

Polarization in Gamma-Ray Bursts Produced by Pinch Discharge *

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Abstract Large-voltage, high-temperature plasma columns produced by pinch discharge can generate γ -ray flashes with energy spectra and spectral evolution consistent with what are observed in γ -ray bursts (GRBs), and the inverse Compton scattering (ICS) during the discharge process can produce high linear polarization. Our calculation indicates that the observed polarization depends on the angle between the line-of-sight to the GRB and the direction of the pinch discharge, but only weakly depends on observed γ -ray energy.

Key words: gamma-ray: bursts — radiation mechanism: non-thermal — polarization

1 INTRODUCTION

Coburn & Boggs (2003) reported their analysis of GRB 021206 observed with the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI). They found that a high degree, $(80 \pm 20)\%$, of linear polarization is present in the prompt emission in 25–2000 keV. However, due to the limited signal to noise ratio of the data, Rutledge & Fox (2004) concluded a null polarization and Wigger et al. (2004) obtained a linear polarization degree of $(41_{-44}^{+57})\%$ from the same data. Here, the study on polarization is important for understanding the production mechanism of GRBs, though the detection is still uncertain at the present stage. It is expected that more reliable measurements of GRB polarization in future may give a strong constraint on the different GRB models.

Based on the fireball model, some theoretical considerations have been carried out to explain the possible polarization. Lyutikov et al. (2003) argued that large scale ordered magnetic fields produced at the central source may produce highly polarized GRB prompt emission. The calculation demands the magnetic field in the emission region to be dominated by the toroidal

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field and is concentrated in a thin shell near the surface of the shell expanding with the Lorentz factor, and the synchrotron emission is produced by an isotropic population of relativistic electrons with a power law distribution of energy. Strong polarization might arise in a jet when the line-of-sight to the GRB is close to the jet edge (Medvedev & Loeb 1999; Gruzinov 1999; Waxman 2003). In this case, the polarization signal may be not averaged out. Dar & De Rujula (2003) and Eichler & Levinson (2003) examined polarization as a characteristic signature of inverse Compton up-scatter. Lazzati et al. (2003) considered Compton drag as a mechanism for high linear polarization. In such a scenario, relativistic electrons are contained in a fireball, and the shape of the soft photon field is selected in order to reproduce the GRB spectrum.

We have proposed an electrical discharge model of GRBs (Li & Wu 1997): large-voltage and high-temperature pinch plasma columns produced by disruptive electrical discharges can generate γ -ray flashes with energy spectra and spectral evolution characters consistent with what are observed in GRBs. In this paper we show that the pinch discharge process can naturally produce a high polarization.

2 DISCHARGE MODEL

Alfvén (1981) stressed the importance of electric currents in plasmas to the understanding of phenomena occurring in the magnetosphere through galactic dimensions. A current flowing in the plasma may contract by magnetic confinement and form a plasma cable with a much larger density than the surroundings. He held that many of the explosive events observed in cosmic physics are produced by disruptive discharges of electric double layers in current cables. A disruptive discharge will cause the plasma cable to pinch into a very narrow column by inward magnetic pressure of the discharge current (Krall & Trivelpiece 1973). The resulting compressed, large-voltage and high-temperature discharge column will radiate flaring energetic photons due to ICS (Inverse Compton Scattering) between the accelerated electrons and thermal photons, as sketched in Fig. 1.

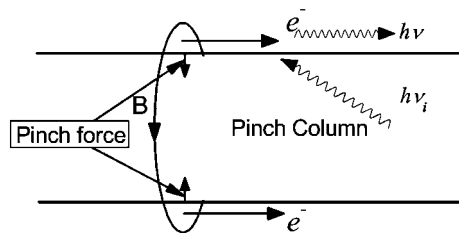


Fig. 1 Pinch discharge model of GRBs.

