J. Astron. Space Sci., Vol. 4, No. 2, 1987
〈解說記事〉

On the Nature of the Gamma-ray Bursts

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(Received December 15, 1987; Accepted December 20, 1987)

Abstract

Review of the γ-ray burst phenomena are presented. History of the γ-ray bursts, characteristics, and three radiation mechanisms of thermal bremsstrahlung, thermal synchrotron, and inverse Compton scattering processes are considered.

I. Introduction

High energy Astrophysics has grown enormously over the past two decades with the launching of a number of satellites into space. And since the discovery of γ-ray bursts by Klebesadal et al. in 1973, γ-ray burst detection has been done roughly in the range between 0.1 MeV and 10 MeV. The occurrance of the γ-ray bursts used to be considered as a rare phenomenon; today, however, due to substantially improved detectors, it is not rare any more(See Table 1). From the observations by many authors, general agreement of the characteristics of the γ-ray bursts are: (1)short timescales for intensity variation(<1 sec), (2)high energy features ground 420 keV and 740 keV, and (3)low energy features around 50 keV. Absorption and emission lines around 50 keV, 420 keV, and 740 keV have been detected by many authors and commonly are they interpreted as cyclotron and gravitationally redshifted annihilation lines(Teegarden and Cline 1980; Kirk and Meszaros 1980; Mazets et al. 1981; Fenimore et al. 1982; Bussard and Lamb 1982; Katz 1983; Lamb 1984).

If the low energy features of around 50 keV absortption lines are considered as cyclotron absorption lines, a strong magnetic field($B \geq 10^{12}G$) must be considered to produce the γ-ray bursts. In this strong magnetic fields, thermal synchrotron spectrum can be expected and it does fit to the observed spectra pretty well, indeed(Liang, Jernigan, and Rodrigues 1983; Hameury et al. 1985). Nonthermal synchrotron emission has also been suggested to explain the observed spectra(Bussard 1984). Optically thin thermal bremsstrahlung is a strong candidate as a radiation mechanism(Gilman et al. 1980; Gould 1980, 1981, 1982; Mazets et al. 1981a, b, c, d; Katz 1982; Mazets et al. 1983). In spite of several constraints, optically thin thermal bremsstrahlung spectra fit extremely well to the observed specta. For soft photons, the inverse Compton scattering process has been considered but it is less significant and the fitness to the observed spectra is poor(Fenimore et al. 1982; Lamb 1984; Laros et al. 1984; Matz et al. 1985).

On this review article, we present the generality of the γ-ray bursts. In section II, we present general history of the γ-ray burst detections, in section III, characteristics of the γ-ray bursts are presented, and in section IV, review of the suggested radiation mechanisms is presented. In addition to the conclusion, suggested sources of the γ-ray bursts, though it is still curious, are presented in section V.

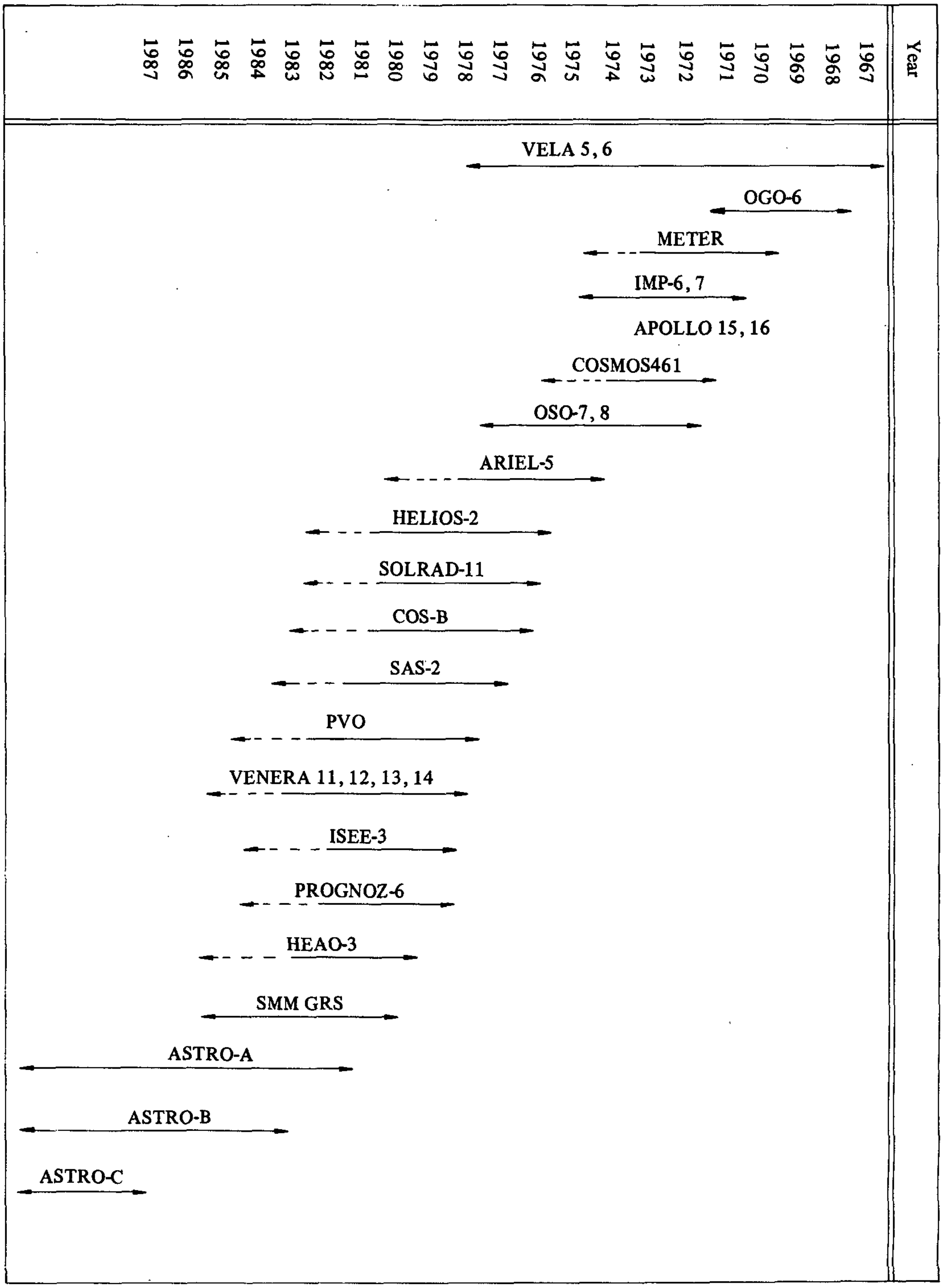
II. Brief History of the γ-Ray Burst Detectors

