A BURST OF SPECULATION

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ABSTRACT

Self-consistent models of gamma-ray burst source regions at 100 Kpc distance are possible if the radiating plasma is confined to very thin sheets, and I estimate parameters. Energy sources might be elastic (by starquakes) or magnetic (by reconnection), but mechanisms remain obscure. I discuss a very speculative model involving collisions between comets in a hypothetical inner Oort cloud.

INTRODUCTION

Discoveries by the BATSE\textsuperscript{1,2} have reduced theories (and theorists) of gamma-ray bursts (GRB) to a state of confusion. The field is nearly as open as it was when GRB were first announced in 1973. In order to understand GRB, it will be necessary to answer some questions about the physical conditions within them:

1. Is the energy of a GRB (or a sub-burst, in the case of GRB with distinct sub-structure) released promptly in the form of energetic particles and radiation, which gradually dissipate, or is the release continuous, with an instantaneous power proportional to the instantaneously observed intensity?
2. How do GRB time histories indicate characteristic physical time scales?
3. Are there any intermediate reservoirs of energy between its ultimate source and the radiating plasma (for example, vibrations in models driven by elastic energy)?
4. Is the geometry of the source region line-like, sheet-like, or sphere-like?
5. What is the optical depth of the source region?
6. Does an individual GRB have preferred power levels and decay time scales, as may be suggested by repetitive sub-burst structure in at least one observed GRB\textsuperscript{2}?
7. How isotropic or beamed is the radiation pattern?
8. Does the time history of observed intensity indicate the time history of total radiated power, or is an anisotropic beam pattern variable or rotationally modulated?
9. Is the continuum radiation mechanism annihilation, bremsstrahlung, curvature radiation, or some other process?
10. Is the energy distribution of the particles in the source region strongly nonthermal or partly thermalized?
11. Is the radiating plasma freely expanding or magnetically trapped?

The answers to these physical questions are closely related to the unsolved astronomical questions of the distances to GRB and the existence of counterparts in other energy bands. The astronomical questions having so far proved intractable, the attention of the theorist should turn to the physical questions.

ESTIMATES

Arguments\textsuperscript{3,4} concerning the reported\textsuperscript{5} 511 KeV annihilation line in the March 5, 1979 GRB led to the inference that the emitting region was a geometrically and optically thin sheet. Although this soft gamma repeater (SGR) may not be representative of GRB, and the status of the annihilation line in GRB spectra is controversial, it may still be useful to consider this geometry. Magnetic reconnection, in analogy to a Solar flare, was one of the first suggested models of GRB\textsuperscript{4,6}, and would be expected to release energy in a thin sheet.
Consider a pair or electron-proton sheet plasma of thickness $L$, with particle energies $\sim mc^2$, where $m$ is the electron mass, and density $n$. The transverse optical depth $\tau$ is

$$\tau \sim n\sigma_0 L,$$

where the cross-section $\sigma_0 = (e^2/mc^2)^2$ is roughly applicable to Coulomb and Compton scattering and to two photon annihilation and pair production. The characteristic power density (per unit area) is

$$P \sim n^2mc^3\sigma_0L \sim \frac{n^2e^4L}{mc},$$

Define a dimensionless length $\ell \equiv Lmc^2/e^2$ and power density $p \equiv Pl^3/m^4e^6$. Then

$$n \sim \frac{\tau}{\ell \alpha^3} \frac{m^3c^3}{h^3},$$

where $\alpha \equiv e^2/\hbar c$ is the usual fine structure constant. Use of (1) tacitly assumes that $\tau$ is not large, as implied by the observed nonthermal spectra. Similarly, from (2):

$$n \sim \left(\frac{p}{\ell \alpha^3}\right)^{1/2} \frac{m^3c^3}{h^3}.$$  

Equating (3) and (4) yields

$$\ell \sim \frac{\tau^2}{p\alpha^3}.$$  

These estimates lead to an energy content per unit area

$$\Sigma \sim nmc^2L \sim \frac{m^3c^6}{e^4} \sim 1.0 \times 10^{19} \tau \text{ erg/cm}^2,$$

and a radiation time scale (also the annihilation time scale $t_a \sim 1/n\sigma_0c$)

$$t_r \equiv \frac{\Sigma}{P} \sim \frac{\tau}{p mc^4} \sim 2 \times 10^{-17} \left(\frac{\tau}{p}\right) \text{ sec.}$$

