CIRCULAR POLARIZATION FROM GAMMA-RAY BURST AFTERGLOWS

MAKOTO MATSUMIYA AND KUNIHITO IOKA

Department of Earth and Space Science, Graduate School of Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan; matumiya@vega.ess.sci.osaka-u.ac.jp, ioka@vega.ess.sci.osaka-u.ac.jp

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ABSTRACT

We investigate the circular polarization (CP) from gamma-ray burst (GRB) afterglows. We show that a tangled magnetic field cannot generate CP without an ordered field, because there is always an oppositely directed field, so that no handedness exists. This implies that the observation of CP could be a useful probe of an ordered field, which carries valuable information on the GRB central engine. By solving the transfer equation of polarized radiation, we find that the CP reaches 1% at radio frequencies and 0.01% at optical for the forward shock and 10%–1% at radio and 0.1%–0.01% at optical for the reverse shock.

Subject headings: gamma rays: bursts — gamma rays: theory — polarization — radiation mechanisms: nonthermal — shock waves

1. INTRODUCTION AND SUMMARY

Recently a very large linear polarization (LP), \( \sim 80\% \pm 20\% \), in the prompt gamma-ray emission of GRB 021206 was discovered (Coburn & Boggs 2003). The degree of LP was at the theoretical maximum of the synchrotron emission, which implies a uniform ordered magnetic field over the visible region (but see also Eichler & Levinson 2003 for the scattering origin of LP). Since the causally connected region is smaller than the visible one (Gruzinov & Waxman 1999), an ordered field could be advected from the central engine of the gamma-ray burst (GRB) and even drive the GRB explosion (Coburn & Boggs 2003; Lyutikov, Pariev, & Blandford 2003).

On the other hand, LP of \( \sim 10\% \) (typically a few percent) has been detected in the GRB afterglows (Covino et al. 2003 and references therein), which is attributed to synchrotron emission behind a shock (e.g., Mészáros 2002). In most popular models (Gruzinov 1999; Ghisellini & Lazzati 1999; Sari 1999; Rossi et al. 2002), the magnetic field is generated at the shock front and completely tangled (Medvedev & Loeb 1999). LP arises because of the geometric asymmetry provided by the afterglow jet observed off-axis if the magnetic fields parallel and perpendicular to the jet have different strengths. The gamma-ray LP mentioned above could be also explained in this model if the jet is very narrow (Waxman 2003; Nakar, Piran, & Waxman 2003; but see also Granot 2003).

Thus the present issue is whether an ordered magnetic field exists or not. If an ordered field exists in afterglows, its fraction to a tangled field carries valuable information on the GRB central engine. In this Letter, we show that observations of the circular polarization (CP) could be a useful probe of the ordered field. CP has been detected in active galactic nucleus jets (Wardle et al. 1998; Homan & Wardle 1999; Bower et al. 2002) and X-ray binaries (Fender et al. 2000, 2002) in recent years. Theoretically, these observations are explained by a plasma effect in synchrotron sources. We apply this theory to the GRBs for the first time.

There are two main mechanisms to generate CP: intrinsic CP of synchrotron emission (Legg & Westfold 1968) and Faraday conversion (FC) in sources. FC is a plasma effect that converts LP into CP (e.g., Jones & O’Dell 1977a, 1977b). These are treated all together by solving the transfer equation of polarized radiation in § 2. Then, we show that the tangled field cannot generate CP. Next, we estimate CP from GRB afterglows in the presence of an ordered field together with a tangled field in § 3. We find that if the ordered field is comparable to or more than the tangled one, the degree of CP is about 1% at radio frequencies and 0.01% at optical for the forward shock, and it reaches 10%–1% at radio and 0.1%–0.01% at optical for the (early) reverse shock. The radio CP of the reverse shock remains to be \( \sim 1\% \) even if the ordered field is weak (1% of the tangled one). CP in reverse shock radio emission of GRB 990123 has an upper limit of 37% at the 99.9% confidence level (Kulkarni et al. 1999; see also Finkelstein, Ipatov, & Gnedin 2002). Further observation of CP will be a diagnosis of the ordered field and bring clues to the nature of the GRBs.

