{cm}^{-2} \cdot \mathrm{sec.} \tag{3}$$

DATA FROM THE KONUS CATALOGUE

Recently Liang *et al.*[14] have completed a detailed analysis of the entire Konus Catalogue (Mazets *et al.*[16]), which represents the largest collection of recorded gamma-burst spectra, using the TS model. Some of the key results are summarized here.

(a) The characteristic frequency ν_c has a distribution peaking near 3 keV and cutting off sharply above 12 keV. For a nominal field of 2×10^{12} gauss, this means a temperature distribution of around .4 mc^2 (Fig. 3).

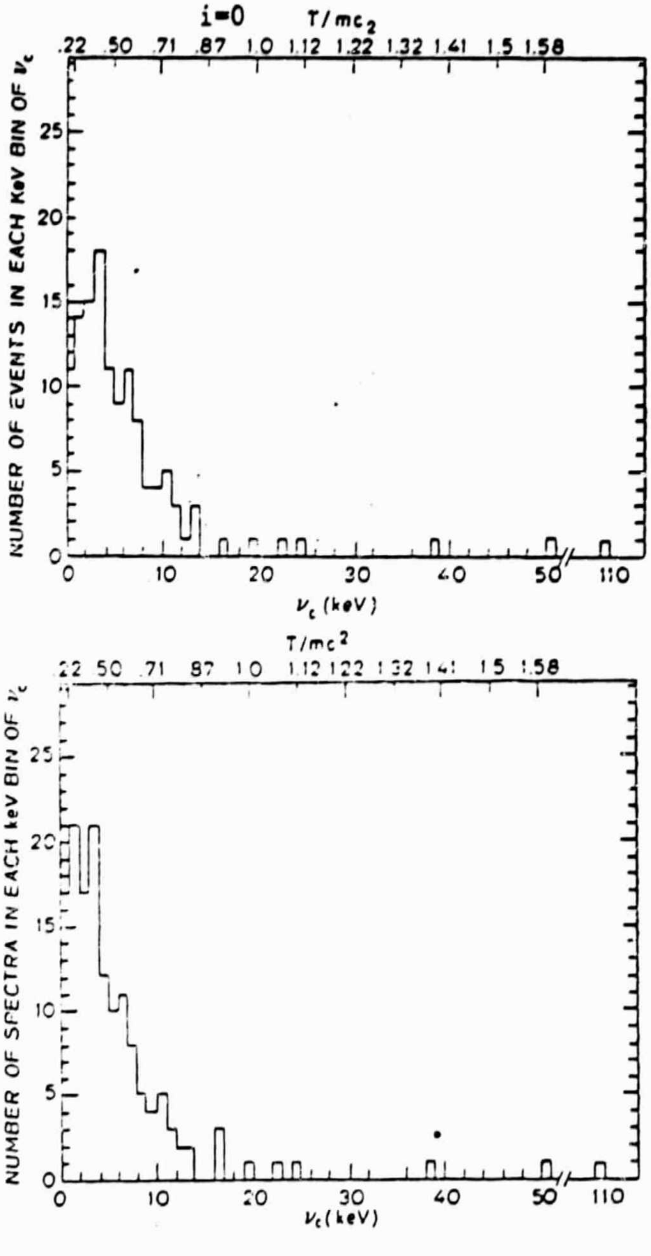


Fig. 3. Distribution of ν_c for the spectra of the Konus catalogue (from Ref. 14).

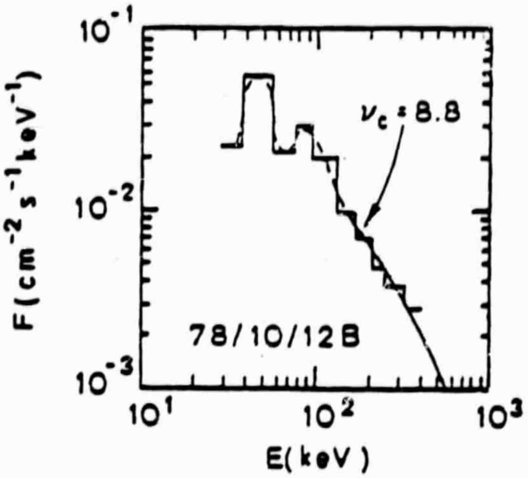


Fig. 4. Example of Konus spectrum showing possible first and second harmonic emissions (from Ref. 14).