The γ-ray burst is one of the newest study in Astronomy and Astrophysics. Its own history is only about two decades but, including its pre-history of X- and γ-ray Physics and Astronomy, it is about a half century. The first cosmic γ-ray experiment was done in 1948 by Hulsizer and Rossi, with a balloon-borne ionization chamber. As time went on, many balloon-borne experiments on γ-rays were done(Morrison 1958; Svennson 1958; Savedoff 1959; Kraushaar and Clark 1962; Kraushaar et al. 1965; etc.), and there were various kinds of detectors including; Geiger-Muller tubes in the low energy of < 50 MeV(Rest et al. 1951), alkali-halide scintillation counters(Anderson 1961; Jones 1961; Vette 1962), CsI(Tl) crystals(Jones 1961; Arnold et al. 1962; Metzger et al. 1964), etc., and those detectors had been improved progressively.

By this improvement of the instruments, the Ranger spacecraft could detect the first extraterrestrial γ-ray flux(Arnold et al. 1962 and Metzger et al. 1964), using CsI(TI) detectors and a 32-channel pulse height analyzer(PHA). The results of their detection were significant spectral lines at 0.511 MeV and 2.223 MeV due to $e^+ - e^-$ annihilation and n-p capture, respectively.

One remarkable experiment was done by the MIT group supervised by W. Kraushaar with the satellite Explorer 11(Kraushaar and Clark 1962; Kraushaar et al. 1965). They used the sandwich scintillation counter consisted of five alternate slabs of CsI and NaI, and the Cerenkov detector. It was the most sophisticated experiment in the early days. There were several other experiments on the γ-ray detection in space; OSOs, SASs, TDs, etc.

Table 1. List of the satellites which have detected the gamma-ray burst events



On 1973 June, there was a historical announcement of intense bursts of flux about 10^{-4} ergs cm^{-2} s^{-1} of extraterrestrial γ-rays by Klebesadal et al. This first observation of the γ-ray bursts was done between 1969 June and 1972 July on the four equidistant Vela satellites; Vela 5A, 5B, 6A, and 6B, with a geocentric radius of about 1.2×10^5km. Each spacecraft carried six CsI scintillation counters of 10cm which responded to the energy range of 0.2 to 1.0 MeV and 0.3 to 1.5 MeV for Vela 5 and Vela 6, respectively.

Immediately after this announcement, observations by Clark et al.(1973) on the IMP-6 satellite made the γ-ray bursts to be more confident by showing the agreement with Klebesadal's observations regarding times of occurrence, photon flux, and temporal and spectral characteristics of the bursts. Thereafter, the investigation of this new phenomenon has been done fast with launching many γ-ray burst detectors into space. Table 1 is a list of the satellites which have detected the γ-ray burst events up to date.

The first instrument designed specifically to study cosmic γ-ray bursts themselves was the solar orbiter satellite Helios-2 with the radius from the earth of up to 2AU. One of the most remarkable experiments would be the KONUS experiment on Venera 11 through 14 carried out by the Leningrad group in the USSR. The instruments consist of a sensor system of six NaI(Tl) scintillation detectors, six devices for γ-ray burst detection, a system for the burst arrival time, scalars for the count rates, time and pulse height analysers, logics, and other auxiliary devices. Details of the konus instrumentation is given by Mazets et al. (1983).

The newest satellite of the γ-ray burst detector is Japanese ASTRO-C. ASTRO-C has been launched on 1987 January with its primary purpose on detecting X-rays. It was still on testing when SN 1987A had occurred; however, it was one of three spacecrafts which had detected SN 1987A, and was the only one where the X- and γ-ray parts had been seen by.

III. Characteristics

a) Brief Timescales

Mazets et al.(1981a) showed an experimental distribution of the burst durations for 143 γ-ray burst events(Figure 1). With some exceptions of long durations, for example, ~30 sec or even 20 min on 1977 July 8 and 1978 November 4 events, respectively, typical γ-ray burst timescales are ~0.1 sec to 100 sec as shown in Figure 1. From this short timescale, two significances have been studied. One is the size of burst sources and the other is several types of the γ-ray bursts.

Sizing γ-ray burst sources is to limit the source size. Using the speed of light c as its velocity and its rise time δt, the maximum size becomes $c\delta t$. For a typical rise time of the bursts known as of order ~1 ms(Mazets et al. 1981a, b, c; Barat et al. 1984b), the source would be smaller than ~3×10^7cm. This compact size is roughly suitable to that of neutron stars(typical size of a neutron star is ~10^6 cm). But as Ruderman pointed out, there is the relativistic effect that makes the size bigger by a factor of relativisitc term γ, so sizing burst sources is very rough idea, not convincing(Ruderman 1975).

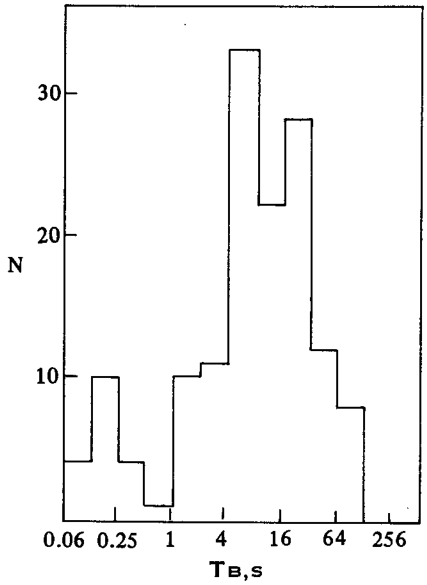


Fig. 1. Distribution of the burst durations for 143 events done during KONUS experiment on Venera 11 and 12(From Mazets et al. 1981a).