In order to maintain a radiating plasma there must be a continuing injection of energy from an electric field. An elementary estimate of the electrical conductivity is

$$\sigma_{el} \sim \frac{e}{mc\sigma_0} \sim \frac{mc^3}{e^2} \sim 10^{23} \text{ sec}^{-1}.$$  

The required electric field $E$ may be estimated from the condition of energy balance

$$P = \sigma_{el}E^2L,$$

with the result

$$E \sim \left(\frac{p\alpha^3}{\ell}\right)^{1/2} \frac{m^2e^4}{e^3} \sim \frac{p\alpha^3}{\tau} \frac{m^2c^4}{e^3} \sim 2 \times 10^9 \frac{p}{\tau} \text{ cgs.}$$

It is necessary to replenish annihilating pairs. The fastest processes, with cross-sections $\sim \sigma_0$, are $e^+ + e^- \rightarrow \gamma + \gamma$ and $\gamma + \gamma \rightarrow e^+ + e^-$, which conserve the sum of the numbers of leptons and photons. To supply an escaping flux of gamma-rays requires injection of both energy and particles. The electric field directly supplies only energy. Particle number may be resupplied by processes such as $\gamma + e^\pm \rightarrow e^\pm + \gamma + \gamma$, $e^+ + e^- \rightarrow e^+ + e^- + \gamma$, $e^+ + e^- \rightarrow \gamma + \gamma + \gamma$, and $\gamma + \gamma \rightarrow e^+ + e^- + \gamma$, with cross-sections $\sim \sigma_0\alpha$. Perhaps more important may be synchrotron radiation and magnetic one-photon pair production, which occur because leptons and photons are produced and scattered with large cross-field momenta.
The electric field (10) also produces a mean leptonic drift velocity $\sim c$. This may lead to a two-stream or ion-acoustic plasma instability, constrained by the magnetic field to be one-dimensional. The effective conductivity may be reduced far below (8). Such an increased resistivity in regions of high current density is a familiar feature of magnetic reconnection. Quantitative understanding would require plasma simulations which include collisionsal as well as collective processes.

**GAMMA-RAY BURSTS AT 100 KPC?**

The BATSE data\textsuperscript{1} demonstrated the impossibility of a Galactic disc origin of all GRB, and increased the attractiveness of earlier suggestions\textsuperscript{7–9} that they are distributed in an extended halo of radius $\sim 100$ Kpc. If so, then their luminosities approach those of the March 5, 1979 event in the LMC, and many arguments\textsuperscript{3–5,10,11} made for it may be applied to GRB in general.

A typical GRB luminosity at 100 Kpc is $10^{41}$ erg/sec, corresponding to an observed flux $\sim 10^{-7}$ erg/cm$^2$sec. With an effective radiating area of $10^{12}$ cm$^2$, $P \sim 10^{29}$ erg/cm$^2$sec and $p \sim 2 \times 10^{-7}$. Then (5) yields $\ell \sim 10^{13} \tau^2$ and $L \sim 3\tau^2$ cm. In the absence of plasma instabilities $E \sim 500$ cgs, insufficient to sustain a curvature radiation cascade. It is evident that $\tau_r$ is extremely short unless $p$ is so small that the GRB are within the Oort cloud.

A power density $P \sim 10^{29}$ erg/cm$^2$sec corresponds to a black body of effective temperature $T_e \sim 20$ KeV, inconsistent with the observed hard spectra. At semi-relativistic energies equilibration by Compton scattering is rapid, even in the absence of true absorption, so that the more energetic part of the spectrum must be produced in optically thin regions. This argument need not apply at photon energies $h\nu \ll 100$ KeV; self-absorption may limit reradiation from a neutron star’s surface.