(b) Over half a dozen events show double peak features at low energies (< 70 keV) with the second peak sitting at twice the frequency of the first, suggestive of fundamental harmonics (Fig. 4). Using the temperature deduced from the fit to the continuum, we can try to estimate the ratio of the first to the second harmonic peak flux. Figure 5 compares the theory prediction and the observed flux ratio. The result is clearly very encouraging. Future observations should concentrate on the search of the harmonics, in the X-ray energies, if possible.

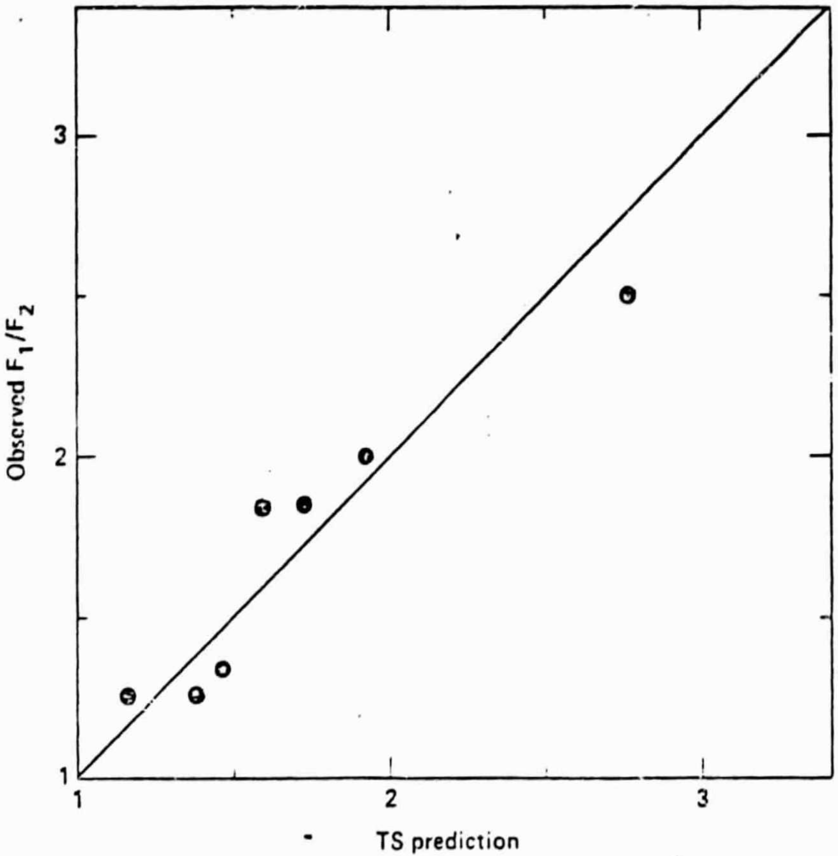
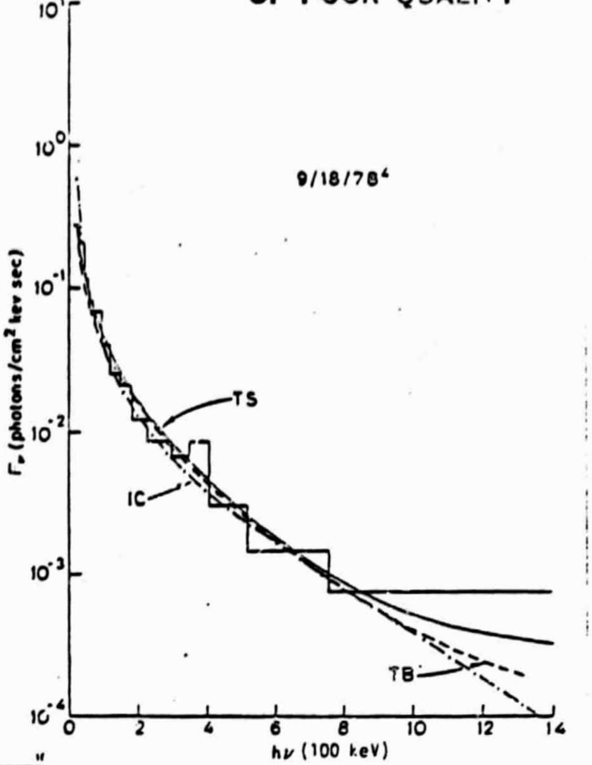
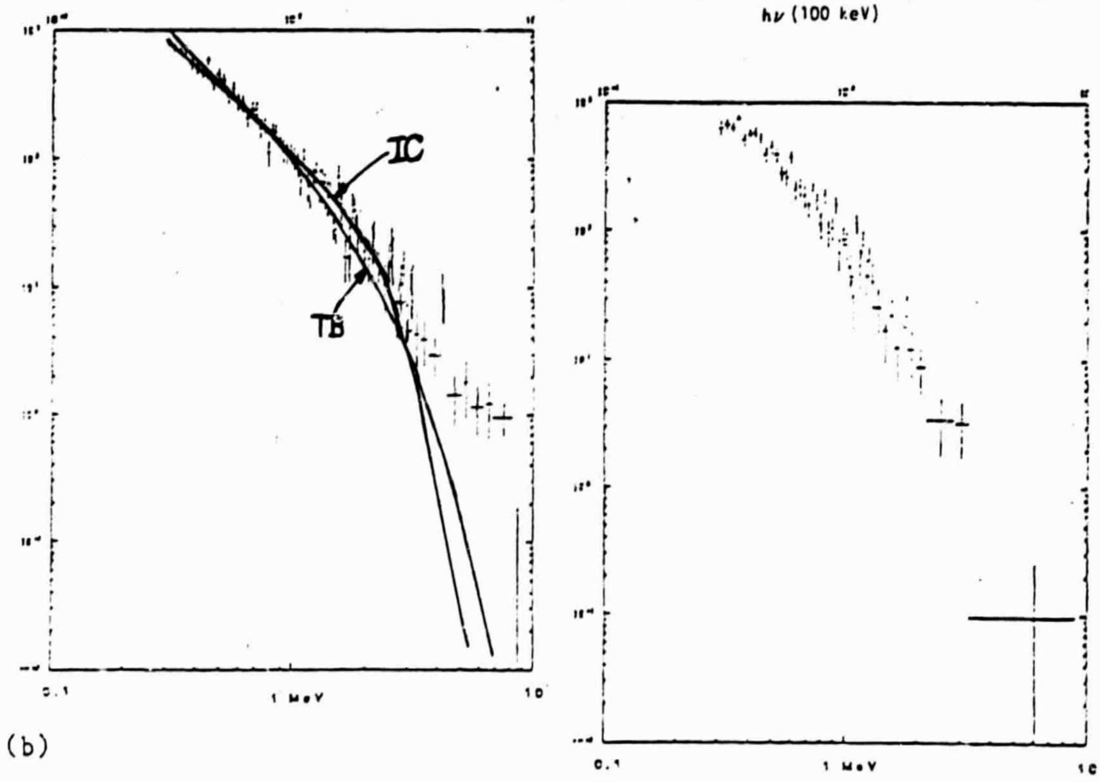


