ON THE NATURE OF NONTHERMAL RADIATION FROM COSMOLOGICAL $\gamma$-RAY BURSTERS

Vladimir V. Usov
Dept. of Physics, Weizmann Institute, Rehovot 76100, Israel

ABSTRACT

Relativistic electron-positron winds with strong magnetic fields are considered as a source of radiation for cosmological $\gamma$-ray bursters. Such a wind is generated by a millisecond pulsar with a very strong magnetic field. An electron-positron plasma near the pulsar is optically thick and in quasi-thermodynamic equilibrium. It is shown that the main part of radiation from the pulsar wind is nonthermal and generates in the following way. Kinetic energy which is released in the process of deceleration of the neutron star rotation transforms mainly to the magnetic field energy. The magnetic field is frozen in the outflowing plasma if the distance to the pulsar is smaller than $\sim 10^{13}$ cm. This field transfers the energy from the pulsar environment to the region outside the $\gamma$-ray photosphere of the electron-positron wind. At a distance of more than $\sim 10^{13}$ cm the magnetohydrodynamic approximation for the pulsar wind is broken, and intense electromagnetic waves are generated. The frequency of these waves is equal to the frequency of the pulsar rotation. Outflowing particles are accelerated in the field of intense electromagnetic waves to Lorentz factors of the order of $10^6$ and generate nonthermal synchro-Compton radiation. The typical energy of nonthermal photons is $\sim 1$ MeV. A high-energy tail of the $\gamma$-ray spectrum may be up to $\sim 10^4$ MeV. Baryonic matter is ejected occasionally from the pulsar magnetosphere. The baryonic matter ejection and subsequent suppression of the $\gamma$-ray emission may be responsible for the time structure of $\gamma$-ray bursts.

INTRODUCTION

The BATSE experiment on board the Compton Gamma Ray Observatory found that the $\gamma$-ray burst sources are distributed isotropically in the sky, and it sees the edge of the distribution\(^1\). These two facts can be naturally explained if $\gamma$-ray bursters are at cosmological distances\(^2\)\(^–\)\(^8\). Besides, there are other indications of a cosmological origin for $\gamma$-ray bursts (see ref. 7 and references therein).

A generic problem with a cosmological model is that the huge initial energy density implies a very large optical depth to electron-positron pairs, thermalization of the electron-positron plasma, and a blackbody spectrum with small modifications\(^9\),\(^10\). This is a clear conflict with the observed spectra of $\gamma$-ray bursts, which are well fitted either as power laws or as broken power laws\(^11\),\(^12\). It was suggested\(^13\),\(^14\) that a very strong magnetic field may be in the electron-positron plasma which flows away from the $\gamma$-ray burster. Here it is shown that outflowing particles may be accelerated outside the $\gamma$-ray photospheres of relativistic electron-positron winds with strong magnetic fields. These particles may be responsible for the nonthermal radiation of $\gamma$-ray bursts.

PARTICLE ACCELERATION AND $\gamma$-RAY EMISSION
Below, I assume that millisecond pulsars with extremely strong magnetic fields, \( B_s \approx \text{a few} \times 10^{15} \text{ G} \), are a cosmological source of \( \gamma \)-ray bursts\(^{13}\). In such a model the neutron star rotation is a source of energy for \( \gamma \)-ray bursts. The rotation of the magnetic neutron star decelerates because of the electromagnetic torque. The rate of kinetic energy loss for a supposedly nearly orthogonal magnetic dipole is\(^{15}\)

\[
- \frac{dE_{\text{kin}}}{dt} \simeq L_{\text{md}} = \frac{2}{3} \frac{B_s^2 R^6 \Omega^4}{c^3} \simeq 2 \times 10^{51} \left( \frac{B_s}{3 \times 10^{15} \text{ G}} \right)^2 \left( \frac{\Omega}{10^4 \text{ s}^{-1}} \right)^4 \text{ erg s}^{-1},
\]

where \( E_{\text{kin}} \) is the rotational kinetic energy, \( R \approx 10^6 \text{ cm} \) is the radius of the neutron star and \( \Omega \) is the angular velocity.

