1. INTRODUCTION

It is easy to imagine that gamma-ray burst (GRB) fireballs, which are apparently baryon-pure, pass through a “birth canal” ensheathed by an optically thick wall of baryons while the fireballs are still within their compact scales. The collimation of the fireball into jets, as is now almost universally thought to occur, can be understood as the collimating effects of such a sheath (Levinson & Eichler 2000). The puzzling problem of baryon purity can be understood if one invokes an event horizon that prevents baryons, but not energy, from escaping along the magnetic field lines that thread it (Levinson & Eichler 1993). However, since the black hole must be fed matter to power the GRB, matter that is heated on its way in would also power a baryon-rich wind, which would ensheneathe the baryon-pure jet (BPJ). The association of GRBs with supernovae suggests that they take place inside a host star, and then the matter in the host star could in any event play the role of the sheath.

The BPJ that emanates along horizon-threading field lines can pick up neutrons that drift in from the sheath (Eichler & Levinson 1999). It has been recently argued (Levinson & Eichler 2003) that such neutrons would be converted by collisions to a roughly equal mixture of neutrons and protons before penetrating too far into the BPJ. This collisional avalanche is the basic pickup mechanism, although it needs to be jump-started (if by nothing else) by a small number of decaying neutrons.

An optically thick but geometrically thin viscous boundary layer develops between the baryon-poor and baryon-rich regions. It is dragged along by neutron-dominated viscosity to a Lorentz factor that can vary extremely rapidly with distance inward from the outer wall of baryons. Because the neutrons are coupled by collisions to the protons, which are trapped on given field lines, the neutrons cannot freely stream (fs) into the inner part of the BPJ until their density drops to below a value given by

\[ n_{fs} \Gamma_{fs}^2 < \sigma v > R/c \leq 1; \]  

(1)

\( \Gamma_{fs} \) is determined self-consistently by the loading condition \( c \Gamma_{fs} n_{fs} h \sim F \), where \( h \) is the enthalpy per baryon and \( F \) is the flux of the outflow. The value for \( n_{fs} \) so obtained yields a value for \( \Gamma_{fs} \) of

\[ \Gamma_{fs} = L/\eta_{fs} mc^2 \pi \theta^2 \tau^2 c h = \frac{26 c_{fs}^{1/3} L_{50}^{1/3} \theta^{-2/3} h^{-1/3}}{1}, \]  

(2)

where \( c_{fs} = R/10^{12} \) cm, \( L_{40} = L/10^{50} \) ergs s\(^{-1}\), and \( h \) is the specific enthalpy in units of the proton rest energy. The quantity \( \Gamma_{fs} \) so derived represents a plausible estimate of the Lorentz factor of the photosphere, \( \Gamma_{ph} \), although not completely reliable. Photons have a somewhat shorter mean free path than relativistic neutrons, so their free-streaming boundaries are not identical. On the other hand, radiation drag can slow down the matter to Lorentz factors less than the estimate for \( \Gamma_{fs} \).

The qualitative picture that emerges is that a sharp transverse density contrast is established by the pickup of neutrons that leak in from the walls of the BPJ. The innermost optical depth of the baryon-enriched viscous transition layer (i.e., the inner photosphere) can be moving relativistically \( \Gamma_{fs} \gg 1 \). This is what we hypothesize. Photons that are generated in the BPJ interior can scatter off this relativistic sheath and be scattered by an angle \( 1/\Gamma_{fs} \) from the velocity vector of the sheath. If the angle \( 1/\Gamma_{fs} \) is larger than the opening angle \( \theta \), of the velocity cone of the sheath, then the solid angle over which the GRB becomes viewable is about \( \pi/\Gamma_{fs}^2 \). Otherwise, it is defined by an annulus \( \theta_0 \) with thickness \( 1/\Gamma_{fs} \).