Fig. 5. Comparison between theoretical predictions and the observed ratios of first to second harmonic peak fluxes for several Konus spectra.

(c) Most of the Konus data, which cover only the range up to several hundred keV to 1 MeV, really cannot distinguish between TS, TB, or inverse Compton (IC) spectral fits (proposed by Fenimore *et al.*[17]). (See Fig. 6a.) However, preliminary data from the SMM (Nolan *et al.*[18], Fig. 6b) up to 10 MeV seem to suggest that single temperature TB or IC fits would fall short at high energies due to the exponential cutoff, whereas the TS spectrum has no problem because of its hardness (cf. Eqn. (1).



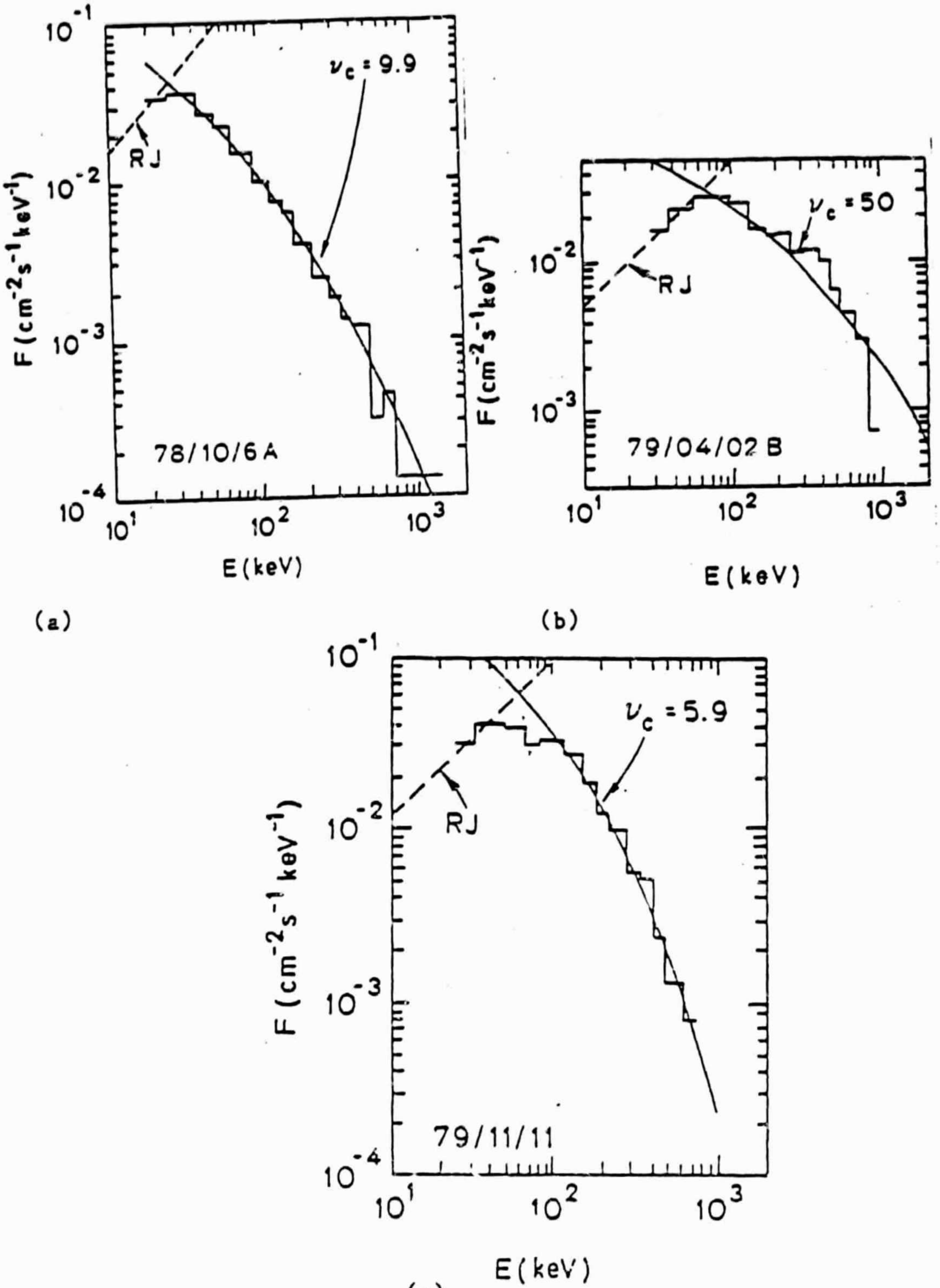
(a)



(b)

Fig. 6. (a) TS, TB and IC fits to the observed spectrum of GB780918 how little distinction (from Ref. 14). (b) SMM gamma-burst spectra (raw data) out to 10 MeV show that TB and IC fits fall short at higher energies (from Ref. 18; the high-energy data are expected to move up after detector corrections).

(d) A small fraction of Konus spectra show low energy turnover, suggestive of self-absorption (Fig. 7).



(a)

(b)

(c)

Fig. 7. Examples of Konus spectra showing self-absorption (from Ref. 14).

Table I summarizes data on these events. Note that unless the emission area is much smaller than a km^2, several events could be extragalactic, maybe even as far as the March 5 event. Note also the uniform thinness of the emission depth ($n_e h \sim 10^{20} - 10^{21}$ cm^{-2}).