Like ordinary known pulsars, electron-positron pairs are created in the magnetosphere of a millisecond pulsar with a very strong magnetic field. The electron-positron plasma and radiation are in quasi-thermodynamical equilibrium in the environment of such a pulsar\(^{13}\).

The electron-positron plasma with strong magnetic fields flows away from the pulsar at relativistic speeds. During outflow, the electron-positron plasma accelerates and its density decreases. At a distance \( r_{\text{ph}} \) from the pulsar where the optical depth for the main part of photons is \( \tau_{\text{ph}} \approx 1 \), the radiation propagates freely. If we don’t take into account the magnetic field, the radius of the \( \gamma \)-ray photosphere for a spherical optically thick electron-positron wind is\(^{9}\)

\[
r_{\text{ph}} \approx \left( \frac{L_p}{4\pi \sigma T_0^4 \Gamma_{\text{ph}}^2} \right)^{1/2},
\]

where \( T_o \) is the temperature of electron-positron plasma at \( r \approx r_{\text{ph}} \) in the co-moving frame, \( \sigma = 5.67 \times 10^{-5} \text{ erg cm}^{-2} \text{ K}^{-4} \text{ s}^{-1} \) is the Stefan-Boltzmann constant and \( \Gamma_{\text{ph}} \) is the mean Lorentz factor of plasma particles at \( r \approx r_{\text{ph}} \).

Since \( \Gamma_{\text{ph}} \simeq r_{\text{ph}}/r_{lc} \) and \( T_o \approx 2 \times 10^8 \text{ K} \) (ref. 3), we have

\[
r_{\text{ph}} \simeq \left( \frac{L_p r_{lc}^2}{4\pi \sigma T_0^4} \right)^{1/4} \approx 3.5 \times 10^8 \alpha^{1/4} \left( \frac{B_s}{3 \times 10^{15} \text{ G}} \right)^{1/2} \left( \frac{\Omega}{10^4 \text{ s}^{-1}} \right)^{1/2} \text{ cm},
\]

\[
\Gamma_{\text{ph}} \approx 10^2 \alpha^{1/4} \left( \frac{B_s}{3 \times 10^{15} \text{ G}} \right)^{1/2} \left( \frac{\Omega}{10^4 \text{ s}^{-1}} \right)^{3/2},
\]

where \( r_{lc} = c/\Omega \) is the radius of the pulsar light cylinder.

At \( r < r_{\text{ph}} \) the optical depth increases sharply with decreasing \( r \). Therefore, any energy which is inherited by particles and radiation at a distance to the pulsar a few times smaller than \( r_{\text{ph}} \) will be thermalized before it is radiated at \( r \approx r_{\text{ph}} \).

The luminosity of the \( \gamma \)-ray photosphere is \( \alpha L_{\text{md}} \sim (0.01 - 0.1) L_{\text{md}} \). The temperature which corresponds to the blackbody-like radiation from the \( \gamma \)-ray photosphere is \( \sim 2\Gamma_{\text{ph}} T_0 \sim 10^{10} \text{ K} \), and the typical energy of \( \gamma \)-rays is \( \sim 1 \text{ MeV} \).

Kinetic energy which is released in the process of deceleration of the neutron star rotation transforms mainly to the magnetic field energy but not
to the energy of particles\textsuperscript{16,17}. The pulsar luminosity in magnetic fields is $(1 - \alpha)L_{\text{md}} \simeq L_{\text{md}}$. The strength of the magnetic field which is generated outside the pulsar light cylinder because of the neutron star rotation is

$$B \simeq B_s \left( \frac{R}{r_{lc}} \right)^3 \left( \frac{r_{lc}}{r} \right) \simeq 3.3 \times 10^{14} \frac{R}{r} \left( \frac{B_s}{3 \times 10^{15} \text{ G}} \right) \left( \frac{\Omega}{10^4 \text{ s}^{-1}} \right)^2 \text{ G}. \quad (5)$$

The magnetic field is frozen in the outflowing electron-positron plasma if the distance to the pulsar is not too large (see below). This field can transfer the energy from the pulsar environment to the region outside the $\gamma$-ray photosphere, $r > r_{\text{ph}}$, without its thermalization.