2. TRANSFER EQUATION

We first consider the evolution of the Stokes parameters, \( I, Q, U, \) and \( V \) (in units of ergs \( s^{-1} \ cm^{-2} \ sr^{-1} \ Hz^{-1} \)), in a homogeneous plasma with a weakly anisotropic dielectric tensor (Sazonov & Tsytovich 1968; Sazonov 1969a, 1969b; Jones & O’Dell 1977a). It is described by the transfer equation of the polarized radiation,

\[
\frac{dI}{ds} + \kappa_I = \kappa_Q \cos 2\phi - \kappa_Q \sin 2\phi \\
\frac{dQ}{ds} + \kappa_Q \cos 2\phi = \kappa_Q \sin 2\phi \\
\frac{dU}{ds} + \kappa_U = \kappa_U \cos 2\phi - \kappa_U \sin 2\phi \\
\frac{dV}{ds} + \kappa_V = \kappa_V \cos 2\phi - \kappa_V \sin 2\phi
\]

where \( \phi = 0 \) is the azimuthal projection angle of the magnetic field on the plane perpendicular to the line of sight (see Fig. 1), \( \kappa_I, \kappa_Q, \kappa_U, \kappa_V \) are the absorptivity, \( \eta_I, \eta_Q, \eta_U, \eta_V \) are the emissivity, and \( \kappa^* \) and \( \kappa^* \) are rotativity and convertibility, respectively. These coefficients for a relativistic plasma with a power-law energy distribution have been derived by Sazonov (1969a, 1969b) for
The former is defined by \((\theta_{\text{ord}}, \varphi_{\text{ord}})\), while the latter is stochastic and describes as a function of \((\theta_{\text{nom}}, \varphi_{\text{nom}})\). The observer is in the direction of the axis \(\zeta\), which is specified by the angle \(\chi\) on the \(x\)-\(z\) plane. Right: It is convenient to take a new coordinate in order to deal with the radiation transfer. In this coordinate, the magnetic field direction is specified by \((\theta, \phi)\).

Fig. 1.—Magnetic field orientation in the shocked fluid frame. Left: The fluid flow is along the \(z\)-axis. We introduce the ordered and tangled magnetic field. The ordered field is characterized by the strength shown in Figure 1. The fluid moves. The ordered field is expected in the patchy model (Gruzinov & Waxman 1999), where the parameters \(\xi\) vanish as a result of the axisymmetry and reflection symmetry about the \(x\)-\(y\) plane. Therefore, the tangled field alone cannot generate CP. Intuitively this is because there is always an oppositely directed pair of magnetic fields, so that no handedness exists.

3. APPLICATIONS TO GRB AFTERGLOWS

First we consider the forward external shock with energy \(E\) propagating into a constant surrounding density \(n\). According to the standard afterglow model (Sari, Piran, & Narayan 1998), the Lorentz factor of the shocked fluid and the radius of the shock evolve as \(\gamma = (17E/1024\pi mn_c^2 t^3)^{1/8}\) and \(R = (17E/4\pi m_n c^2 t^4)^{1/4}\), respectively, where \(t\) is the observer time. The shell thickness in the shocked fluid frame can be estimated by \(R/\gamma\), which we use as the path length of the transfer equation (1). We assume that electrons are accelerated in the shock to a power-law distribution of Lorentz factor \(\gamma\). \(N(\gamma)\)d\(\gamma\) \(\propto \gamma^{-p} d\gamma\) for \(\gamma > \gamma_{\text{min}}\), where \(N(\gamma)\) is the electron number density in the shocked fluid frame and \(p > 2\). The minimum electron energy and the magnetic field strength in the shocked fluid frame are given by \(\gamma_{\text{min}} = \epsilon_e (p - 2)/(p - 1) (m_e/m_n)\gamma c\) and \(B = (32\pi m_e \epsilon_e n)^{1/2} / c\), respectively, where the parameters \(\epsilon_e\) and \(\epsilon_B\) are fractions of shock energy that go into the electrons and the magnetic energy, respectively. Thus we can calculate \(\gamma, \gamma_{\text{min}}, B, R/\gamma,\) and \(N_e\) as a function of \(t\) for given \(E, n, p, \epsilon_e,\) and \(\epsilon_B\). We adopt \(E = 10^{52}\) ergs, \(n = 1\) proton \(\text{cm}^{-3}\), \(p = 2.2, \epsilon_e = 0.1,\) and \(\epsilon_B = 0.01\) (Panaitescu & Kumar 2002). For simplicity, we temporally neglect the jet effects. The typical synchrotron frequency is \(\nu_s = eB^2 a_{\mu 2}/\gamma c^3\).
The perpendicular tangled component dominates the parallel one, i.e., $V_{\perp} = 0.2V_{\parallel}$. The suppression factor is given by $\xi = E_{\gamma}/(E_{\gamma} + E_{\parallel})$. The ordered field is directed to $\theta_{\text{ord}} = 0$. The perpendicular tangled component dominates the parallel one, i.e., $\xi = 0.1$. The observer is in the direction $\chi = \pi/4$ (see Fig. 1). For this configuration, $V < 0$. We adopt $E = 10^{52}$ ergs, $n = 1$ proton cm$^{-3}$, $p = 2.2$, $\epsilon_i = 0.1$, and $\epsilon_e = 0.01$.