At least one GRB reported at this meeting\textsuperscript{2} apparently consisted of distinct but very similar sub-bursts, each with a pronounced time-skewness\textsuperscript{12} consisting of a rapid rise and more gradual decay over roughly one second. This suggested injection of energy into a reservoir, followed by its gradual radiation. It is apparent that pair plasma cannot be such a reservoir. Although a magnetic field of $10^{12}$ gauss provides sufficient stress to confine $10^{41}$ erg ($10^{20}$ gm) of pair plasma, its opacity $\kappa \sim e^4/m^3c^4 \sim 100$ cm$^2$/gm would lead to an optical depth $\tau \sim 10^{10}$, inconsistent with the emergent hard and nonequilibrium spectrum. If confined, the energy would leak out over a time $\tau r/c \sim 3 \times 10^5$ sec, also inconsistent. Similarly, its energy density of $\sim 10^{23}$ erg/cm$^3$ corresponds to a black-body temperature of $\sim 160$ KeV. An unconfined fireball of this temperature would lead to a flash of gamma-rays with mean energy $\sim 500$ KeV, but with a thermal spectrum and a duration $\leq r/3c \sim 10^{-5}$ sec. Thus pair gas cannot be an energy reservoir, whether magnetically confined or exploding in a fireball; energy must be continuously replenished.

An unconfined fireball continuously resupplied with energy will have a lower energy density. The energy density is $\sim P/c$, and $\tau \sim Pr\kappa/3c^3 \sim 10^9$, still enough to ensure thermalization of the spectrum. This problem is exacerbated at cosmological distances. Adiabatic expansion has the effect of collimating the particle and photon momenta, but preserves the equilibrium spectral shapes, inconsistent with observation.

Models of the type discussed here suffer from the well-known problem of a high pair-production optical depth for MeV gamma-rays. Electric fields produce opposing streams of $e^+$ and $e^-$ whose gamma-rays interact head-on. The well-known solution of relativistic collimation may work if the radiating particles have sufficient energy and the majority are collimated. This is naturally obtained in an electrically driven nucleus-electron plasma in an erupting flux loop, in which the leptons are predominantly $e^-$, all of which are accelerated in the same direction.
SOURCES AND MECHANISMS

The release of magnetic energy by reconnection and the release of elastic energy in starquakes have been considered as possible mechanisms of GRB at Galactic distances since their discovery. They are plausible qualitative explanations of much of the phenomenology, including the observed zoo of diverse GRB shapes and durations. The suggestion that much of the energy release and radiation comes from a thin sheet may also be explicable if the immediate mechanism is magnetic reconnection. The gross energetics may be consistent with GRB at 100 Kpc distance.

It is also possible to consider hybrid models, in which the eruption of current loops requires crust-breaking. The chief difficulty faced by magnetic reconnection is to release energy suddenly in regions of low optical depth. Dissipation requires resistivities between those of the interior (large) and vacuum (0); turbulent plasmas are plausible. The details of both physics and field geometry are likely to be complex.

A CRAZY IDEA

Comets in an inner Oort cloud may occasionally collide with velocities $\sim 1$ km/sec. It is conceivable, if implausible, that such a collision of cold masses of dirty ice might produce gamma-rays by electrostatic processes. Deformation of piezoelectric components, heating of pyroelectric components or frictional charging, as the comets splatter in a subsonic collision, might lead to multi-MeV potentials. Pure ice is believed not to be piezoelectric or pyroelectric, but this has been controversial, and dirty ice or comets could be more complex. Ice has been reported to be triboluminescent, indicating the production of multi-eV potentials. To produce gamma-rays requires that MeV potentials accelerate electrons through the vacuum. This is not unprecedented; pyroelectrics accelerate electrons to sufficient energy to produce X-rays. Complex intensity histories might be attributed to complex collision geometries. Efficiency requires that no current flow through solids, where electrons would thermalize; this is consistent with the high resistivity and dielectric strength of cold ice.