The magnetic field does not change qualitatively the motion of relativistic electron-positron wind inside the $\gamma$-ray photosphere. At $r \simeq r_{\text{ph}}$, the density of electrons and positrons drops sharply, and the particle acceleration because of the magnetic field may be essential.

Acceleration of particles in the pulsar wind at $r > r_{lc}$ is characterized by the following dimensionless parameter\textsuperscript{18}

$$\eta = \frac{\Omega^2 \Phi^2}{4 \pi f c^3}, \quad (6)$$

where

$$f = \rho v_r r^2, \quad \Phi = r^2 B_r, \quad \rho = n_\pm m, \quad (7)$$

$n_\pm$ is the laboratory frame number density, $m$ is the mass of electron, $v_r$ is the radial velocity and $B_r$ is the radial component of the magnetic field.

Continuity of the magnetic flux gives $\Phi = \text{constant}$. At the pulsar light cylinder, $r = r_{lc}$, we have $B_r \simeq B_s (R/r_{lc})^3$ and $\Phi \simeq B_s R^2 (\Omega R/c)$. Using this value of $\Phi$ and taking into account that $v_r \simeq c$ for relativistic flow, from equations (1), (6) and (7) we obtain

$$\eta \simeq \frac{L_{\text{md}}}{mc^2 \dot{N}_\pm}, \quad (8)$$

where $\dot{N}_\pm$ is the flux of electrons and positrons from the pulsar.

For the electron-positron wind the flux of particles at $r > r_{ph}$ is\textsuperscript{9}

$$\dot{N}_\pm \simeq \frac{4 \pi c r_{ph}^2 \Gamma_{ph}^2}{\sigma_T} \simeq 2 \times 10^{48} \alpha^{3/4} \left( \frac{B_s}{3 \times 10^{15} \text{ G}} \right)^{3/2} \left( \frac{\Omega}{10^4 \text{ s}^{-1}} \right)^{7/2} \text{ s}^{-1}, \quad (9)$$

where $\sigma_T = 6.65 \times 10^{-25}$ cm$^2$ is the Thomson cross section.

Equations (1), (8) and (9) yields:

$$\eta \simeq 10^9 \alpha^{-3/4} \left( \frac{B_s}{3 \times 10^{15} \text{ G}} \right)^{1/2} \left( \frac{\Omega}{10^4 \text{ s}^{-1}} \right)^{1/2}. \quad (10)$$

The density of electron-positron plasma at $r \simeq r_{ph}$

$$n_\pm = \frac{\dot{N}_\pm}{4 \pi c r_{ph}^2} \simeq 4 \times 10^{19} \alpha^{1/4} \left( \frac{B_s}{3 \times 10^{15} \text{ G}} \right)^{1/2} \left( \frac{\Omega}{10^4 \text{ s}^{-1}} \right)^{5/2} \text{ cm}^{-3} \quad (11)$$
is essentially higher than the critical value

\[ n_{cr} = \frac{\Omega B}{4\pi c e} \simeq 4 \times 10^{16} \frac{R}{r} \left( \frac{B_s}{3 \times 10^{15} \text{G}} \right) \left( \frac{\Omega}{10^4 \text{s}^{-1}} \right)^3 \text{cm}^{-3}. \]  

(12)

Therefore, the magnetic field is frozen in the plasma, and the magnetohydrodynamic (MHD) approximation can be used to describe the wind motion. In this approximation, particles may be accelerated to Lorentz factors of the order of \( \eta^{1/3} \) (ref. 18), which is an order of magnitude more than \( \Gamma_{ph} \). However, the \( \eta^{1/3} \) estimate of \( \Gamma \) is valid only if either the interaction between particles and photons is negligible or the mass density of radiation, \( \rho_\gamma = a T^4 / c^2 \), is smaller than the mass density of particles, \( \rho_\pm = n_\pm m \) (here \( a = 7.56 \times 10^{-15} \text{erg cm}^{-3} \text{K}^{-4} \) is radiation density constant). Near the \( \gamma \)-ray photosphere the density of radiation is very high, and the interaction between particles and radiation is strong. This interaction results in the increase of the mass density of accelerated matter. Substituting \( \rho_\gamma \) for \( \rho \) in equation (6), we have the following estimate for the Lorentz factor of accelerated particles near the \( \gamma \)-ray photosphere: \( \Gamma_m \simeq (\eta \rho_\pm / \rho_\gamma)^{1/3} \).