In an isotropic thermal emission with mean photon energy $\overline{h\nu}$, the mean energy of a scattered photon from an electron with energy $\epsilon = \gamma mc^2$ is $\overline{E} = \frac{4}{3}\gamma^2\overline{h\nu}$ (Ginzburg & Syrovatskii 1964). For a pinch discharge column with temperature $T = 10^6$ K, the mean photon energy $\overline{h\nu} \sim 230$ eV, then the mean energy of the scattered photons from electrons with $\gamma = 30$ ($\epsilon \sim 15$ MeV) will be $\overline{E} \sim 276$ keV. For a blackbody emission of 10^6 K, the photon density $n \approx 2 \times 10^{19} \text{ cm}^{-3}$, the Compton cross-section $\sigma_c \approx 6 \times 10^{-25} \text{ cm}^2$, so the electron free path $l_c = 1/n\sigma_c \approx 1$ km. A large voltage and high temperature discharge column with a length $l \gtrsim l_c$ should be an efficient radiator of hard X-rays and soft γ -rays.

Intense gamma-ray flashes of atmospheric origin observed by BATSE/*CGRO*, known as TGFs, are quite similar to GRBs in emission energy band and morphology. An evident correlation of TGFs with thunderstorm system (Fishman et al. 1994) and their features of energy dependence of time profiles (Feng et al. 2002) indicate that TGFs are produced by upward explosive electrical discharges at high altitude, giving observational evidence that the discharge process can produce high-energy explosive events. Before the burst the energy is supposed to be stored in an electric circuit with current I and inductance L as inductive energy $W = LI^2/2$. It has been realized that there is an atmospheric electrical global circuit, in which a current flows between the ionosphere and the earth with thunderstorms as a d.c. generator (see e.g. Markson & Muir 1980). Another kind of high-energy transients similar to GRBs is the solar hard X-ray flare. Alfvén & Carlqvist (1967) suggested exploding discharges of electric double layers to be responsible for solar flares. In their model, the energy release and particle acceleration of a flare are produced by the disruption discharge of a current of $10^{11} - 10^{12}$ A, flowing in a solar atmosphere circuit with a typical length $10^9 - 10^{10}$ cm and inductance ~ 10 H.

The pinch discharge scenario could account for the energy budget even for GRBs at cosmological distances. For the typical 10^{53} erg isotropic-equivalent output, collimation reduces the burst energy budget to $\sim 10^{49}$ erg. For a circuit with a radius of stellar dimension, we can expect its inductance $L \sim 10^2$ H, then the needed current $I \sim 10^{20}$ A. The required current circuit is possible in the astrophysical context (see e.g., Raadu 1989). Large-scale current circuits have been proposed both for the heliosphere and for the galaxy (Alfvén 1978). In the galactic case currents of $10^{17} - 10^{19}$ A have been estimated (Alfvén & Carlqvist 1978). Since the typical GRB photon energy is ~ 100 keV, $\sim 10^{56}$ photons must be scattered to lead to a GRB. The needed radius r and length l of the discharge column to produce $N_b = 10^{56}$ photons in $t_{\text{burst}} = 30$ s can be estimated by $2\pi r l f t_{\text{burst}} = N_b$, where f is the emission intensity of the black body with temperature kT (keV), $f = 5 \times 10^{32} (kT)^3 \text{ cm}^{-2} \text{ s}^{-1}$. Then the required column size $rl \sim 10^{21} / (kT)^3 \text{ cm}^2$. Bursts consisting of spiky components are produced by branching discharges, the size of each individual column can be much smaller.

The pinch discharge mechanism can naturally interpret many observed GRB characteristics (Li & Wu 1997; Li 1998). Complicated morphological patterns in GRBs, such as the wide variety of profile configurations, richly fluctuating or structurally smooth, rapid rise vs slower fall, weak precursor and secondary pulse, etc., are common in various electrical discharges. Producing energy spectra of smoothly-joining broken power law, so called the Band model to describe GRB spectra, is a general property of the discharge mechanism. The distribution feature of the low-energy power law slope α and peak energy E_{peak} from the discharge model is similar to what is observed in the GRBs. Spectral evolution features observed in GRBs, e.g. the hard-to-soft spectral evolution and time-resolved low-energy spectra over a pulse, can be reproduced by the discharge model. The typical energy dependence of GRB time profiles, the variability of hard emission which is earlier and narrower than that of soft emission, are characteristic of a disruptive discharge mechanism as well. We will show in the next section that the discharge mechanism can also naturally produce strongly polarized emission.