Shapes of the γ-ray bursts proposed from the short timescale are generally classified as single bursts, double bursts, and multipulse bursts(Mazets and Golenetskii 1979 and Pizzichini 1979). Pulsed γ-ray bursts have been studied(Mazets and Golenetskii 1979; Pizzichini 1979), while some others believe that the bursts do not pulse(Joss 1978). Recurrence of the bursts have been studied, too(Mazets and Golenetskii 1981). Figure 2, 3, and 4 show a single, a double, and a multipulse bursts.

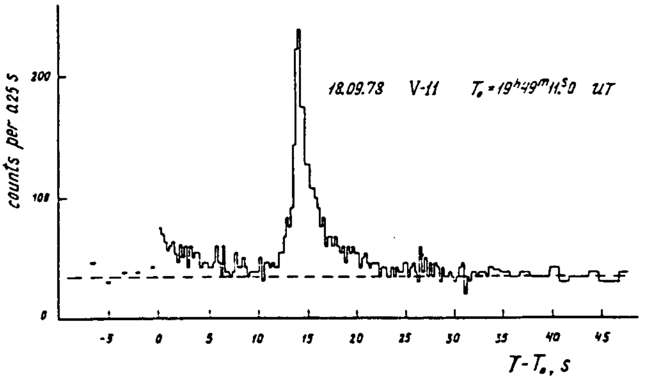


Fig. 2. Single burst event of GB 780918(From Mazets et al. 1981a).

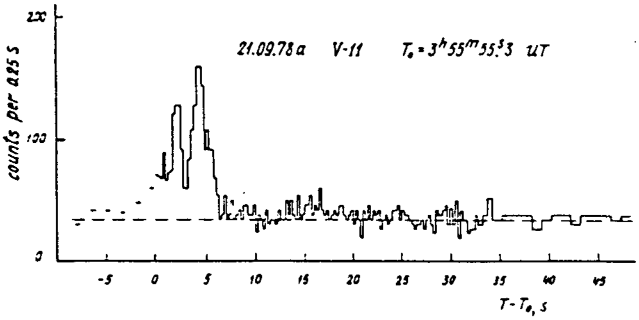


Fig. 3. Double burst event of GB 780921(From Mazets et al. 1981a).

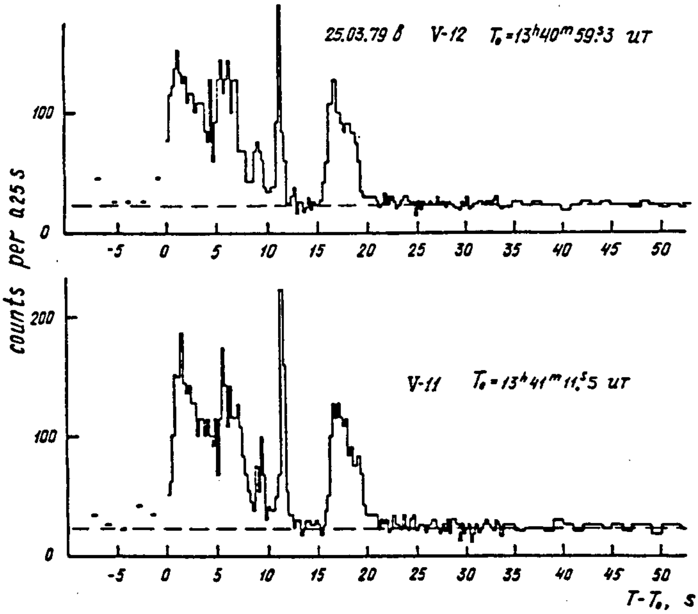


Fig. 4. Multipulse burst event of GB 790325(From Mazets et al. 1981a).

b) High Energy Features

A broad emission line around ~450 keV has been seen in many spectra and it is shown in Figure 5(Bussard and Ramaty 1979; Mazets et al. 1980, 1981d; Teegarden and Cline 1980; etc.). In general, these lines are interpreted as gravitationally redshifted $e^+ - e^-$ annihilation lines(Teegarden and Cline 1980; Mazets et al. 1980, 1981d, 1983; Barat 1983; Barat et al. 1984d, e). There is another interesting line of this class in the energy band of ~700 – 800 keV and it is inter-