For \( B_s \simeq 3 \times 10^{15} \text{G}, \Omega \simeq 10^4 \text{s}^{-1}, T = T_0 \) and \( \alpha \simeq 0.01 - 0.1 \), we have \( \Gamma_m \sim \Gamma_{ph} \).

Hence, there is no essential acceleration of particles because of the magnetic field near the \( \gamma \)-ray photosphere in the MHD approximation. Therefore, the region of the pulsar wind near the \( \gamma \)-ray photosphere is not promising for a generation of strong nonthermal radiation.

With the distance from the pulsar the density of particles decreases in proportion to \( r^{-2} \). The critical density decreases somewhat slower (see equation (12)). At the distance

\[ r_{nth} \simeq 1.3 \times 10^{14} \alpha^{3/4} \left( \frac{B_s}{3 \times 10^{15} \text{G}} \right)^{1/2} \left( \frac{\Omega}{10^4 \text{s}^{-1}} \right)^{1/2} \text{cm} \]  

(13)

the plasma density, \( n_\pm \), is equal to the critical one, \( n_{cr} \). At \( r > r_{nth} \) the MHD approximation is broken for the pulsar wind with the magnetic field which alternates in polarity on the scalelength of \( \sim \pi (c / \Omega) \sim 10^7 \text{cm} \) (refs 18,19), and intense electromagnetic waves with the frequency of \( \Omega \) can propagate outside\(^{19,20}\).

In this case the process of particle acceleration changes qualitatively, namely: particles can be accelerated in this wind zone to Lorentz factors of the order of \( \eta^{2/3} \sim 10^6 \) (refs 21-23) in contrast to the \( \eta^{1/3} \) estimate given by the MHD theory. Particles are accelerated on the scalelength of \( \sim r_{nth} \) and generate synchro-Compton radiation. The radiative damping length for intense electromagnetic waves with the wavelength \( \lambda = 2\pi (c / \Omega) \) is\(^{23}\)

\[ l \simeq \frac{6}{\pi^4} \frac{c^3 \Omega^3}{r_0 n_\pm} \left( \frac{n_{cr}}{n_\pm} \right) \text{ wavelengths}, \]  

(14)

where \( r_0 = e^2 / mc^2 = 2.8 \times 10^{-13} \text{cm} \) is classical electron radius.

For a millisecond pulsar with a very strong magnetic field, \( B_s \simeq 3 \times 10^{15} \text{G}, \Omega \simeq 10^4 \text{s}^{-1} \) and \( \alpha \simeq 0.1 \), from equation (14) we have \( l \simeq 10^2 \lambda \simeq 2 \times 10^9 \text{cm} \ll r_{nth} \) at \( r \simeq 2r_{nth} \). Hence, at a distance of the order of \( r_{nth} \sim \text{...} \)
10^{13} \text{ cm} the energy of intense electromagnetic waves is transformed to both the energy of accelerated particles and the energy of nonthermal synchro-Compton radiation. The luminosity in accelerated particles at $r > r_{\text{nth}}$ is $mc^2 \Gamma N_x \approx mc^2 \eta^{2/3} N_x \approx \eta^{-1/3} L_{\text{md}} \sim 10^{-3} L_{\text{md}} \ll L_{\text{md}}$ (see equation (8)). Therefore, low-frequency intense electromagnetic waves have to be reradiated into nonthermal high-frequency emission with the luminosity up to $(1 - \alpha)L_{\text{md}} \approx L_{\text{md}}$. The typical energy of nonthermal photons, $\epsilon_\gamma \approx (\pi/4) \hbar \Omega \eta^2 \sim 1 \text{ MeV}$ (ref. 23), is suitable to be identified with the energy of breaks which are observed in the spectra of $\gamma$-ray bursts. A long high-energy tail of the $\gamma$-ray spectrum may be up to $\hbar (e B/mc) \eta^{4/3} \sim 10^4 \text{ MeV}$. A detailed study of the $\gamma$-ray spectrum of electron-positron winds with strong magnetic fields is beyond the framework of this paper and will be addressed elsewhere.