Below we consider the consequences for polarization of a significant fraction of the photons emitted in the BPJ scattering of the baryon-enriched sheath. We make the reasonable assumption that, at sufficiently large radius, the photon mean free path can be large compared to the scale of the density scale height. This follows naturally if there is transverse density stratification: the inner tenuous high-\( \Gamma \) regions become transparent at smaller radii (Eichler & Levinson 2000) than the outer regions, which are more heavily baryon-enriched. As illustrated in Figure 1, the radius of the inner photosphere is thus an increasing function of transverse distance from the axis. A photon emitted in an optically thin region near the axis (at point A) could scatter off the photosphere at a point (B) that is at larger radius from the source and larger cylindrical radius from the axis than point A. Given that the photon mean free path is large, a scatterer close to the photosphere sees a highly anisotropic bath of photons, and this allows for polarization via scattering.

Although we have in our earlier work argued (for other motivations) for the particular geometry in which the soft photon source is ensheneathed by the scatterer, we note that, for the
purposes of polarization, the scattering geometry proposed by Lazzati et al. (2000), in which the scatterer is within a surrounding soft photon bath, would work just as well (although the implications for time variability of the polarized component might be different). We also note that Begelman & Sikora (1987) many years ago proposed the same mechanism for polarization of blazar emission (see also Dermer & Schlickeiser 1993). Our polarization calculations, as far as we can tell, agree with theirs. Here we also calculate the likelihood that a previously unidentified source would display a particular polarization for a homogenous distribution of sources.

2. POLARIZATION BY SCATTERING

In the geometry illustrated in Figure 1, which is but one of several variations, slight collimation of the BPJ is portrayed, and the opening angle of the scattered photons is larger than the final opening angle of the BPJ. The collimation could be stronger than indicated in the figure, and then most of the photons emitted by the BPJ, no matter how strongly beamed forward, would be intercepted by the walls before escaping. Alternatively, the opening angle of the scattered photons could be less than the opening angle of the velocity cone of the photosphere, and in this case the scattered photons form an annulus. We do not need to assume that most photons are scattered off the sheath, only that most photons in the observer’s direction are.

Consider a fluid element A just axisward of the photosphere as in Figure 1. Half of its photons are beamed outward relative to the local direction of the outflow. They enter the denser viscous transition layer and are scattered in fluid element B, which is by assumption near the photosphere. Assuming that \( \Gamma \) varies very rapidly through the value of \( \Gamma_{\infty} \) then in the frame of B, they are moving nearly in the direction of the outflow itself and scatter off B after a rear approach. Alternatively, if they enter element B from most other directions (as seen in the lab frame), then in the frame of B they are moving nearly opposite to B’s motion (referred to by Begelman & Sikora 1987 as the head-on approximation). If they now scatter off an electron in element B, the polarized emissivity as a function of angle \( \psi_{\infty} \) in frame B satisfies, in the limit of a perfect photon beam, \( j_{\psi_{\infty}}(\psi_{\infty}) \propto 1 - \cos^2 \psi_{\infty} \), and the total intensity \( j_{\psi_{\infty}}(\psi_{\infty}) \propto 1 + \cos^2 \psi_{\infty} \). By the aberration relation of \( \cos \psi \) to \( \cos \psi_{\infty} \), they can also be expressed as a function \( \psi \) in the lab frame (assuming a power-law spectrum for the scattered photons):

\[
I_{\psi}(\psi) \propto \frac{(1 - \beta \cos \psi)^2 - (\cos \psi - \beta)^2}{\Gamma^4(1 - \beta \cos \psi)^{k+2}},
\]

(3)

\[
I_{\psi}(\psi) \propto \frac{(1 - \beta \cos \psi)^2 + (\cos \psi - \beta)^2}{\Gamma^4(1 - \beta \cos \psi)^{k+2}}.
\]

(4)