Although the microscopic physics of these electrostatic processes is poorly understood, it is possible to examine the energetics. Consider a mass $M$ of comets, each of size $a$ and mass $\rho a^3$ ($\rho \approx 1$ gm/cm$^3$), symmetrically filling a sphere of radius $R$ centered on the Sun. There are $N = M/\rho a^3$ comets, with number density $n = M/\rho a^3 R^3$. A collision cross-section $a^2$ leads to a mean collision time $t_c \sim a \rho R^7/2 / M (GM_{\odot})^{1/2}$. The total kinetic energy is $E \sim GM_{\odot} M/2R$, and the mean power density at Earth is

$$F \sim \frac{E \epsilon}{4\pi R^2 t_c} \sim \frac{GM_{\odot} M \epsilon}{8\pi R^3 t_c} \sim \frac{(GM_{\odot})^{3/2} M^2 \epsilon}{8\pi \rho a R^{13/2}},$$

where $\epsilon$ is the efficiency of converting kinetic energy to gamma-rays. The collision rate is

$$\dot{N} \sim \frac{M^2 \sqrt{GM_{\odot}}}{\rho^2 a^4 R^{7/2}}.$$ 

The observed $F \sim 3 \times 10^{-12}$ erg/cm$^2$ sec, and for the BATSE $\dot{N} \sim 10^{-5}$ sec$^{-1}$. Defining $M_{-3} \equiv M/10^{-3} M_{\odot}$ and $\epsilon_{-3} \equiv \epsilon/10^{-3}$ and combining (11) and (12) yields

$$R \sim \frac{N^{2/45} (GM_{\odot})^{11/45} M^{14/15}}{\rho^{4/45}} \left( \frac{\epsilon}{8\pi F} \right)^{8/45} \sim 3.2 \times 10^{15} M_{-3}^{4/15} \epsilon_{-3}^{-8/45} \text{ cm},$$

and

$$a \sim \frac{M^{4/15}}{(GM_{\odot})^{4/45} \rho^{19/45} N^{13/45}} \left( \frac{8\pi F}{\epsilon} \right)^{7/45} \sim 1.2 \times 10^{6} M_{-3}^{4/15} \epsilon_{-3}^{-7/45} \text{ cm}.$$
The collision time is

\[ t_c \sim \rho^{4/15} M^{1/5} (GM_\odot)^{4/15} \left( \frac{\epsilon}{N^2 F} \right)^{7/15} \sim 1.0 \times 10^{17} M^{-1/5} \epsilon^{-3/5} \text{ sec}, \]  

consistent with the age of the Solar System of \( 1.5 \times 10^{17} \text{ sec} \) if \( \epsilon > 10^{-3} \).

This model makes a number of predictions. It cannot explain any repeating source. The distance scale (13) implies a typical parallax of \( 1 \text{ AU}/R \approx 15' \) if \( \epsilon \sim 10^{-3} \). This may be tested by overdetermined GRB position measurements, and the model may be excludable by extant data. The distribution of GRB on the sky should show an annually time-periodic dipole moment of \( O(1 \text{ AU}/R) \), with its peak towards the Sun. There will be no cyclotron lines, and any annihilation lines will have no redshift. Atomic X-ray lines of abundant species may be present. There may be a simultaneous visible flash, of unpredictable intensity, resulting from scintillation by impacting energetic electrons. The predicted apparent visual magnitude of an \( a = 12 \text{ km} \) comet at a distance \( R \) is about 32, but a comet disrupted by a collision into a spray of fragments could be many magnitudes brighter, depending on fragment size. Such a spray would disperse at an angular rate \( \sim 1''/\text{day} \). Dust could also be an effective scatterer of sunlight. A fraction, perhaps large, of the kinetic energy of collision (\( \epsilon^{-1} \) times the gamma-ray energy) would be thermalized and reradiated in the near-infrared; the time scale depends on the fragment size and the thermal conductivity, and is in calculable. The hypothesis of gamma-ray production could itself be tested in laboratory collisions, if the nature of cometary material were well enough known.

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