Until now, I have considered relativistic winds which consist of a pure electron-positron plasma. However, the luminosity of a very young neutron star is highly super-Eddington, and the ordinary baryonic matter has to flow away from the neutron star surface. A characteristic mass-loss rate is $\dot{\mathcal{M}} \sim 0.005 M_\odot \text{ s}^{-1}$ (refs 25, 26). Such a large mass-loss rate almost completely obscures any prompt electromagnetic display and certainly rules out the production by any model of $\gamma$-ray bursts situated at cosmological distances. Extremely strong magnetic fields in the pulsar magnetosphere can prevent the gas outflow from the neutron star surface threaded by closed magnetic field lines if the surface temperature is smaller than the value of $\sim (B_{lc}^2 / 8\pi a)^{1/4} \sim 1.5 \times 10^{10} (B_{lc}/10^{14} \text{ G})^{1/2} \text{ K}$ at which the density of radiation energy, $aT^4$, is equal to the density of magnetic field energy, $B_{lc}^2 / 8\pi$, at the pulsar light cylinder. For $B_s \sim 3 \times 10^{15} \text{ G}$, $\Omega \sim 10^4 \text{ s}^{-1}$ and $B_{lc} \sim B_s (R/r_{lc})^3 \sim 10^{14} \text{ G}$, this upper limit is a few times higher than the surface temperature of a neutron star which is formed from an accreting white dwarf. As to the polar caps near the magnetic poles, the gas outflow from the neutron star surface in these regions may be suppressed by the ram pressure of backward flux of particles (Usov, in preparation) which is predicted by all modern models of pulsars.

It is worth noting that baryonic matter may be ejected occasionally from the neutron star magnetosphere because of some kind of plasma instabilities (Usov, in preparation), and the $\gamma$-ray emission may be suppressed for some time. This process may be responsible for the time structure of $\gamma$-ray bursts. It is expected that the flux variations in nonthermal $\gamma$-rays is as short as

$$\tau_o \approx \frac{r_{\text{nth}}}{2c\Gamma^2} \approx \frac{r_{\text{nth}}}{2c\eta^{2/3}},$$

where $\Gamma$, the Lorentz factor of the outflowing plasma particles, is $\sim \eta^{1/3}$ at $r_{\text{ph}} \ll r < r_{\text{nth}}$. For a pulsar with $B_s \sim 3 \times 10^{15} \text{ G}$, $\Omega \sim 10^4 \text{ s}^{-1}$ and $\alpha \simeq 0.1$, from equations (10), (13) and (15) we have $\tau_o \approx 10^{-4} \text{ s}$.

The expansion energy of baryonic matter can be reconverted into non-thermal radiation when it interacts with an external medium. Another component of nonthermal radiation which may be observed in the burst spectra is annihilation lines. Positrons which are responsible for these lines can be produced by burst photons interacting with a medium surrounding a $\gamma$-ray burster.
CONCLUSIONS AND DISCUSSION

I have considered in this paper the radiation from relativistic electron-positron winds with strong magnetic fields. Such a wind is generated by a millisecond pulsar with a very strong magnetic field, and may be responsible for the radiation of cosmological γ-ray bursters. Electron-positron plasma near the pulsar is optically thick and in quasi-thermodynamic equilibrium. It is shown that the radiation of the pulsar wind consists of two components. One of them is thermal radiation with a blackbody-like spectrum. This radiation is emitted by the γ-ray photosphere of outflowing electron-positron plasma at the distance of the order of $10^8$ cm from the pulsar. The other component is nonthermal synchro-Compton radiation of very high energy particles which are accelerated at the distance of $\sim 10^{13}$ cm where the MHD approximation for the pulsar wind is broken and intense electromagnetic waves with the frequency of $\Omega$ can propagate. For this nonthermal radiation, the characteristic time of the γ-ray flux variations is as short as $\sim 10^{-4}$ s. Besides, an additional component of nonthermal radiation can be generated because of the interaction between baryonic matter which is ejected from the neutron star magnetosphere and an external medium. For this kind of nonthermal radiation the characteristic time of flux variations cannot be essentially smaller than one second.