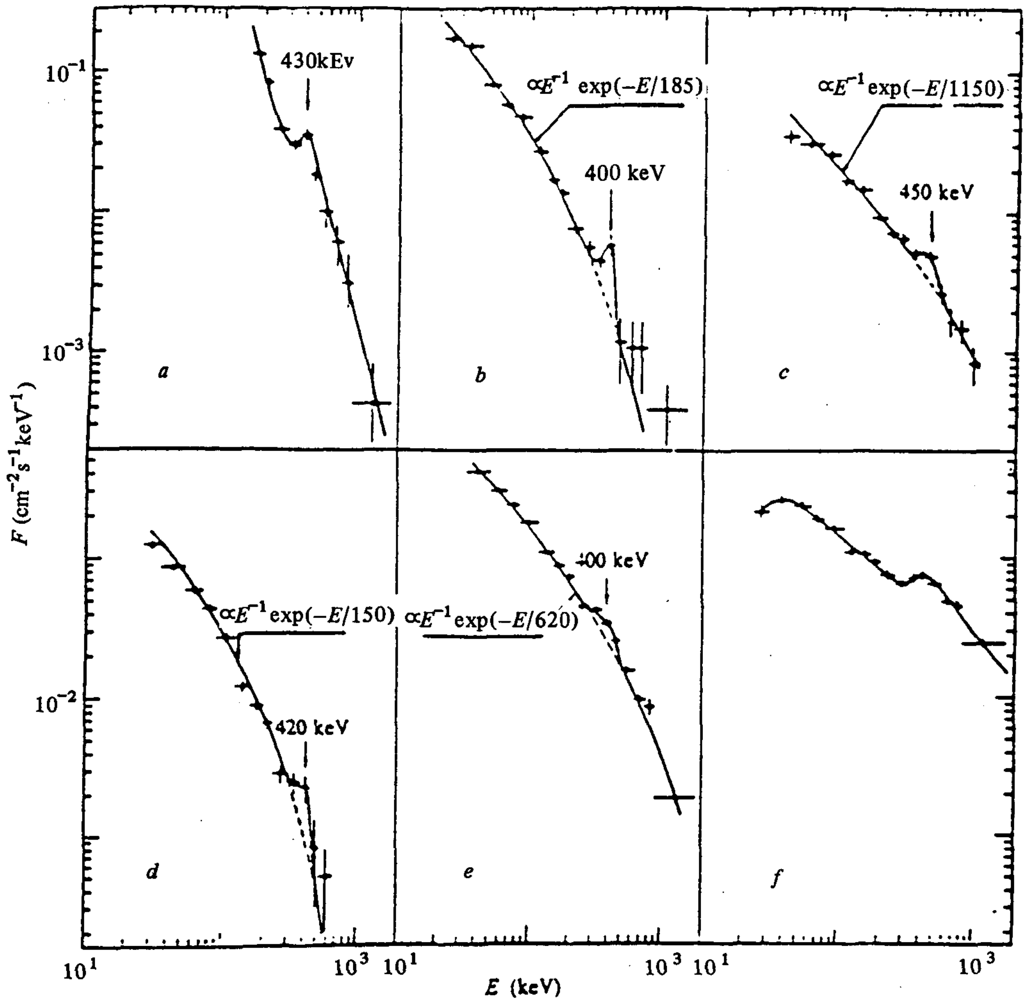


Fig. 5. Energy spectra of emission lines around 450 keV(From Mazets et al. 1981d).

preted as a redshifted line of ^{56}Fe from 847 keV(Ramaty et al. 1979; Teegarden and Cline 1980; Mazets et al. 1981d). While an emission around 420 keV is broad and weak, one around 740 keV is narrow and strong.

If these interpretations for ~420 keV and ~740 keV are true, it is possible to get the size of the object and its mass using the redshift constant z, where

$$z = (1 - 2GM/Rc^2)^{-1/2} - 1 \quad \cdots\cdots\cdots \quad (1)$$

with the gravitational constant G, mass M, the Schwarzschild radius R, and speed of light c(Lang 1980). With the spectra of ~420 keV shifted from 511 keV and ~740 keV from 847 keV lines observed on the ISEE-3, z becomes about 0.1-0.3. For this value, $(M/M_\odot)$ $(R/10^6\,\mathrm{cm})$ would be around 0.7 and it enables us to consider neutron stars as the most suitable burst source(Cline et al. 1980; Teegarden and Cline 1980).

Also, since the surface gravity g is inversely proportional to the square of the radius of the object, it is considered that the γ-ray burst objects have high surface gravities(Matz et. al. 1985).

c) Low Energy Features

An absorption line around 50 keV has been detected by many authors(Ling et al. 1978; Mazets et al. 1981d; Fenimore et al. 1982; Katz 1983). This line is assumed to be an absorption line of the burst radiation, with the absorption energy $\delta E = h\delta\omega$ at the cyclotron frequency $\omega = eH/mc$(Mazets et al. 1981; Fenimore et al. 1982; Matz et. al. 1985). (See Figure 6).

If this interpretation is correct, it is possible to get the strength of the magnetic field of the γ-ray burst sources from the cyclotron frequency, and it is known to be of order 10^{12}G for ~50 keV line. Such strong fields can produce different ways of radiation processes. It will be in section IV.

VI. Radiation Mechanism

Numbers of different suggestions and interpretations for the γ-ray burst phenomena have been demonstrated by different authors to determine what the burst sources are, where they are, and which energy mechanisms produce the bursts, etc. Significant explanations of the γ-ray burst spectra area; optically thin thermal bremsstrahlung(Gilman et al. 1980; Gould 1980, 1981, 1982;

