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Abstract. The emission mechanism and the origin and structure of magnetic fields in gamma-ray burst (GRB) jets are among the most important open questions concerning the nature of the central engine of GRBs. In spite of extensive observational efforts, these questions remain to be answered and are difficult or even impossible to infer with the spectral and lightcurve information currently collected. Polarization measurements will lead to unambiguous answers to several of these questions. Recent developments in X-ray and γ-ray polarimetry techniques have demonstrated a significant increase in sensitivity enabling several new mission concepts, e.g. *POET* (Polarimeters for Energetic Transients), providing wide field of view and broadband polarimetry measurements. If launched, missions of this kind would finally provide definitive measurements of GRB polarizations. We perform Monte Carlo simulations to derive the distribution of GRB polarizations in three emission models; the synchrotron model with a globally ordered magnetic field (SO model), the synchrotron model with a locally random magnetic field (SR model), and the Compton drag model (CD model). The results show that *POET*, or other polarimeters with similar capabilities, can constrain the GRB emission models by using the statistical properties of GRB polarizations. In particular, the ratio of the number of GRBs for which the polarization degrees can be measured to the number of GRBs that are detected (N_m/N_d) and the distributions of the polarization degrees (Π) can be used as the criteria. If $N_m/N_d > 30\%$ and Π is clustered between 0.2 and 0.7, the SO model will be favored. If instead $N_m/N_d < 15\%$, then the SR or CD model will be favored. If several events with $\Pi > 0.8$ are observed, then the CD model will be favored.

Keywords: γ-ray sources; γ-ray bursts; Radiation mechanisms; polarization
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INTRODUCTION

In spite of extensive observational and theoretical efforts, several key questions concerning the nature of the central engines of the relativistic jets and the jets themselves of gamma-ray bursts (GRBs) remain poorly understood. In fact, some of these questions are very diffi cult or even impossible to answer with the spectral and lightcurve information currently collected. On the other hand, polarization information, if retrieved, would lead to unambiguous answers to these questions. In particular, polarimetric observations of GRBs can address the following: (i) It is unclear whether a globally structured magnetic fi eld plays essential roles on the jet dynamics and the burst emission. (ii) It is unclear what is the most relevant emission mechanism; synchrotron, Comptonization, thermal emission, or else. (iii) The distribution of the jet opening angles and the observer's viewing angles, and the structure of the jet are not well understood.

Recently there has been an increasing interest in the measurement of X-ray and γ-ray polarization, and the observational techniques can now achieve signifi cant sensitivity in the relevant energy band. Several polarimetry mission concepts, such as *POET*, are being planned. The *POET* concept has two polarimeters, GRAPE (60-500 keV) and LEP (2-15 keV) both of which have wide fi elds of view. If launched, missions of this type would provide the fi rst defi nitive detection of the polarization of GRB prompt emission. This would enable the discussion of the statistical properties of the polarization degree and polarization spectra, which will give us diagnostic information on the emission mechanism of GRBs and the nature of the GRB jets that cannot be obtained from current spectra and

lightcurve observations.

So far it has been shown that similarly high levels of linear polarization can be obtained in several GRB prompt emission models; the synchrotron model with a globally ordered magnetic field, the synchrotron model with a small-scale random magnetic field [1, 2, 3], and the Compton drag model [4, 5]. Thus the detections of GRB prompt emission polarization would support these three models. In this paper, we show that these models can be distinguished by their statistical properties of observed polarizations. We performed detailed calculations of the distribution of polarization degrees by including realistic spectrum of GRB prompt emission and assuming realistic distributions of the physical parameters of GRB jets, and show that *POET*, or other polarimeters with similar capabilities, can constrain the GRB emission models. We use the limits of *POET* for GRB detection and polarization measurements as realistic and fiducial limits. For detailed descriptions of our theoretical calculations and the properties of *POET*, see [6, 7, 8].