Table I Spectra with self-absorption (data from Ref. 14)

				Assuming $^{o}_{L} \le \nu_{ab}$			
Spectrum	ν_{ab} (keV)	ν_c (keV)	$n_e h/TK_2(T^{-1})$ $(10^{22}/cm^2)$	$T \ge$	$\tau_{es}(10^{-4}) \ge$ Thompson scattering depth	$\frac{L_{syn}}{A(km^2)} \ge$	$\frac{d(kpc)}{A^{1/2}(km)} \ge$
10-06-78A	30	9.9	1.3	.39	1.8	1.6×10^{40}	18
11-04-78A	25	2.1	4.2	.22	.27	1.1×10^{39}	6
11-07-78	42	6.0	3.8	.29	1.4	1.2×10^{40}	22
11-11-78	28	1.9	6.1	.20	.2	1.1×10^{39}	65
11-19-78[1]	40	110	0.5	.87	.16	1.7×10^{42}	23
11-19-78[3]	40	6.0	3.4	.29	1.2	1.1×10^{40}	6
11-21-78A	26	4.8	1.8	.31	1.0	3.9×10^{39}	11
2-14-79	30	4.1	2.8	.28	0.8	3.9×10^{39}	7.7
4-02-79B[1]	60	50	1.4	.56	7.7	6×10^{41}	29
4-06-79	45	38	1.0	.56	5.5	2.7×10^{41}	30
6-13-79	50	1.9	25.7	.17	.26	3.3×10^{41}	43
10-14-79[1]	40	5.9	3.5	.28	.9	1.0×10^{40}	9
11-11-79[1]	50	5.9	5.5	.24	.5	1.3×10^{40}	18

(e) Many of the Konus spectra have candidate annihilation lines at 400 - 450 keV. Some of these appear in conjunction with low-energy self-absorption, in which case the pair density at the source can be estimated if we assume that the annihilation line source coincides with the TS source and that the annilation region is approximately one annihilation depth thick. Table II summarizes the data on these spectra. Note that n_+ lies in the range 10^{23} to 10^{26}. Combined with the nh limits, we are forced to consider very thin emission layers with $h \sim 10^{-3}$ to 10^{-4} cm.

Table II Data on Konus spectra exhibiting redshifted pair annihilation lines

Event (GB)	511 flux (ph/cm$^2\cdot$s)	ν_c (keV)	$\frac{d(kpc)}{A^{1/2}(km)}$*	n_+ (cm^{-3}) (assume $n_-\sigma_T h_{annih} \sim 1$)	$\frac{F^{511}}{F_{>threshold}}$
78-09-18[4]	.18	6.2			.14
78-09-18[5]	.08	3.9			.26
78-10-06A sa	.01	10.0	$\geq$ 30	$\geq 6.0 \times 10^{23}$	.04
78-11-19[1] sa	5.0	110.	$\geq$ 38	$\geq 3.0 \times 10^{26}$	.12
78-11-19[3] sa	.15	6.	$\geq$ 38	$\geq 9.2 \times 10^{24}$	.35
79-01-16	.05	5.			.15
79-03-05**	1.7	0.5	$\sim$ 1	$\geq 5.0 \times 10^{26}$	.42
79-04-02[1] sa	.3	50.	$\sim$ 50$^+$	$\cong 4.8 \times 10^{25}$	.08
79-04-02[3]	.15	13.			.21
79-04-12	.12	19.			.08
79-06-22	.10	13.			.13
79-10-14 sa	.23	6.	$\geq$ 15	$\geq 3.6 \times 10^{24}$	.30
79-11-11[1] sa	.07	6.	$\sim$ 30$^+$	$\cong 4.2 \times 10^{24}$	.09
79-12-30	.06	5.8			.35
		↑		↑	
		harder than average		lie in range 10^{23}-10^{26} => $h_{syn} \lesssim 10^{-3}$-10^{-4}cm	

*for self-abs. cases
**assumed at 55 kpc
$^+$estimated from presence of harmonics at later times

To summarize, the TS interpretation of gamma-burst spectra requires the emission region to be hot ($kT \cong .2 - 1.0\ mc^2$), optically very thin ($nh \lesssim 10^{20} - 10^{22}$ cm^{-2}) with typical synchrotron flux $10^{29} - 10^{32}$ erg/sec. cm^2. Events showing pair-annihilation lines suggest that the emitting plasma may be dominated by pairs ($n_+ \sim 10^{23} - 10^{26}$ cm^{-3}). Hence the big questions are: What is the origin of such an unusual emission layer, and how is it maintained?