3 POLARIZATION

In a pinch discharge in plasma, the electric current is along the surface of the discharge column by the skin effect. The high-temperature pinched plasma is compressed within the column. In the following calculations we suppose the local surface of the pinch column can be seen as a plane, then the electric lines of force on it are parallel to each other.

Figure 2 illustrates the ICS process of a photon with incident energy $h\nu_i$ and a moving electron to produce a scattered photon with energy $h\nu$, where ψ_i and ψ are the angles of the incident and scattered photon with respect to the moving electron, and the scattering angle between the incident and scattered photons $\theta = \psi_i - \psi$. With the Lorentz transformations, the energy ratio between the incident and scattered photons in the electron rest frame (in primed notation) can be derived as

$$\frac{h\nu'_i}{h\nu'} = 1 + \frac{\gamma h\nu_i}{mc^2} (1 - \beta \cos \psi_i) \equiv \lambda(\psi', \theta', h\nu_i), \quad (1)$$

where β is the electron velocity in units of c , $\gamma = \sqrt{1 - \beta^2}$, and m the electron rest mass. We also used the relations $\psi_i = \arccos\left(\frac{\beta + \cos \psi'_i}{1 + \beta \cos \psi'_i}\right)$ and $\psi'_i = \theta' + \psi'$.

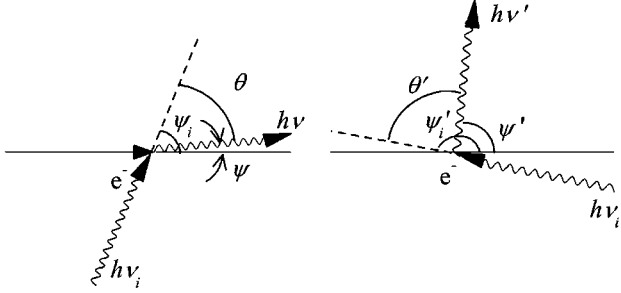


Fig. 2 Geometry for inverse Compton scattering. *Left panel:* in the lab system. *Right panel:* in the electron rest system.

At scattering angle θ' the polarization ξ of an ICS photon with incident energy $h'\nu_i$ can be expressed as Akhiezer & Berestetskii (1965),

$$\xi(\psi', \theta', h\nu_i) = \frac{\sin^2 \theta'}{\frac{h\nu'_i}{h\nu'} + \frac{h\nu'}{h\nu'_i} - \sin^2 \theta'} = \frac{\sin^2 \theta'}{\lambda + \lambda^{-1} - \sin^2 \theta'}. \quad (2)$$

The differential scattering cross-section in the electron rest system is (Klein & Nishina 1929)

$$\begin{aligned} \frac{d\sigma_T}{d\psi'} &\propto \left(\frac{h\nu'}{h\nu'_i}\right)^2 \left(\frac{h\nu'_i}{h\nu'} + \frac{h\nu'}{h\nu'_i} - \sin^2 \theta'\right) \sin \psi' \\ &= \lambda^{-2} (\lambda + \lambda^{-1} - \sin^2 \theta') \sin \psi' \\ &\equiv \mu(\psi', \theta', h\nu_i). \end{aligned} \quad (3)$$

For isotropic photons in the lab system, the number density of photons colliding with the moving electron at a certain incident angle ψ_i is

$$\frac{dN}{d\psi_i} \propto (1 - \beta \cos \psi_i) \sin \psi_i \equiv \eta(\psi', \theta'). \quad (4)$$

The polarization is a Lorentz invariant, we can calculate it in the electron rest frame. From ICS of photons with energy spectrum $p(h\nu_i)$ in the lab system, the average polarization $\bar{\xi}(\psi)$ of the scattered photons at a certain angle ψ can be calculated as

$$\bar{\xi}(\psi) = \bar{\xi}(\psi') = \frac{\int \xi(\psi', \theta', h\nu_i) \mu(\psi', \theta', h\nu_i) \eta(\psi', \theta') p(h\nu_i) d\theta' d(h\nu_i)}{\int \mu(\psi', \theta', h\nu_i) \eta(\psi', \theta') p(h\nu_i) d\theta' d(h\nu_i)}. \quad (5)$$

For different angles ψ of the observer's line-of-sight to the GRB with the discharge direction, we calculate the polarization for three blackbody photon energy distributions $p(h\nu_i)$ in the lab system, with $kT = 1, 5$ and 10 keV. For each temperature, the Lorentz factor γ of the moving electron is taken to be 10 and 50 , respectively. As the pinched high-temperature plasma is concentrated in the discharge column, the incident angles ψ of photon are restricted to the range $0 - \pi$. The results are shown in Fig. 3.