THEORETICAL MODELS

We calculate the linear polarization for instantaneous emission from a thin spherical shell moving radially outward with a bulk Lorentz factor $\gamma \gg 1$ and an opening angle θ_j. The comoving-frame emissivity has the functional form of $j_{\nu'}^{\prime I} = A_0 f(\nu')\delta(t' - t_0')\delta(r' - r_0')$, where A_0 is the normalization which may depend on direction in the comoving frame and other physical quantities of the shell and $f(\nu')$ represents the spectral shape. A prime represents the physical quantities in the comoving frame. The delta functions describe the instantaneous emission at $t = t_0$ and $r = r_0$. The normalization, A_0, has units of erg cm^{-2} str^{-1} Hz^{-1}. Using the spherical coordinate system (r, θ, ϕ) in the lab frame, where $\theta = 0$ is the line of sight, we obtain the spectral fluence:

$$I_\nu = \frac{1+z}{d_L^2} \int d\phi \int d(\cos\theta) r_0^2 \frac{A_0 f(\nu')}{\gamma^2 (1 - \beta\cos\theta)^2}, \tag{1}$$

where z and d_L are the redshift and the luminosity distance of the source, respectively, and $\nu' = (1+z)\nu\gamma(1 - \beta\cos\theta)$. The integration is performed within the jet cone, so that it depends on the viewing angle θ_v, i.e., the angle between the jet axis and the line of sight. The corresponding Stokes parameters of the local emission (i.e., the emission from a given point on the shell) are given by $j_{\nu'}^{\prime Q} = j_{\nu'}^{\prime I}\Pi_0'\cos(2\chi')$ and $j_{\nu'}^{\prime U} = j_{\nu'}^{\prime I}\Pi_0'\sin(2\chi')$, where Π_0' and χ' are the polarization degree and position angle of the local emission measured in the comoving frame, respectively. The Stokes parameters of the emission from the whole shell can be obtained by integrating those of the local emission similarly to the intensity I_ν:

$$\left\{ \begin{array}{c} Q_\nu \\ U_\nu \end{array} \right\} = \frac{1+z}{d_L^2} \int d\phi \int d(\cos\theta) r_0^2 \frac{A_0 f(\nu')}{\gamma^2 (1 - \beta\cos\theta)^2} \Pi_0 \left\{ \begin{array}{c} \cos(2\chi) \\ \sin(2\chi) \end{array} \right\}. \tag{2}$$

The polarization degree is Lorentz invariant, i.e., $\Pi_0' = \Pi_0$. The position angle χ is calculated by taking account of the Lorentz transformation of the electromagnetic waves, and it is measured from a fixed direction, which we choose to be the direction from the line of sight to the jet axis. Then by calculating $\{I, Q, U\} = \int_{\nu_1}^{\nu_2} d\nu \{I_\nu, Q_\nu, U_\nu\}$, we obtain the time-averaged linear polarization in the given wavebands $[\nu_1, \nu_2]$:

$$\Pi = \frac{\sqrt{Q^2 + U^2}}{I}. \tag{3}$$

We consider synchrotron and Compton drag (CD) mechanisms for the GRB prompt emission. In the synchrotron case, the magnetic field consists of a globally ordered field, $\mathbf{B}_{ord}$, and small-scale random field, $\mathbf{B}_{rnd}$, i.e., $\mathbf{B} = \mathbf{B}_{ord} + \mathbf{B}_{rnd}$. The field $\mathbf{B}_{ord}$ may originate from the central engine, while $\mathbf{B}_{rnd}$ may be produced in the emission region itself. Here we consider two extreme cases; synchrotron model with an ordered field (SO), in which $B_{ord}^2 \gg \langle B_{rnd}^2 \rangle$, and a synchrotron model with a random field (SR), in which $B_{ord}^2 \ll \langle B_{rnd}^2 \rangle$. For the SO model, in particular, we assume a toroidal magnetic field. We give A_0, $f(\nu')$, Π_0, and χ as functions of (θ, ϕ) for each model, and calculate the linear polarization for given parameters γ, θ_j, θ_v, and z.

