Delayed Hard Photons from Gamma-Ray Bursts

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Abstract

The delayed hard (up to 25 GeV) photons observed more than an hour following a
gamma-ray burst on February 17, 1994 may result from the collisions of relativistic nucleons
with a dense cloud, producing $\pi^0$. The required cloud density is $\sim 2 \times 10^{11}$ cm$^{-3}$. This
cloud may be the remains of the disrupted envelope of a neutron star, and may survive as
an excretion disc of $\sim 10^{14}$–$10^{15}$ cm radius around the coalescing binary.
1. Introduction

The recent observation by EGRET (Hurley, et al. 1994) of a $\approx 25$ GeV photon from the direction of a gamma-ray burst (GRB) on February 17, 1994, but following it by about 77 minutes, and of several $\sim 100$ MeV photons at comparable (but not identical) time lags, cannot be accommodated within models in which a GRB is the result of synchrotron emission in a collisionless shock-heated plasma produced by relativistic fireball debris impinging upon interstellar gas (Rees and Mészáros 1992, Mészáros and Rees 1993, Katz 1994). The time delay is the difficulty. In these models high energy radiation is associated with high Lorentz factors, short pulse durations and short intervals from the onset of emission. At later times synchrotron radiation is observed from fireball debris whose kinetic energy has been degraded by sweeping up interstellar matter, and its spectrum will therefore be softer than that observed early in the burst. Further, a burst duration of more than an hour could only be obtained for interstellar densities many orders of magnitude less than $1 \text{ cm}^{-3}$. In the case of most GRB (including that of February 17, 1994) this would be inconsistent with the values of the parameters implied by their emission of $\sim$ MeV photons over durations of seconds to minutes.

I suggest an explanation of these observations as the result of collisions between energetic nucleons in the fireball debris and a dense cloud of low velocity gas near the site of the GRB. §2 contains estimates of the required parameters. In §3 I discuss the problem of forming and maintaining the required cloud. §4 contains a brief summary discussion.

2. Collisional Gamma-Rays

The observed energetic gamma-rays may be produced by the process

$$p + p \rightarrow p + p + \pi^0,$$  

$$\pi^0 \rightarrow \gamma + \gamma.$$  

A significant fraction of the nucleons in the universe are neutrons, stabilized by their
presence in helium or heavier nuclei, so that
\[ p + n \rightarrow p + n + \pi^0 \]  \hspace{1cm} (1a')
may often take the place of (1a). Reaction channels which include products in addition to \( \pi^0 \) should be considered at high energies.

The total cross-section of nucleons on nucleons at multi-GeV energies is roughly 30 millibarns, nearly independent of energy. The partial cross-section for \( \pi^0 \) production is several times smaller. The laboratory frame energies of the gamma-rays are typically about 10% of that of the incident nucleon, so the observation of a \( \approx 25 \text{ GeV} \) photon suggests a nucleon of \( \sim 300 \text{ GeV} \), corresponding to a Lorentz factor \( \gamma \sim 300 \). This is within the range assumed in fireball models of GRB, and might be taken as support for those models if the hard gamma-ray production can be explained.

The chief difficulty in fireball models of GRB is turning debris kinetic energy into observable gamma-rays, which is why these models usually assume collective interactions (collisionless shocks). Without collective interactions, at ordinary interstellar densities (1 cm\(^{-3}\)) the nucleon-nucleon interaction length is about 10 Mpc! An alternative resolution of this problem is to assume extraordinarily high densities. This cannot explain the lower energy emission of GRB, because the resulting radiation is a combination of high energy (mean energy \( \geq 70 \text{ MeV} \)) gamma-rays from \( \pi^0 \) decay and visible, ultraviolet, and X-ray radiation from the heated matter, and because the time scales are much too long, but it may be the explanation of the delayed hard gamma-rays.

The characteristic interaction time of a relativistic nucleon moving through a gas of nucleon density \( n \) (the mean density averaged over particle paths) is
\[ t \sim \frac{1}{n\sigma c}, \]  \hspace{1cm} (2)
where \( \sigma \approx 3 \times 10^{-26} \text{ cm}^2 \) is the total interaction cross-section. Here we assume that the energetic particles are moving roughly isotropically through the gas cloud (collimation
toward the observer would reduce the observed duration), so that the observed \( t \approx 5 \times 10^3 \) s may be used in (2), with the result

\[
n \sim 2 \times 10^{11} \text{ cm}^{-3}. \quad (3)
\]