Here \( \cos \psi = \hat{n} \cdot \hat{\beta} \), where \( \hat{n} \) and \( \hat{\beta} \) are unit vectors along the line of sight and in the direction of fluid element B, respectively, and the index \( k \) depends on the spectral index of the scattered radiation and the kinematics of the scattering region. For a spectral index of \( \alpha, k = \alpha + 2 \) if the center of emissivity is stationary with respect to the observer (e.g., a continuous jet) and \( k = \alpha + 3 \) if the center of emissivity moves with velocity \( \beta c \) (e.g., a discrete blob; see Lind & Blandford 1985). Typically \( k \) lies in the range 2.5–3.5. Below we adopt \( k = 3 \) for illustration. We suppose that all scatterers are moving on a cone of opening angle \( \theta_{\infty} \). Choosing a local coordinate frame such that \( \hat{n} = \sin \phi x + \cos \phi y \), and \( \hat{\beta} = \sin \phi \vec{x} + \sin \phi \vec{y} + \cos \phi \vec{z} \), and defining \( \hat{t} = \hat{n} \times \hat{\beta}/|\hat{n} \times \hat{\beta}| \), and \( \hat{b} = \cos \phi \hat{x} - \sin \phi \hat{z} \) (\( \hat{t} \) is a unit vector normal to the velocity vector as projected on the plane of the sky, and \( \hat{b} \) defines the axis of symmetry on the plane of the sky), the Stokes parameters for a given sight line integrated over all scatterers directions can be expressed as

\[
Q(\theta) = \int I_{\psi}(\psi) \cos(2\chi)d\phi.
\]

(5)

\[
I(\theta) = \int I_{\psi}(\psi)d\phi.
\]

(6)

where \( \cos \chi = \hat{t} \cdot \hat{b} \). (The Stokes parameter \( U \) vanishes for the above choice of coordinate system.) The corresponding polarization degree is given by

\[
P(\theta) = |Q(\theta)|/I(\theta).
\]

(7)

Equations (5) and (6) have been integrated numerically. Figure 2 shows the resultant polarization degree versus \( \Gamma(\sin \theta_{\infty} - \sin \theta) \) for different values of \( \Gamma\theta_{\infty} \). As seen, large polarization can be observed in the case of viewing from outside a narrow velocity cone (that is, \( \Gamma\theta_{\infty} \ll 1 \)) for viewing angles \( \theta \approx 1/\Gamma \). For this case, the polarization is always in the same direction, and, if the velocity vector of the scattering material were to wobble or be spread by less than \( \theta \), there would still be a net polarization.

If, however, most GRBs are viewed from an annulus at angular inset \( \theta_{\infty} \ll \theta_{\infty} \) from a cone of opening angle \( \theta_{\infty} \), then the observed polarization would typically be smaller. The relative probabilities are plotted in Figure 3 both for a narrow beam with spread \( 1/\Gamma\theta_{\infty} \) and a thin inset annulus for homogeneous distribution. In the case of viewing from within the thin inset
degree of polarization reported by the original discovery paper
this particular burst, a reasonable explanation for the high de-
the observer's line of sight.
The polarization in the inner bump of the $P$ curves (around $\theta = \theta_0$) is parallel
to the projection of the jet axis on the sky.

If the primary emitter does not have large $\Gamma$ relative to the
scattering material, then the photons can enter the latter neither
from a parallel, overtaking direction (i.e., from behind) nor
from the antiparallel direction, but, rather, offset by a small
angle from the parallel direction. In this case, the direction of
total polarization is beamed forward and strong polarization
can take place with less of a sacrifice of intensity.

3. DISCUSSION

In independent earlier work (Nakamura 1998; Eichler & Lev-
inson 1999), it was noted that GRB 980425, thought to be
associated with SN 1998bw, had an unusual light curve. The
lack of multiple peaks and the relatively soft spectrum were
suggestive of a scattered component, where the spikiness of the
typical GRB light curve could be washed out by multipath scattering into the observer’s line of sight. The extremely
small gamma-ray luminosity implied by the association with
the relatively nearby SN 1998bw is also consistent with the
hypothesis that it was scattered off some sort of baryonic
sheath. Finally, the unusually large ejection velocity observed
in the supernova remnant may suggest that it was “dragged”
by the GRB fireball, possibly by the interaction of high-energy
neutrinos from the BPJ with the surrounding baryonic material.