STRUCTURE OF THE THIN EMISSION SHEET

Figure 8 illustrates conceptually one possible configuration of the emission layer. The surface of the neutron star, threaded by 10^{12} gauss field lines, is heated by energy fluxes streaming down along the field lines. To avoid shielding the outgoing gamma rays, the downward energy flux cannot be in the form of particles (ions, electrons or pairs). More likely it is in the form of electromagnetic or Alfvén waves. These waves dissipate within a skin depth of the surface, generating suprathermal electrons and creating pairs. These then pitch-angle scatter and thermalize within a column density corresponding to a pitch-angle scattering depth. This is also the region where the hot thermal synchrotron radiation is emitted. The cooled pairs then annihilate over a thicker layer, corresponding to about one annihilation depth for positrons. The emission region is confined sideways by the magnetic field. Vertically it is held down by the momentum flux (or "RAM pressure") of the same waves that are heating it. It is also known that the standard coulomb scattering between protons and pairs cannot maintain a thermal distribution due to the much faster synchrotron decay rate (Langer[19], Bussard[20], Bussard and Lamb[21]). It seems likely that either collective processes, which operate at close to one tenth of the electron plasma frequency, or coulomb scattering with heavy ions (e.g., Z = 26) must dominate to maintain a thermal population of higher Landau levels. In fact, one can conceive of a self-adjusting mechanism in which the pair density is maintained at a level in which the decay rate matches the pitch-angle scattering rate. When the pair density is too low, synchrotron cooling is inefficient because it is governed by the pitch-angle scattering rate, and the heated

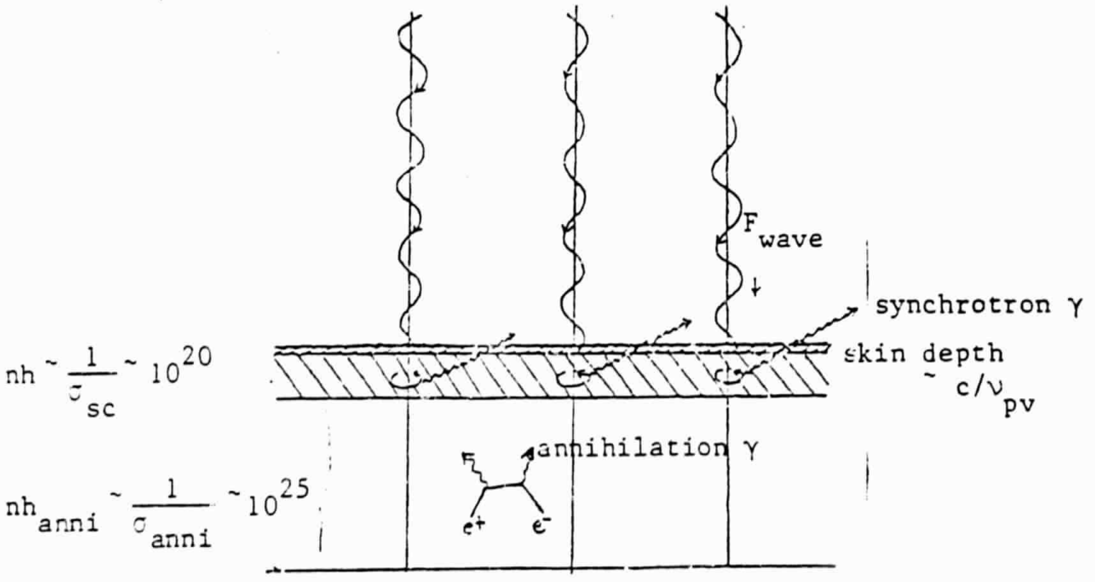


Fig. 8. Schematic diagram illustrating a possible configuration of the emitting layer of the gamma rays.

region can cool only by creating more pairs. On the other hand, when there are too many pairs, thermal and radiation pressure would exceed the wave pressure, and the layer would expand and decrease the density. While this scenario requires more detailed investigation, one can at least derive the steady-state structure from simple first-principles arguments. It turns out that the three structure variables -- n (assumed equal to $2n_+ = 2n_-$), h and T -- are uniquely determined by three steady-state requirements (for details see Liang and Antiochos[25]):

(a) energy balance:

$$F_{wave} \sim nh\,\dot{\varepsilon}_{syn} \quad \text{, where } \dot{\varepsilon}_{syn} \text{ is syn cooling rate}$$

(b) momentum balance:

$$\frac{F_{wave}}{c} = \text{pressure}_{wave} \sim n\, mc^2 T$$

(c) thermalization requirement:

$$\lambda_{pitch\ scatt} << \lambda_{syn\ cool} \Rightarrow h \sim (\lambda_{pitch\ scatt}\,\lambda_{syn\ cool})^{1/2}$$