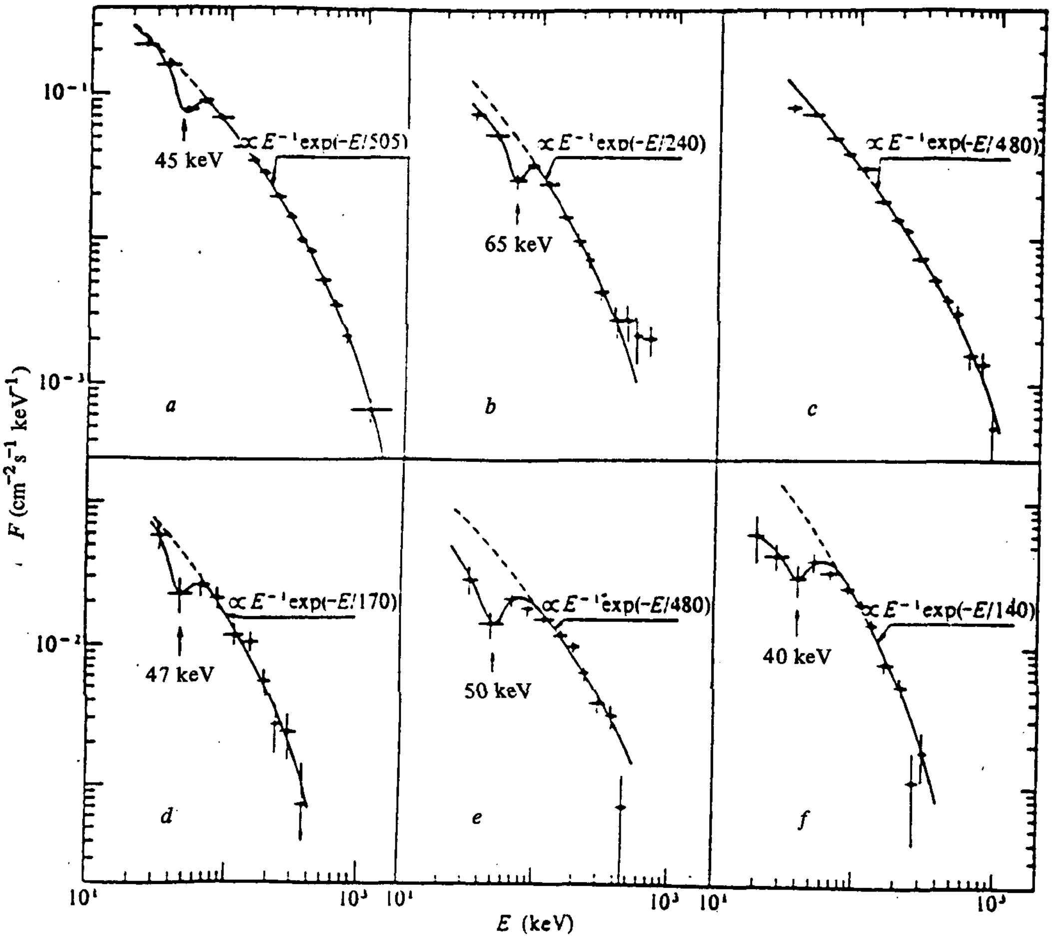


Fig. 6. Energy spectra of cyclotron absorption lines around 50 keV(From Mazets et al. 1981d).

Mazets et al. 1981a; Katz 1982), inverse Compton scattering(Fenimore et al. 1982), thermal synchrotron radiation(Ramaty, Lingenfelter, and Bussard 1981; Liang 1982, 1983; Liang, Jernigan, and Rodrigues 1983; Hameury et al. 1985), nonthermal synchrotron(Bussard 1984), power law(Matz et al. 1985), superposition of a blackbody and thermal synchrotron (Lasota and Belli 1983), and so on.

Most attempts have been done by fitting the observed spectra into given mechanisms that produce γ-ray bursts and then calculating the expected spectra. None of these can, however, completely explain the whole range of the γ-ray burst events. As Woosley said, the γ-ray burst phenomena might be a composite of emission by many processes for various categories of bursts(Woosley et al. 1985). Reviews of various processes of bursts are given by Ruderman(1975), Chupp (1976), Katz(1983), Lamb(1984), and Woosley et al.(1985).

In this section, we present three significant energy mechanisms; optically thin thermal bremsstrahlung, thermal synchrotron radiation, and inverse Compton scattering, and compare each with observed spectra and with each other mechanisms to determine the better interpretations.

a) Optically Thin Thermal Bremsstrahlung(TB)

Optically thin thermal bremsstrahlung was first considered by Mazets et al.(1981a, b, c, d) with 143 burst data from the KONUS experiment. They have got the differential energy spectra for 143 burst events and found that they fit the $dN/dE \propto E^{-1} \exp(-E/kT)$ law. Gilman et al. (1980) also showed the spectra form the Apollo 16 which fitted extremely well by the thermal bremsstrahlung. Figure 7 shows dN/dE graphs from Apollo 16.

In both cases, optically thin thermal bremsstrahlung has been adopted just because the fits were so good. We should mention, however, that this explanation of the γ-ray bursts does not include the emission and absorption lines and the magnetic field. Fenimore et al.(1982), Katz (1982), Lamb(1982, 1984), and Liang(1982) gave some demonstrations on it.

Lamb(1984)'s comparison of the luminosity and spectral properties of many suggested mechanisms tells us that TB is good only in a weak magnetic field. Also Fenimore et al.(1982) pointed out a problem involved in the luminosity and the source distance.

Using the optical depth $\tau = n_e \sigma_c l$,, where $\sigma_c = 4\pi r_e^2/3$ is half of the Thomson cross section and l is the size of the emitting region, the bremsstrahlung luminosity L by

$$L = 2.4 \times 10^{-27}\ t^{1/2}\ n_e^2(\text{Volume}), \quad \cdots\cdots \quad (2)$$

and the flux $F = L/4\pi D^2$, Fenimore et al.(1982) found the source distance D to be

$$D = \left| \frac{2.4 \times 10^{-27}\ \bar{g}}{3\sigma_c^{\ 2}} \right| \frac{T^{1/4}}{F^{1/2}}\ \tau l^{1/2} \quad \cdots\cdots \quad (3)$$

D is in cm, $\bar{g}$ is the temperature averaged Gount factor, and F is the flux observed on earth. Here we can see the distance D depends on the optical depth τ and weakly on the temperature T and the size l(Figure 8).

A constraint of TB is shown in Figure 9. It is shown that the γ-ray burst source can have a

