THE ASTROPHYSICAL JOURNAL, 473:L79–L82, 1996 December 20


# RELATIVISTIC PRECESSING JETS AND COSMOLOGICAL GAMMA-RAY BURSTS

ERIC G. BLACKMAN
Institute of Astronomy, Madingley Road, Cambridge, CB3 OHA, England

INSU YI
Institute for Advanced Study, Olden Lane, Princeton, NJ 08540

AND

GEORGE B. FIELD
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
*Received 1995 August 10; accepted 1996 October 2*

## ABSTRACT

We discuss the possibility that gamma-ray bursts may result from cosmological relativistic blob-emitting neutron star jets that precess past the line of sight. Beaming reduces the energy requirements, so that the jet emission can last longer than the observed burst duration. One precession mode maintains a short-duration timescale while a second keeps the beam from returning to the line of sight, consistent with the paucity of repeaters. The long life of these objects reduces the number required for production as compared to short-lived jets. Blobs can account for the time structure of the bursts. Here we focus largely on kinematic and timescale considerations of beaming, precession, and blobs—issues that are reasonably independent of the acceleration and jet collimation mechanisms. We do suggest that large-amplitude electromagnetic waves could be a source of blob acceleration.

*Subject headings:* gamma rays: bursts — ISM: jets and outflows — pulsars: general

## 1. INTRODUCTION

Gamma-ray bursts (GRBs) are an isotropically distributed class of transient gamma-ray emitters (Meegan et al. 1994) showing fluxes $\gtrsim 10^{-7}$ ergs s$^{-1}$ cm$^{-2}$. All except three have not been seen to repeat and thus have a repetition timescale $\tau_{\rm rep} > 20$ yr. GRBs have durations 0.1 s $\leq \tau_{\rm dur} \leq 1000$ s $\sim 20$ s. The time profiles vary substantially but statistically show rise times shorter than fall times (Nemiroff et al. 1994). The repeaters show smoother profiles, but all show variabilities on the smallest $\lesssim 1$ ms observable scales. GRB spectra are nonthermal (Meegan et al. 1994).

Here we introduce the idea that GRBs may result from cosmological blob-emitting pulsars formed (PSRs) from accretion-induced collapse (van den Heuvel 1986) of white dwarfs (WDs). Two types of emitting PSRs can result from the collapse process: those that spin faster than their gravitationally unstable limit, which we call supercritical rotators (SPRs), and those that spin below this limit, which we call subcritical rotators (SBRs). The two objects are distinct in that the former loses most of its rotational energy through gravitational radiation during a very short time. We investigate the possibility that these PSRs are a source of GRBs when their emission accelerates blobs relativistically within a collimated jet. Two precession (PN) modes associated with the binary companion then conspire to move the jet out of the line of sight, the first accounting for a short $\tau_{\rm dur}$, and the second keeping $\tau_{\rm rep} > 100$ yr (Blackman 1995).

There have been previous associations of pulsars with GRBs (see, e.g., Usov 1992, 1994; Fatuzzo & Melia 1993; Thompson 1994). In our scheme, however, beaming reduces the energy requirements, and so we do not require the anomalously strong magnetic fields of $\sim 10^{15}$ G (see, e.g., Usov 1992, 1994; Thompson 1994). Beaming also allows the objects to emit for a period much longer than their observed durations. We will point out that this reduces the number of bursts required to be produced per year when compared to a model for which the anisotropic emitter has a lifetime $= \tau_{\rm dur}$.

In §§ 2, 3, and 4, we discuss the role of beaming, precession,[1] and blobs for GRBs. These ingredients are independent of the particular emission and jet collimation mechanisms, and thus the relevant discussion is largely kinematic. We suggest a possible emission mechanism in § 5, but other acceleration processes could also be subject to beaming and precession. Using the particular mechanism of § 5, we discuss how the observed kinematic requirements constrain the PSR properties. We find that typically $\tau_{\rm life} \sim 10^4$ yr with $B_{s0} \sim 10^{12}$ G and $\Omega_s \sim 10^4$ s$^{-1}$, where $\tau_{\rm life}$ is the gamma source lifetime, $B_{s0}$ is the surface magnetic field, and $\Omega_s$ is the PSR angular velocity. In § 6, we discuss the required rate of production and compare our GRB sources to SS 433.