For example, assuming that pitch-angle scattering is dominated by plasma collective modes, we find:

$$T \sim 0.4\,(F_{wave}/10^{30})^{.2}(B/10^{12})^{-.8};\ nh \sim 2.5 \times 10^{21} \left(\frac{Fwave}{10^{30}}\right)^{.6}\left(\frac{B}{10^{12}}\right)^{.4}$$

etc.,

which falls in the general ballpark of the observed parameters. These results also lead to additional predictions about correlations between the above variables and the field strength. This could be tested with future observations.

MAGNETIC FLARE MODELS

Where do the energies come from that heat the above conjectured layer? The most natural candidate seems to be reconnection of closed magnetic loops. The above sheets would then be sitting at the footpoints of the reconnecting flux tubes. Because of the high field strength, most of the reconnection energy release would likely be in the form of field perturbations rather than particles. At a flux of $\sim 10^{30}$ erg/cm$^2 \cdot$ s, a perturbation of a few percent of a 10^{12} gauss field would be adequate to account for the majority of the bursts.

What could be causing the flux tubes to develop non-potential stress fields? There are at least three conventional sources of primary energy: transient accretion (e.g., Colgate and Petschek[22]) including impact by comets or satellites; surface thermal nuclear explosion (Woosley[23]); and internal disturbances, including vibration (Ramaty *et al.*[7]) and differential rotations. At present we have no idea how any one of these energy sources couples to the field.

However, both the accretion and explosion pictures involve primary energy sources which are highly optically thick and therefore must be accompanied by cooler X-ray burst precursors. The hypothesis of internal energy sources does have the advantage of being capable of bypassing any optically thick phase by coupling mechanical energy of the star directly to the field in a low-density environment. For example, twisting of the footpoints due to relative motion or restructuring of the crust could produce stressed fields. In fact, it is highly likely that gamma-ray burst sources may involve a totally different class of neutron stars from radio or X-ray pulsars, which are believed to have rigid dipolar fields.

It should be mentioned that at least the majority of gamma-ray bursts, excluding the subclass which Mazets *et al.*[24] called the short bursts, have time structures analogous to solar flares, with a typical duration of tens of seconds broken into many spikes of subsecond duration and rise times of milliseconds or less. In the magnetic reconnection model of solar flares, most authors tend to associate the overall duration with the linear growth time of the resistive tearing mode given by the geometric mean of the Alfvén time and magnetic diffusion time, while the spikes are associated with the nonlinear Petschek type growth time equal to 10-100 Alfvén time scales. It is interesting that at least in the case of gamma-ray bursts, these two time scales also fall into the general range of the observed time scales (see Liang and Antiochos[25]).

ESCAPE OF THE HIGH-ENERGY GAMMAS

The latest SMM data (cf. Fig. 6b) shows that up to 10 MeV the gamma rays seem to emerge unattenuated by pair production self-absorption. Some authors try to argue that this puts a strong constraint on the source distance. However, as Katz[6] has pointed out, this is not necessarily the case since reannihilation may compensate for the removed photons. However, no detailed transport calculation has been attempted, and it is not clear how the original single-temperature, optically thin spectrum will be altered. In the case of TS emission, we might be saved by the fact that the highest energy gammas are all emitted close to 90 degrees from the field orientations, and therefore the relative angle with which gamma-gamma collision can occur, at least for the gamma along the line of sight, would be smaller than for isotropic sources.

A more severe difficulty is presented by the apparently unavoidable gamma-B collisions. Since gamma-B pair production cross-section depends exponentially on the parameter $h\nu/m_e c^2 (B/4.4 \times 10^{13}$ G) (see Erber[26]), a 1 MeV photon would be completely wiped out by a $3 \cdot 10^{12}$ gauss field orthogonal to its path but emerge untouched from a $2 \cdot 10^{12}$ gauss field. Similarly, a $3 \cdot 10^{11}$ gauss field is opaque to a 10MeV photon, but a $2 \cdot 10^{11}$ gauss field is transparent. Unless there is something we totally miss here, observation of unattenuated spectra up to 10 MeV can only be possible if the field is quite weak or we are viewing at small angles with respect to the field lines, in which case the emission temperature must be quite high. In any case, this whole area is currently under investigation.

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