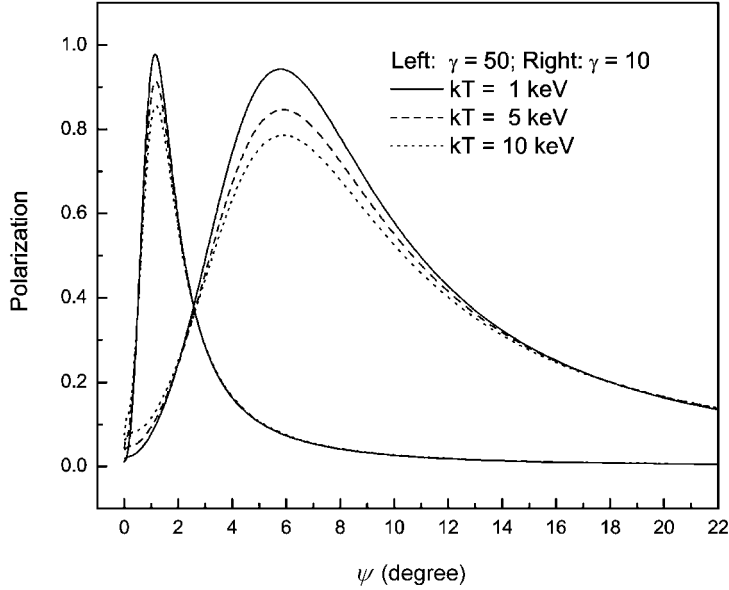


Fig. 3 Polarization vs. angle ψ of line-of-sight to the discharge direction for electron Lorentz factor $\gamma=10, 50$, and pinched plasma temperature $kT=1, 5$ and 10 keV, respectively. The calculation is for energy of scattered photons limited in the range $25-2500$ keV.

To see the expected relationship of polarization to GRB photon energy in the discharge mechanism, we calculate the polarization for different value of $h\nu$ with given γ , kT and ψ , the results are shown in Fig. 4.

From Figs. 3 and 4 we can see that a discharge column, shown in Fig. 2, can produce prompt γ -ray emission polarized in the direction perpendicular to the scattering plane, the observed amount of polarization depends on the kinetic energy of the moving electron, the temperature of the pinched plasma and the angle between the line-of-sight to the GRB and the direction of the discharge. It also depends on the observed γ -ray energy, but for $h\nu \geq 500$ keV the dependence is slight.

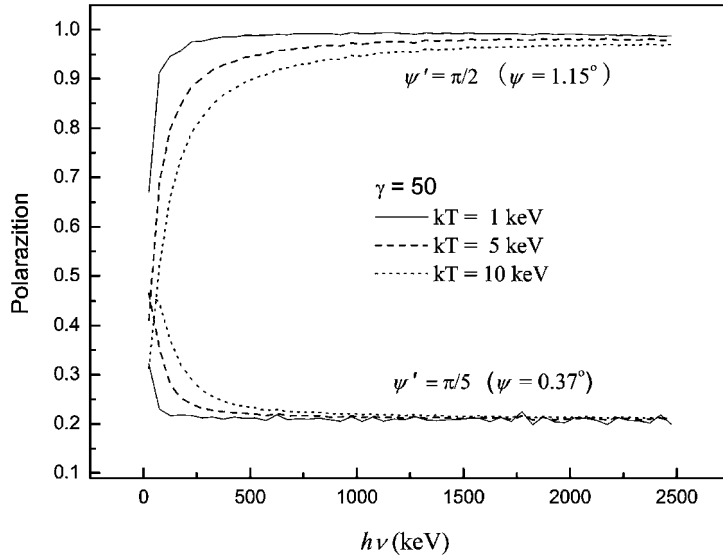


Fig. 4 Polarization vs. energy of scattered photon for electron Lorentz factor $\gamma = 50$ and for different scattered angles ($\psi' = \pi/2, \pi/5$) and pinched plasma temperatures ($kT = 1, 5$ and 10 keV).