## 2. KINEMATICS AND PULSAR CLASSES

If GRB emission comes from collimated blobs moving along the line of sight, the blob power source must have an intrinsic luminosity of (Meegan et al. 1994),

$$L_{\rm int} \sim \gamma^{-2} L_{\rm obs} \sim \gamma^{-2} 10^{51} \text{ ergs s}^{-1}, \quad (1)$$

where $L_{\rm obs}$ is the observed luminosity received per solid angle.

If the blob energy source is PSR rotational kinetic energy, $L_{\rm int}$ is given by the magnetic dipole formula (Usov 1992)

$$L_{\rm int} \sim f L_{\rm dip} \sim [10^{44} \text{ ergs s}^{-1}] f (\Omega_s / 10^4 \text{ s}^{-1})^4 \times (B_{s0}/10^{12} \text{ G})^2 (R_s / 10^6 \text{ cm})^6, \quad (2)$$

where $R_s$ is the PSR radius and $f < 1$ is the fraction of luminosity going into the observed accelerated particle emis-

[1] See Fargion & Salis (1996) for a different context.

sion. The gravitational radiation luminosity for a PSR is given by (Ostriker & Gunn 1969):

$$L_{\rm gr} \sim [10^{33} \text{ ergs s}^{-1}](\epsilon/10^{-11})^2 \times (E_{\rm kin}/10^{53} \text{ ergs})^2(\Omega_s/10^4 \text{ s}^{-1})^2 , \quad (3)$$

where $E_{\rm kin}$ is the rotational energy and $\epsilon$ is the PSR ellipticity (Usov 1992) with $\epsilon \sim 10^{-11}(B_{s0}/10^{12} \text{ G})^2$, for $\Omega_s < \Omega_{\rm uns}$ and $\epsilon \sim 10^{-1}$ for $\Omega_s \geq \Omega_{\rm uns}$, where $\Omega_{\rm uns} \gtrsim O(10^4)$ s$^{-1}$ is the angular velocity above which the PSR is gravitationally unstable (Friedman 1983). Thus the emission lifetime, $\tau_{\rm life}$, satisfies

$$\tau_{\rm life} = E_{\rm kin}/(L_{\rm int} + L_{\rm gr}) . \quad (4)$$

When initially, $L_{\rm gr} > \sim L_{\rm int}$, we have an SPR whereas, when $L_{\rm int} \ll L_{\rm gr}$, we have an SBR.

The GRB PSRs would form from accretion-induced collapse of a WD in a close binary (van den Heuvel 1986). For an angular momentum–conserving collapse,

$$\Omega_s \sim 10^6(R_{\rm wd}/10^9 \text{ cm})^2(R_s/10^6 \text{ cm})^{-2}\Omega_{\rm wd} , \quad (5)$$

where $\Omega_{\rm wd}$ and $R_{\rm wd}$ are the WD angular velocity and radius. For the SPRs, $\Omega_s > \Omega_{\rm uns}$, and the jump in $\epsilon$ at $\Omega_s \sim \Omega_{\rm uns}$ means that there are two phases to the emission as determined by $L_{\rm gr}$. We have from equations (3) and (4),

$$\tau_{\rm SPR} \sim [0.1 \text{ s}](E_{\rm kin}/10^{53} \text{ ergs})^{-1}(\Omega_s/10^4 \text{ s}^{-1})^{-2} . \quad (6)$$