STATISTICAL PROPERTIES

In this section we show the results of our Monte Carlo simulation of the GRB prompt emission polarization. We generated 10,000 GRB jets with Lorents factor, γ, and opening angle, θ_j, and a random viewing angle for each
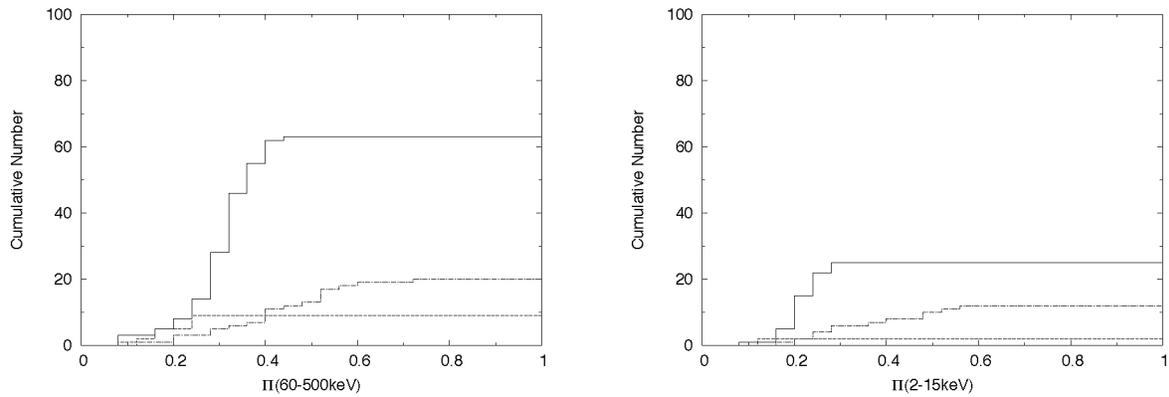
FIGURE 1. The cumulative distribution of Π that can be measured by GRAPE (*left*) and LEP (*right*) in the SO (*solid*), SR (*dashed*), and CD (*dot-dashed*) models in which the number of detectable bursts is 200. The adopted parameters are $\gamma = 100, q_1 = 0.5, q_2 = -2.0, \alpha = -0.2, \beta = 1.2$, and $T = 20$ s.

jet according to the probability distribution of $\sin\theta_v d\theta_v d\phi$. We give the values of the model parameters so that the observed fluences and peak energies of simulated bursts are consistent with the data obtained with the *HETE-2* satellite. The distributions of γ and θ_j for GRB jets are highly uncertain. We fi x $\gamma = 100$. We assume the distribution of θ_j as $f(\theta_j)d\theta_j \propto \theta_j^{q_1} d\theta_j$ for $0.001 \leq \theta_j \leq 0.02$ and $\propto \theta_j^{q_2} d\theta_j$ for $0.02 \leq \theta_j \leq 0.2$, where $q_1 = 0.5$ and $q_2 = -2.0$. We also fi x the values of low and high spectral indices of the burst, $\alpha = -0.2$ and $\beta = 1.2$ respectively, and the duration $T = 20$ s.

We calculate the linear polarization, Π, for each GRB jet to obtain the polarization distribution. We obtain the distribution of polarization that can be measured, by using the MDP (Minimum Detectable Polarization) values of *POET*. We interpret the simulated events with $\Pi > MDP$ as 'Π-measurable events'. Figure 1 shows the cumulative distribution of Π that can be measured by GRAPE and LEP in the SO, SR, and CD models. We have set the number of detectable events $N_d = 200$. In the SO model, the number of Π-measurable bursts is $N_m > 60$, and the cumulative distribution of measurable Π varies rapidly at $0.3 < \Pi < 0.4$ for the GRAPE band. In the SR model, $N_m < 10$, and the maximum polarization is $\Pi_{\max} < 0.4$, In the CD model, $N_m < 30$, and $\Pi_{\max} < 0.8$.

[6] derive more general conclusion for $\gamma \geq 100$, $q_1 \geq 0.5$, and $q_2 \geq -3.0$, taking account of realistic distributions of α and β. In conclusion, we can constrain the emission mechanism of GRBs by using the cumulative distribution obtained by GRAPE. If $N_m/N_d > 30\%$, the SR and CD models may be ruled out, and in this case if the measured polarizations are clustered at $0.2 < \Pi < 0.7$, the SO model will be favored. If $N_m/N_d < 15\%$, the SO model may be ruled out, but we cannot distinguish between the SR and CD models with different distributions of $(\gamma\theta_j)$, α, and β. If several bursts with $\Pi > 0.8$ are detected, however, the CD model which includes adequate number of small $(\gamma\theta_j)$ bursts will be favored.

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