$2\pi m_e c = 145\epsilon_p^{1/2} E_r^{1/2} T_{1/2}^{3/2}$ GHz, where the convention $Q = 10^2 Q_1$ is used except for $t_{\text{aw}} = t/1$ day. For $r > r_e$ and $v < v_e$, we use equations (C3)–(C10) in Jones & O’Dell (1977a) and equation (A1), respectively. We can estimate the self-absorption frequency from $\nu_{\text{sa}}(r/\gamma) = 1$ as $\nu_{\gamma} = 41\epsilon_e^{-1} (p/3)^{1/5} E_r^{4/5} n T_{1/5}^{3/5}$ GHz, where we put $\sin \theta = 1$. The flux is given by $F_p \propto t^{-2} p^{-4}$ with $\beta = 2$ and $\lambda$ for $r < r_e$ and $v < v_e$, respectively (Sari et al. 1998). We can neglect the electron cooling for our interests.

Figure 2 illustrates CP from a forward shock. The degree of CP is about 1% at the self-absorption frequency $\nu_{\gamma}$ and 0.01% at optical for $\chi \approx 1$. We have found that the dependence of CP on $t$ and $\xi$ is weak and the dependence on $\chi$, $\theta_{\text{ord}}$, $\phi_{\text{ord}}$, and $\chi$ is roughly proportional to $[\gamma(1 + \gamma)]^{1/2} \cos \theta_{\text{ord}}$, (see Fig. 1) for the relation between $\theta_{\text{ord}}$, $\phi_{\text{ord}}$, and $\chi$. The CP is due mainly to intrinsic emission.

Next we consider the reverse shock propagating the ejected shell itself (Mészáros & Rees 1997; Sari & Piran 1999b). Let $\gamma_{\Theta}$ and $T$ be an initial Lorentz factor of the shell and the burst duration, respectively. Then the Lorentz factor at the shock crossing time is given by $\gamma_{\Theta} = \min(\gamma_{\theta}, \gamma_{\text{def}})$. Let $\gamma_{\text{def}} = (3E_\gamma/2\pi m_p c T)^{1/4}$ be a critical Lorentz factor (Kobayashi 2000; Kobayashi & Zhang 2003; Zhang, Kobayashi, & Mészáros 2003; Sari & Piran 1999a, 1999b). The shock crossing time is given by $t_s = (\gamma_{\Theta}/\gamma_{\text{def}})^{1/3} T$. At $t = t_s$, the minimum electron energy, the magnetic field strength, and the electron number density in the shocked fluid are given by $\gamma_{\text{min}} = \epsilon_i [(p - 2)/(p - 1)] (m_p/\mu_n) \gamma_{\Theta}/\gamma_{\text{ord}}$, $B = (32\pi m_p e n)^{1/2} \gamma_{\text{ord}} c$, and $N_c = 4\gamma_{\text{ord}} n/\gamma_{\text{ord}}$, respectively. After the shock crossing, these quantities evolve approximately as $\gamma \propto t^{-7/16}$, $\gamma_{\text{min}} \propto t^{-13/48}$, $B \propto t^{-13/24}$, and $N_c \propto t^{-13/16}$, respectively (Kobayashi 2000; Kobayashi & Sari 2000). The shell thickness in the shocked fluid frame is $R/\gamma$, where $R = (17Et/4\pi m_p n c T)^{1/4}$.
cancellation takes place when $\theta_{\text{ord}} = 0$ or $\pi$. Even when the cancellation occurs, e.g., in the case of $\theta_{\text{ord}} = \pi/2$, some amount of CP remains if the visible region has an asymmetry due to the jet geometry, as in the case of LP.