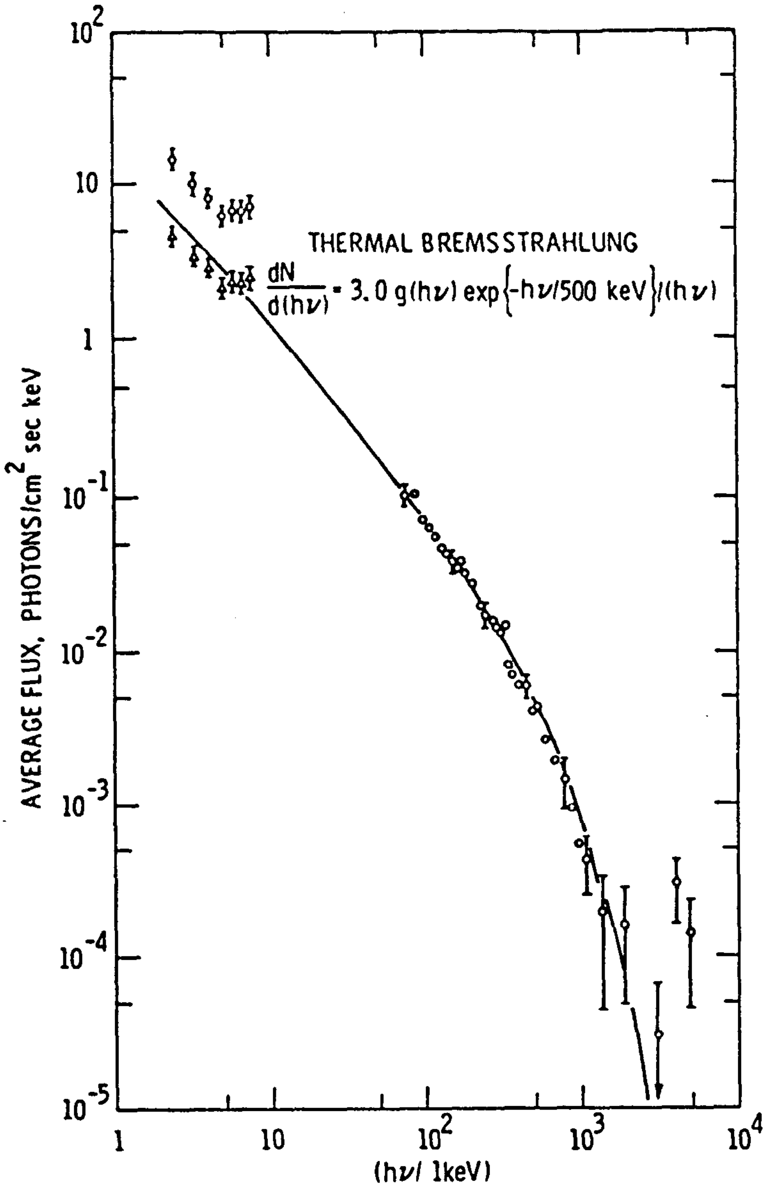


Fig. 7. Best fit with thermal bremsstrahlung spectrum of the GB 720427 event observed by Apollo 16(From Gilman et al. 1980).

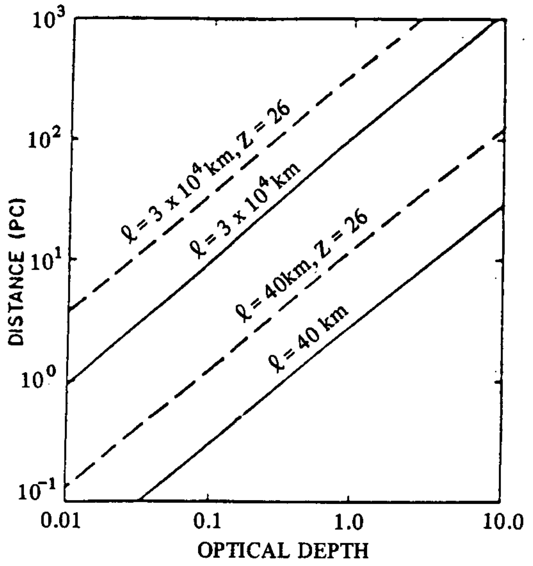


Fig. 8. Distance vs. optical depth assuming thermal bremsstrahlung(From Fenimore et al. 1982).

moderate distance(~100pc) if the source size is of order 10^4km. However, from the spectra of cyclotron absorption lines, it is generally considered that the strongest candidate of the γ-ray source is magnetized neutron stars whose size is of order 10km. And if the size is reasonable (~10km) then the distance becomes shorter than 10pc, and it doesn't seem to be quite correct.

Therefore, thermal bremsstrahlung would not be a proper mechanism of the γ-ray bursts as long as the absorption lines are cyclotron lines and strong magnetic fields exist.

b) Thermal Synchrotron Radiation(TS)

While Mazets et al.(1981d) suggested TB as the γ-ray burst mechanism using the spectra of 143 γ-ray burst events, Liang, Jernigan, and Rodrigues(1983) showed that the same 143 spectra could be well-fitted to TS model(See Figure 9). TS can also explain observed emission and absorption lines in strong magnetic fields, while TB cannot.

With the assumption that the observed emission and absorption lines are redshifted annihilation and cyclotron absorption lines, respectively, a strongly magnetized neutron star with field strength of ~10^{12}G is the most reasonable source. In such a strong magnetic field, relativisitic particles produce the synchrotron emission, and the characteristic frequency becomes much