GRB 021206, on the other hand, was bright, had a typical
light curve containing several peaks, and substantial emission
above 1 MeV. There is no particular a priori reason to suspect scattering off slowly moving material. However, scattering off a relativistic sheath could preserve hardness and spikiness; the photon energy in the frame of the scatterer is still in the Thompson limit, and the relativistic beaming consolidates the area on
the scattering surface that is capable of scattering photons into
the observer’s line of sight.

Synchrotron emission in an ordered magnetic field is, for
this particular burst, a reasonable explanation for the high de-
gree of polarization reported by the original discovery paper
(2003). It was also argued by CB that scattering would imply high angular dilution and a small optical depth, both of which would considerably raise the overall energy requirement of the (already bright) GRB 021206. Nevertheless, we consider the polarization mechanism in view of the following points: First, invoking a relativistic flow for the scattering material (relative to the emitter) perpendicular to the density gradient eliminates the two objections of CB. Relativistic beaming of the scattered radiation allows it to remain collimated. That the incident photons as seen by the scattering material arrive from a direction nearly perpendicular to the density gradient implies that they penetrate the density contours of the scattering material at a very glancing angle $\sim 1/\Gamma_{\text{esc}}$ and always interact at very low optical depth along the shortest path out. In the directions corresponding to strong polarization, i.e., 90° scattering—nearly along the density gradient—there is negligible attenuation by a second scattering despite the high optical depth to a first scattering. That we have ignored the opacity encountered by the scattered radiation on its way out of the scattering material suggests that we may have in fact underestimated the polarization. We have also neglected multiple scattering within the scattering material, which, when included, would lower the estimated polarization. However, multiply scattered photons within a diverging relativistic outflow would suffer energy losses; the energy would be returned to the matter outflow. Efficiency considerations suggest that the inner photospheric material suffers radiation drag and that it be kept relativistic by viscous interaction with the deeper layers. Energy lost by multiply scattering photons can thus be recovered and rechanneled into polarized radiation.

Scattering can be a significant contributor to polarization without necessarily being the only mechanism. The experimental consequences of such a contribution could be polarization that is occasionally above the theoretical limit for a pure optically thin synchrotron origin. This would require that both mechanisms are working in the same direction of polarization;
for polarization that is parallel to the axis of symmetry (as projected onto the sky) this would mean scattering within an angle less than $1/\Gamma^2$ from the plane of the scattering surface and would allow at most a 25% increase.

Synchrotron emission from an optically thin emitting region has been criticized as being a universal emission mechanism for GRBs on the grounds that it does not for any obvious reason produce energy peaks consistently at 200 keV with the observed sharpness (e.g., Eichler & Levinson 2000). Even a monochromatic electron population would produce synchrotron spectra that for some GRBs contain more than the observed proportion of low-energy photons (Preece et al. 2002). Even if the frequently observed paucity of low-energy photons could be attributed to the low-energy cutoff in the electrons or to self-absorption, a strong energy dependence in the polarization would be implied at low energies. This could be tested. A purely scattering origin for polarization would, on the other hand, predict polarization that is frequency independent at low energies.

Synchrotron and scattering mechanisms for polarization could conceivably be distinguished from each other by their time profiles. A scattered component of the polarized emission would have a time profile that was smoothed out on timescales less than $r/c\Gamma^2$, where $r$ is the characteristic scale at which the last scattering takes place. Future experiments that can measure polarization on subsecond timescales would therefore be extremely valuable.

Generally speaking, scattering, when operating alone as a polarizing mechanism, produces somewhat lower polarization than optically thin synchrotron radiation. It will not compete with the latter if polarizations of 0.55 are consistently observed. However, it is capable of producing even stronger polarization than synchrotron sometimes, so an occasional polarization near 100%, if it could be measured with sufficient precision, would suggest scattering. In any case, we have argued that, with the unfolding technology to detect gamma-ray polarization, polarization by scattering may be detectable and distinguishable from polarization by synchrotron emission.

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