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APPENDIX A

TRANSFER COEFFICIENTS

We summarize the transfer coefficients in equation (1) at an angle $\theta$ to the magnetic field $B$ (Sazonov 1969a, 1969b; Sazonov & Tsytovich 1968). In this section we measure all quantities in the shocked fluid frame. We assume that the electron number density in the interval of the Lorentz factor $d\gamma_c$ is power-law $dN_c = N_c(\gamma_c) d\gamma_c = \tilde{N}_c \gamma_c^{-\eta} d\gamma_c$ for $\gamma_{\text{min}} \leq \gamma_c < p > 2$. At frequencies $\nu_{\text{min}} \equiv \gamma_{\text{min}}^\eta \ll \nu$, the coefficients are given in equations (C3)–(C10) of Jones & O’Dell (1977a). [But we use the different value of $\kappa^{\nu}_{\perp \perp} = (\alpha + 3/2)/4$. The appropriate integration of eq. (9) in Sazonov (1969a) gives the above value.] For the frequency region, $\nu \ll \nu_{\text{min}}$, the analogous representations have not been derived yet. Such a frequency region becomes important in the application to the forward shock of GRB afterglow. In this case, we obtain the following expressions:

$$
\eta_c = \eta_{\min}(\nu / \nu_{\min})^{3/5} \gamma_{\text{min}}^{-2a - 2/3}, \quad \eta_{\perp} = \frac{1}{2} \eta_c, \quad \eta_v = -\eta_{\min}^{1/2} \gamma_{\text{min}}^{-2a - 1} \cot \theta,$$

$$
\kappa_c = \kappa_{\min} \gamma_{\text{min}}^{-4/5} \gamma_{\text{min}}^{-2a - 3/5}, \quad \kappa_{\perp} = \frac{1}{2} \kappa_c, \quad \kappa_v = \kappa_{\min}^{1/2} \gamma_{\text{min}}^{-2a + 1} \cot \theta,$$

$$
\kappa_{\nu}^{\nu_{\perp \perp}} = \kappa_{\min}^{1/2} \gamma_{\text{min}}^{-3/5} \gamma_{\text{min}}^{-2a - 3/5}, \quad \kappa_{\nu}^{\nu_{\perp \parallel}} = \kappa_{\min}^{1/2} \gamma_{\text{min}}^{-2a - 1} (\ln \gamma_{\text{min}}^{\eta_{\min}}) \cot \theta.
$$

(A1)

where $\nu \equiv |e|B \sin \theta/2\pi m_e c$, $\eta_{\min} = (e^2/c) \tilde{N}_c \gamma_{\text{min}}$, $\kappa_{\min} = (e^2/m_e c) \tilde{N}_c / \gamma_{\text{min}}$, $\alpha \equiv (p - 1)/2$, and $\gamma_{\text{min}} = 3^{19/2}/(\alpha + 3/2) \Gamma(2/3)/2(\alpha + 5/6)$, $\kappa_{\nu}^{\nu_{\perp \parallel}} = \pi(\alpha + 3/2) / \Gamma(2/3)/2(\alpha + 5/6)$, $\kappa_{\nu}^{\nu_{\perp \perp}} = \pi(\alpha + 3/2) / \Gamma(2/3)/2(\alpha + 5/6)$. Note that the intrinsic LP $(\eta_c/\eta_v)$ in this frequency region is not $(p + 1)/(p + 7/3) \approx 70\%$ but $50\%$. In GRB 021206, considerable photons are below the break energy, i.e., $\nu \ll \nu_{\text{min}}$ (Coburn & Boggs 2003), so that even an ordered field might not explain the observed LP $\approx 80\% \pm 20\%$.

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