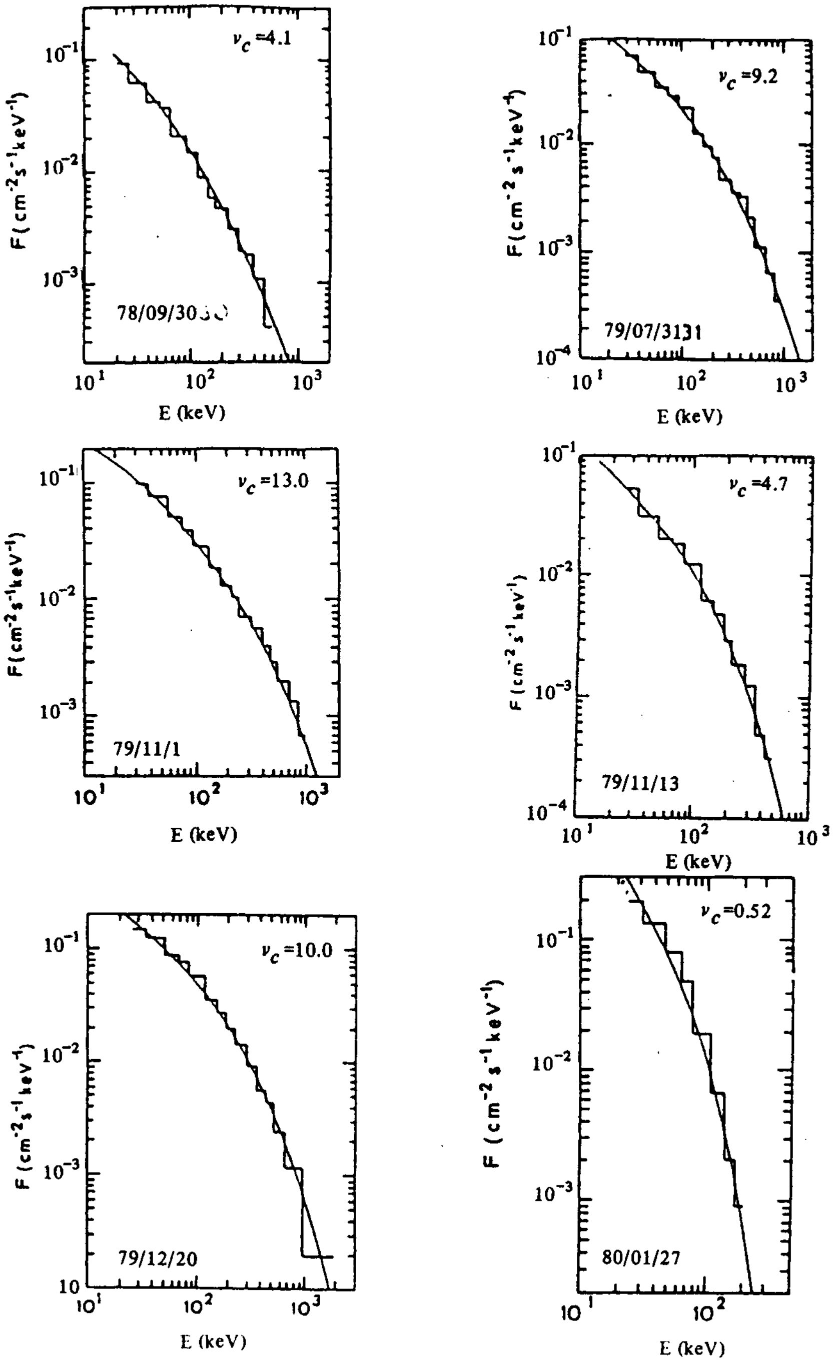


Fig. 9. Best fits with the thermal synchrotron spectrum(From Liang, Jernigan, and Rodrigues 1983).

greater than the gyration frequency by a factor of γ^2(Rybicki and Lightman 1979). So the energy loss rate of the synchrotron radiation in ergs/s is

$$-\frac{dE}{dt})_{\text{synch}} = \frac{4}{3} n_e c \sigma_T \beta^2 \gamma^2 \left(\frac{B^2}{8\pi}\right) \quad \cdots\cdots \quad (4)$$

with β = v/c, pitch angle α, Lorentz factor γ, electron number density n_e, and the strength of magnetic field B in gauss. Therefore, comparing Eq.(4) with Eq.(1), it is shown that TB would dominate TS only if the magnetic field is

$$B \leq 2.9 \times 10^9 Z\, n_{26}^{1/2}\, T_9^{-1/4} \quad \cdots\cdots \quad (5)$$

with $n_{26} = n/10^{26}$cm and $T_9 = T/10^9$K(Lamb 1982). For B ~ 10^{12}G, TS is much more efficient than TB. Figure 10 shows dominant radiation regions considering the strength of magnetic field (Matz 1985).

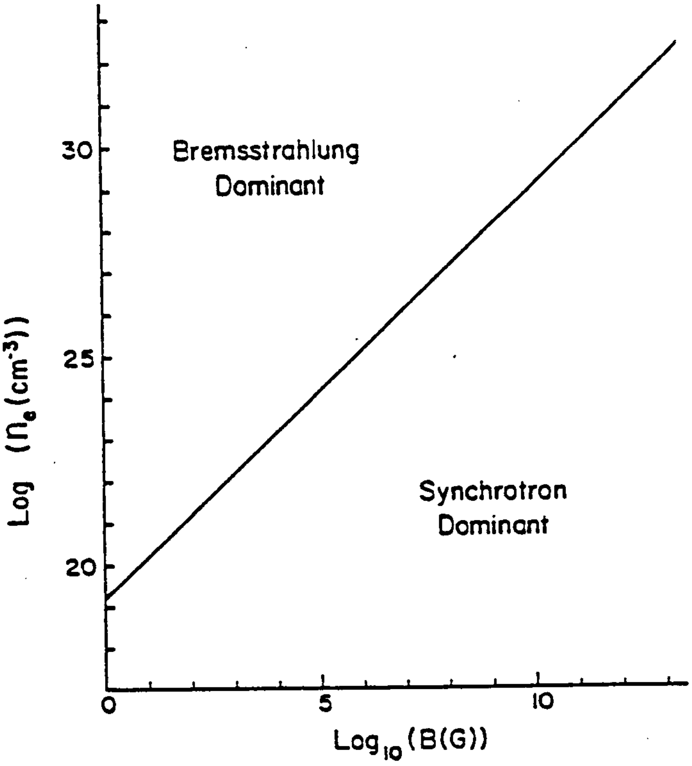


Fig. 10. Radiation regimes, assuming a thermal plasma with KT = 300keV based on the approximate lummosities (From Matz et al. 1985)

Bussard(1982), however, suggested the non-thermal synchrotron, for it is hard to keep a thermal distribution of electrons in such strong magnetic fields ($\rangle 10^{12}$ G).