4 DISCUSSION

During a discharge there is an energy released from the central engine and the pinched high-pressure and high-temperature plasma in its wake may produce a fireball and afterglow emission in the ambient medium. The geometry and environment of the discharge may influence the production of the fireball and afterglow. Different from fireball shock models, the location of the GRB prompt emission in the discharge model is in neither the internal shock nor external shock, but in the central engine itself. In comparison with the blast-wave model, the discharge mechanism provides a more clear postulate on the nature of the GRB prompt gamma-ray emission. The GRB producing mechanism in the scenario has no difficulty with the baryon contamination and compactness problem, and no difficulty with the synchrotron “line-of-death” (Preece et al. 1998) and cooling problem (Ghisellini et al. 2000) in the synchrotron model. There is no need to assume a globally organized strong magnetic field or other unusual configuration or bulk motion for fireballs, the pinch discharge itself can provide the necessary conditions of generating strongly polarized γ -ray emission: high-energy electrons and dense thermal photons for the ICS and the discharge column defining a preferential direction.

From Eq. (2) one can see that in the electron rest frame, at the scattered direction perpendicular to the incident one, $\theta' = \pi/2$, we have the polarization $\xi \simeq 1$ on condition that $h\nu' \simeq h\nu'_i \ll mc^2$. The above condition is usually satisfied by the thermal photons in a pinch discharge column. For isotropic photons in the lab frame, we calculate the number density $\frac{dN}{d\psi'_i}$ at an incident angle ψ'_i in the electron rest frame from Eq. (4) (noted that $\psi_i = \arccos\left(\frac{\beta + \cos\psi'_i}{1 + \beta \cos\psi'_i}\right)$) with Lorentz transformations for $\gamma = 10, 50$, and 100 , respectively, and show the result in Fig. 5. It also can be seen that in the electron rest frame most photons colliding with the electron are concentrated in a tapering half cone with axis along the discharge

direction. Therefore, high linear polarization can be observed if the observer is properly located with respect to the direction of the discharge.

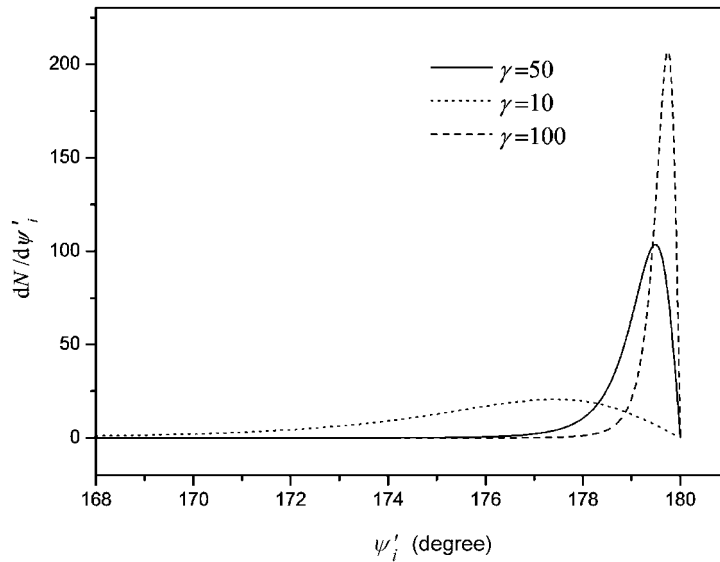


Fig. 5 Distribution of incident angles in the electron rest frame for isotropic photons in the lab frame.

As shown in Fig. 3, the polarization of observed GRBs depends on the angle ψ between the observer's line-of-sight and the axis of the pinch column, and can vary between zero and unity for a fixed γ of discharging electrons. With different observation angles different polarizations (from 0 to 1) can be found. The extreme circumstance is null polarization at the position with $\theta' = 0$. The angle ψ_{\max} where maximum polarization takes place varies with γ . Electrons moving along a discharge column are accelerated by the discharge voltage and the electron kinetic energy increases along the path. At a certain moment, the values of γ of the moving electrons should be distributed over a wide range, and hence high level of polarization can be observed over a considerable range, say several degrees, of the observation angle.

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