The spatial extent of such a cloud of mass \( M_{cl} \), described as a homogeneous sphere of radius \( r \) (surely an oversimplification) is

\[
r \sim \left( \frac{M_{cl}}{M_\odot} \right)^{1/3} \left( \frac{3 \times 10^5}{n} \right)^{1/3} \sim \left( \frac{M_{cl}}{M_\odot} \right)^{1/3} \left( \frac{t}{5 \times 10^3 \text{ s}} \right)^{1/3} 1 \times 10^{15} \text{ cm}. \quad (4)
\]

Because the observed \( ct \approx 10^{14} \) cm the observed radiation comes from only a small inner fraction of the cloud if \( M_{cl} \gg 10^{-3} M_\odot \). If \( ct > r \) were observed it would not contradict the model because isotropized particles, gyrating in a magnetic field, may spend a time much longer than \( r/c \) inside the cloud. For a 300 GeV proton a gyroradius of \( 10^{14} \) cm corresponds to \( B \approx 10^{-5} \) gauss, only a few times greater than typical interstellar values and a modest value for a cloud of the required density.

The total column density of the cloud is

\[
nr \sim \left( \frac{M_{cl}}{M_\odot} \right)^{1/3} \left( \frac{t}{5 \times 10^3 \text{ s}} \right)^{-2/3} 2 \times 10^{26} \text{ cm}^{-2}. \quad (5)
\]

The dominant source of opacity of hydrogenic matter to energetic gamma-rays is pair production. The cross-section per hydrogen atom, assuming complete screening and including pair production by the electrons, is \( 1.7 \times 10^{-26} \text{ cm}^2 \), essentially independent of energy for \( E_\gamma > 1 \) GeV and logarithmically less at lower energies where screening is less complete (Heitler 1954). The implied optical depth to escape of gamma-rays is

\[
\tau_{\text{pair}} \sim 3 \left( \frac{M_{cl}}{M_\odot} \right)^{1/3} \left( \frac{t}{5 \times 10^3 \text{ s}} \right)^{-2/3}. \quad (6)
\]

Energetic gamma-rays escape if \( M_{cl} < 0.03 \ M_\odot \). The proton interaction cross-section is only about twice that for absorption of the gamma-rays, but the gamma-rays may escape
for a wide range of cloud parameters and geometries because photons follow straight line paths while the protons may gyrate many times through a cloud of modest dimensions.

At photon energies below 50 MeV the Klein-Nishina cross-section exceeds that of pair production, and Compton scattering is the dominant source of opacity. The Compton optical depth is approximately

$$\tau_{Compt} \sim 4 \left( \frac{M_{pl}}{M_{\odot}} \right)^{1/3} \left( \frac{t}{5 \times 10^3 \text{ s}} \right)^{-2/3} \left( \frac{50 \text{ MeV}}{E_{\gamma}} \right)$$

(7)

for \( m_e c^2 \ll E_\gamma \), where the logarithmic factor has been taken as a constant.

The threshold energy \( \hbar \omega_{th} \) for \( \gamma-\gamma \) pair production by a gamma-ray of energy \( E_\gamma \) is

\( \hbar \omega_{th} = (m_e c^2)^2/E_\gamma \), and is 10 eV for \( E_\gamma = 25 \text{ GeV} \) and 2.6 KeV for \( E_\gamma = 100 \text{ MeV} \). The ultraviolet photon density will be very low in a cool dense cloud, so that even energetic gamma-rays will not be attenuated by this process. If the cloud becomes heated (by deposition and thermalization of the energy of the energetic nucleons) and is optically thick it will fill with a black body radiation field at a temperature \( T_{bb} \); if \( k_B T_{bb} > 0.1 \hbar \omega_{th} \) the optical depth for \( \gamma-\gamma \) pair production will typically become very large, and the most energetic gamma-rays will not escape. This will introduce an energy-dependent cutoff, with only gamma-rays satisfying the condition

$$E_\gamma < 0.1 \frac{(m_e c^2)^2}{k_B T_{bb}}$$

(8)

escaping. This cutoff will also vary as the thermal radiation field changes. There is thus a transparency window for gamma-rays between attenuation by \( \gamma-\gamma \) pair production at high energies (8) and attenuation by Compton scattering at low energies (7).

3. The Cloud

The model proposed here depends on the existence of a dense cloud near the source of energetic particles. The required density is so high that the cloud cannot be interstellar, and must be associated with the source of the GRB. If we accept the hypothesis (Eichler,
et al. 1989) that GRB have their origin in the coalescence of two orbiting compact objects, we should look to the earlier stages of that coalescence as the source of the required matter. Degenerate dwarfs and nondegenerate stars are not possible sources because the mass-radius relations of these objects imply that as they lose mass their densities decrease and their orbital periods increase; the mass-losing star would only erode slowly until it disappeared. Accelerating orbital evolution culminating in the cataclysmic gravitational radiation-driven coalescence required to make a GRB will occur only if the coalescing objects are neutron stars or black holes.