The following correlation between two mentioned components of nonthermal radiation may be observed for long bursts. So, if fast variable synchro-Compton radiation from the electron-positron wind is suppressed by the baryonic matter ejection, then in a few seconds or more, a slow variable nonthermal radiation of Rees and Mészáros (ref. 27) can appear in the burst spectrum.

Most of the results in this paper are applicable for any compact fast-rotating object for which the rotation decelerates because of the electromagnetic torque and the rate of kinetic energy loss is high enough to explain the luminosities of cosmological γ-ray bursters. One of such an object may be differentially rotating disks which are formed by the merger of binaries consisting of either two neutron stars or a black hole and a neutron star. The strength of the magnetic field near the postmerger object may be as high as $\sim 10^{16} - 10^{17}$ G (ref. 10).

ACKNOWLEDGMENTS

I thank M. Milgrom for helpful conversations and M. Rees for many helpful suggestions that improved the final manuscript.

REFERENCES

1. C.A. Meegan et al., Ap. J. 355, 143 (1992).
2. V.V. Usov and G.V. Chibisov, Soviet Astr. 19, 155 (1975).
3. B. Paczyński, Ap. J. 308, L43 (1986).
4. B. Paczyński, Acta Astr. 41, 257 (1991).
5. T. Piran, Ap. J. 389, L45 (1992).
6. C.D. Dermer, Phys. Rev. Lett. 68, 1799 (1992).
7. W.A.D.T. Wickramasinghe et al, Ap. J. 411, L55 (1993).
8. P. Tamblyn and F. Melia, Ap. J. 417, L21 (1993).
9. B. Paczyński, Ap. J. 363, 218 (1990).
10. R. Narayan, B. Paczyński and T. Piran, Ap. J. 395, L83 (1992).
11. B.E. Schaefer et al., Ap. J. 393, L51 (1992).
12. D. Band et al., Ap. J. 413, 281 (1993).
13. V.V. Usov, Nature 357, 472 (1992).
14. C. Thompson and R.C. Dancan, Ap. J. 408, 194 (1993).
15. J.P. Ostriker and J.E. Gunn, Ap. J. 157, 1395 (1969).
16. M.A. Ruderman and P.G. Sutherland, Ap. J. 196, 51 (1975).
17. J. Arons, in Proc. Workshop "Plasma Astrophysics" (Varenna, Italy, 1981), p. 273.
18. F.C. Michel, Ap. J. 158, 727 (1969).
19. V.V. Usov, Astrophys. Space Sci. 32, 375 (1975).
20. E. Asseo, F.C. Kennel and R. Pellat, Astr. Astrophys 44, 31 (1975).
21. J.E. Gunn and J.P. Ostriker, Ap. J. 165, 523 (1971).
22. F.C. Michel, Ap. J. 284, 384 (1984).
23. E. Asseo, F.C. Kennel and R. Pellat, Astr. Astrophys 65, 401 (1978).
24. A. Shemi and T. Piran, Ap. J. 365, L55 (1990).
25. S.E. Woosley and E. Baron, Ap. J. 391, 228 (1992).
26. A. Levinson and D. Eichler, Preprint , (1992).
27. M.J. Rees and P. Mészáros, MNRAS 258, 41P (1992).
28. P. Mészáros and M.J. Rees, Ap. J. 405, 278 (1993).
29. J. Katz, Ap. J. , (in press).
30. H.S. Fencl, R.N. Boyd and D.H. Hartmann, Ap. J. 407, L21 (1993).