Another constraint is the source distance considering its magnetic field. With a typical γ-burst flux of F $\sim 10^{-5}$ ergs cm^{-2} s^{-1}, strength of the magnetic field is known as

$$B > 5.6 \times 10^{9} (D/1\,kpc)\,(A/1\,km^{2})^{-1/2} \quad \cdots\cdots (6)$$

where D is the source distance and A is the surface area of the source. In this relation, however, we don't get both the distance and the source size. Thus, if the object is 300pc away then B would be $\sim 10^{9}$G and, if it is $\sim$40kpc away then B would be $\sim 10^{12}$G which is too far but a reasonable field strength(Fenimore, Klebesadel, and Laros(1984).

c) Inverse Compton Scattering(IC)

A third model of γ-ray burst spectra is the inverse Compton scattering. IC has been first proposed by Fenimore et al.(1982) on the 4 November 1978(GB781104) event using data from the ISEE-3. Fenimore, Klebesadel, and Laros(1984) explained the low-energy X-rays and the two-component spectra shown on some spectra by IC model and, Shapiro, Lightman, and Eardley (1976) considered that γ-ray burst spectra had a power law form of IC and calculated the power index α. Also, Pozdnyakov, Sobol', and Sunyaev(1979) showed the IC spectra in nonrelativistic, semirelativistic, and ultrarelativisitc cases(Lamb 1984).

Though IC fits well to some events like GB781104, it is comparatively less significant. Since IC occurs when soft photons(i.e., energy of photons less than that of electrons) emerge into a field of energetic(hot) electrons and gain energy from collisions with electrons, its spectra fits well only to the low energy parts(<1MeV). In addition, Liang(1984) showed the inconsistancy of IC with the observed luminosity ratio L_X/L_γ.

Theoretically IC would be a dominant mechanism if it cools hot plasma faster than others. The inverse Compton cooling rate $-dE/dt)_{IC}$ of the hot plasma is known as

$$-\frac{dE}{dt})\,IC = 4\,\sigma_\tau c U_{bb} n_e \frac{kT_e}{m_e c}\left(1 + 4\frac{kT_e}{m_e c^2}\right)$$

$$= 3.6 \times 10^{25}\, L_{bb,37}\, n_{e,26}\, T_9 (1 + 0.68\,T_9) \quad \cdots\cdots (7)$$

in units of ergs $cm^{-3} s^{-1}$, where $cU_{bb} = L_{bb}/4\pi R^2$ is the blackbody radiation energy density, σ_T

Thompson cross section, n_e, electron number density, and T_e is the temperature of the plasma (Shapiro and Salpeter 1975 and Shapiro, Lightman,and Eardley 1976). Comparing this with Eq. (4), we see that IC would dominate TS only in a weak field of

$$B \lesssim 2.6 \times 10^7 L_{bb,37}^{1/2} \quad \cdots\cdots (8)$$

in gauss. Therefore, in a strong magnetic field like $B > 10^{12}$G, TS is better than IC.

From the observations up to date and radiation theories with several assumptions, it is intended that the dominant γ-ray burst radiation would be TS. But the problems exist, though. First, as shown in Figure 11, other mechanisms fit to the observed spectra pretty well; second, TS does not cover the whole range of the bursts; and third, constraints are remaining in its physics.

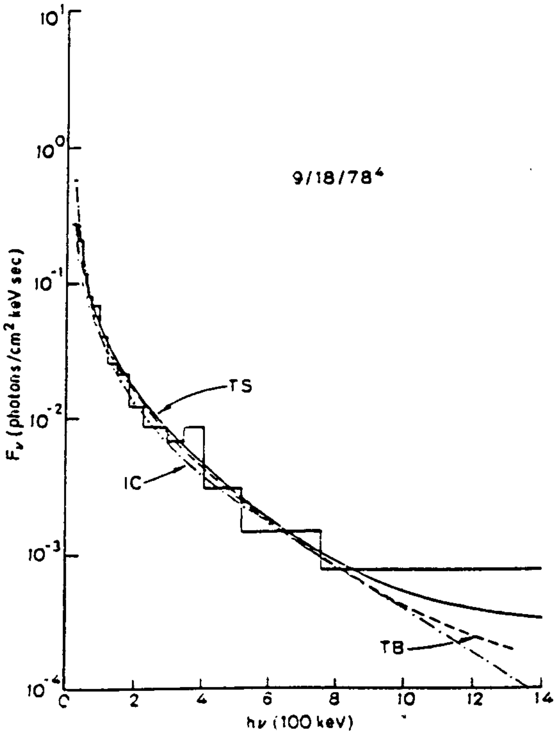


Fig. 11. Comparisons between TS, TB, and IC fits to the continuum spectrum of GB 780918(From Liang, Jernigan, and Rodrigues 1983).

V. Conclusions

General review of the phenomena of the γ-ray burst events was presented considering in its history, characteristics, and the energy mechanisms. As mentioned before, however, none of the suggested mechanisms of the bursts can satisfy this throughly. Basic problems are still remaining: What makes the bursts? What are the burst sources? And where are they?

Localization of the burst sources is one of important studies and has been done generally with three methods: statistical distribution of logN-logS, triangulation, and the anisotropic response of the instrument(Fishman 1979; Mazets et al. 1981a, b, c; Lund 1981, Bussard and Lamb, 1982; Barat et al. 1982b; Hurley 1982; Attenia et al. 1985; Schwartz et al. 1987). Though there are hundreds of decided positions, they are not very convincing due to either poor method and instrument or poor accuracy.

In spite of the unknown properties of the bursts, there are a bunch of burst sources proposed. Proposed sources of the γ-ray bursts are following: magnetized neutron stars(Mazets et al. 1981d; Mazets et al. 1983; Katz 1983; Katz 1983; and many others), solar flares(Dermer and Ramaty 1986 and Bai 1986), black holes(Ruffini 1975), pulsars(Mazets et al. 1979; Mazets and Golenetskii 1981; Daugherty and Harding 1983; Norris et al. 1986); and individual sources like Cyg X-1, supernova remnant N49 in the Large Magellanic Cloud(Cline et al. 1982, 1984), flaring X-ray pulsars in Dorado, etc.

One thing we should mention is that the single- or multi- photon pair-production in superstrong magnetic fields ($> 10^{12}$G) is not included. But it is very important and interesting in γ-ray bursts and, many authors have been studying in this subject(Ramaty and Meszaros 1981; Daugherty and Harding 1983).

Better instruments will be able to detect shorter and weaker burst events and it will provide us more accurate sources and their locations, and the radiation mechanisms. Study on the magnetic field of the bursts would contribute a lot in this subject, too.

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