The simplest explanation of the cloud is that it is the remains of an extended envelope around an inspiraling neutron star (a structure analogous to that of a red supergiant star, though perhaps smaller and less massive). Models of such objects were calculated by Thorne and Żytkow (1977). I use their calculated static structures to describe envelopes undergoing dynamic stripping. The characteristic inspiraling time for one neutron star orbiting in the envelope of another is

\[ t_{sp} \sim \left( \frac{M}{\rho a^3} \right) \left( \frac{a^3}{2GM} \right)^{1/2}, \]  

where \( a \) is the separation between the two neutron stars, \( M \) is the mass of each, and \( \rho \) is the density of the envelope through which the intruder is passing. In the outer layers of the model envelopes \( \rho \sim 0.1M/a^3 \) and \( t_{sp} \) is of order the Keplerian orbit time of several years. However, at smaller \( a \) the calculated \( \rho \) is as small as \( 3 \times 10^{-17} M/a^3 \), and \( t_{sp} \) is much larger. For \( a < 10^{10} \) cm gravitational radiation (rather than hydrodynamic drag) is the dominant mechanism of angular momentum loss. The slowest stage of orbital evolution occurs when \( a \approx 10^{10} \) cm, and has a characteristic time of \( \sim 3 \times 10^{12} \) s for the 5 M_\odot model and \( \sim 2 \times 10^{11} \) s for the 12 M_\odot model of Thorne and Żytkow (1977). These estimates are crude, and the applicability of the static structures uncertain, but they indicate that rapid disruption of the outer stellar envelope is followed by a longer period of slow orbital decay before it is accelerated by gravitational radiation.
The expelled matter may flow through the outer Lagrange point to form an excretion
disk whose initial radius is about twice the envelope’s radius, or $\sim 10^{14}$ cm. This is
comparable to the light (or energetic particle) travel time size implied by the delayed
gamma-rays of the GRB of February 17, 1994, although the time scale may instead be
explained by Eq. (2). Matter which has escape velocity will reach distances $\sim 1$ pc by the
time the neutron stars coalesce, and will be too dilute and distant to have any effect. If
the disrupted envelope is massive the disk may be subject to self-gravitational instabilities,
whose result is incalculable; much of it may be lost. The fraction which must remain when
the GRB occurs is small, and the necessary survival time is only $\sim 10^2$–$10^3$ disk orbits (at $r \sim 10^{14}$ cm), so that it is likely to be there when needed.

Alternatively, it is possible that the slowest stage of orbital evolution only lasts $\sim 10^8$–
$10^9$ s because the disrupting envelope restructures itself and exerts more drag on the
inspiraling neutron star than implied by static models. In this case the cloud may be in
free expansion with $r \sim 10^{15}$ cm when the GRB occurs.

The actual geometry of the cloud must be complex. In order to observe the initial
GRB our line of sight must be transparent to soft gamma-rays. The time scales of the GRB
require a density closer to interstellar values than those discussed here. Yet a substantial
fraction of the fireball debris must intercept dense matter, or be captured on magnetic
field lines which enter it, in order to produce the delayed gamma-rays. Very heterogeneous
distributions are required, with a dense disk or clouds and low density regions elsewhere.
During the period of slow orbital evolution a dilute wind from the continuing disruption
of the inner envelope may blow a bubble inside the massive disrupted envelope, perhaps
out of the plane of the disk, with low enough density to permit formation of a “classical”
GRB with the observed duration.

4. Discussion

The energy radiated in delayed gamma-rays is not small compared to that in the
prompt GRB. The usual estimate of $10^{51}$ erg for a GRB at cosmological distances then implies a comparable energy collisionally deposited in the dense cloud by the relativistic particles. Such an event may qualitatively resemble a Type II supernova, aside from its gamma-radiation. The pre-outburst star would show evidence of rapid mass loss and might also be a binary X-ray source of short period (most of its evolution is spent with $a \sim 10^{10}$ cm and an orbital period $\sim 5$ minutes). Following the period of rapid mass loss the expanding envelope might resemble a planetary nebula, or fade to invisibility because of the absence of ultraviolet excitation. Continuing mass loss from the remains of the envelope might prevent the observation of these systems as binary pulsars, and therefore they might not be included in predictions of the frequency of neutron star coalescence.

The origin of a neutron star with an envelope is also speculative, but might be a quiet core collapse in an ordinary supergiant or the capture of an envelope by a naked neutron star in collision with a nondegenerate star. The latter process is plausible in dense galactic or globular cluster nuclei, in which binary evolution is often determined by close stellar encounters. Collisional capture is likely to be inefficient, leading to envelope masses $\ll M_\odot$.

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References