For typical parameters, in a time $\sim\tau_{\rm SPR} \lesssim$ few s, the ellipticity $\epsilon$ of the pulsar makes a transition, and the electromagnetic $L_{\rm int}$ decreases with the rapid depletion of the available dipole power (Yi & Blackman 1996). This results from a transition of a nonaxisymmetric Jacobi ellipsoid to a axisymmetric Maclaurin spheroid. For a uniform ellipsoid, the angular velocity actually increases during the transition (Chandrasekhar 1987). Although the pulsar energy is depleted on a timescale $\sim \tau_{\rm SPR}$, the exact time variation of the electromagnetic power during this phase depends on several outstanding uncertainties such as the nature of the magnetic field (Usov 1992; Thompson 1994) and the pulsar's dynamical structure including the rotational velocity law inside the star (Yi & Blackman 1996). If the SPR jet loses its gamma-ray luminosity on $\tau_{\rm SPR}$, then $\tau_{\rm dur} \sim \tau_{\rm SPR} \sim \tau_{\rm life}$. For SBRs, $\Omega_s < \Omega_{\rm uns}$ and $\epsilon$ is small. Here the PSR rotates stably, and from equations (2) and (3) we then have

$$\tau_{\rm life} \sim E_{\rm kin}/L_{\rm int} \sim 10^9(E_{\rm kin}/10^{53} \text{ ergs}) \times (\gamma/3 \times 10^4)^2(L_{\rm obs}/10^{51} \text{ ergs s}^{-1})^{-1} \text{ s} . \quad (7)$$

The jet formation timescale is difficult to estimate, but a characteristic dynamical timescale is that of the neutron star rotation, which would be of order $10^{-3}$ s, which is the smallest timescale in our study.

We emphasize that $\tau_{\rm life} \gg \tau_{\rm dur}$ is not a problem, as this is where PN enters the picture. PSR formation by accretion-induced collapse does not produce significant mass ejection (van den Heuvel 1986) and would leave the binary companion as a PN agent. The bursts are seen only when the gamma-ray–emitting cross section of their jet precesses by the line of sight, and we now discuss this further.

## 3. ROLE OF PRECESSION FOR SBRs

The sweep timescale for gamma emission $\tau_{\rm swp} \sim \tau_{\rm dur}$ depends on $\gamma$ as well as the jet PN timescale; ultrarelativistic jet blob emission is beamed in its outflow direction to an angle $\theta \sim \gamma^{-1}$. This links $\tau_{\rm dur}$ to the shortest PN timescale, $\tau_{\rm pn1}$, since

$$1/2\pi\gamma \sim \tau_{\rm dur}/\tau_{\rm pn1} . \quad (8)$$

The more cylindrical the jet channel in which the gamma-ray–emitting blobs move, the less stringent the requirement on the beaming of the whole jet: for a conical jet, the entire jet must be beamed to an angle $\sim\gamma^{-1}$ which is $\sim 10^{-4}$. However, if the jet is cylindrical, then there is no such requirement on the physical jet flow; only that the blobs produced have diameter of order the jet width. These arguments apply to the blobs that emit gamma rays; a cylindrical gamma-ray–emitting jet could be contained within a large conical jet that emits blobs of much smaller $\gamma$'s. Cylindrical jets have been studied in the context of AGNs (Heyvaerts & Norman 1989; Chiueh, Li, & Begelman 1991).

Although $\tau_{\rm dur}$ results from the shortest PN timescale, $\tau_{\rm rep}$ is determined by a combination of PN timescales. A secondary PN can move the PN cone of $\tau_{\rm pn1}$ so that the blob beam will not return to the line of sight on a timescale $\tau_{\rm pn2} \gg \tau_{\rm pn1}$. For multiple PN modes to operate in this way, the timescales must satisfy $\tau_{\rm pn1}/\tau_{\rm pn2} \geq \tau_{\rm swp}/\tau_{\rm pn1} \sim 1/2\pi\gamma$. For large $\gamma$, a wide range of PN timescales can thus account for $\tau_{\rm rep} \gg \tau_{\rm dur}$.

In our PSR-binary system, three important PN frequencies are associated with the binary interaction (Thorne, Price, & MacDonald 1986). In increasing order of magnitude, we denote these by $\mathbf{\Omega}_T$, $\mathbf{\Omega}_J$, and $\mathbf{\Omega}_G$. The first comes from the Newtonian tidal torque. The second results from interaction between the PSR spin and the gravitomagnetic field associated with the companion spin. The third results from (1) PSR spin interaction with the gravitomagnetic field associated with the companion orbit and the external gravitational field of the companion, (2) space-curvature PN, and (3) a "spin-orbit" PN from an additional gravitomagnetic field induced by the orbital motion of the neutron star in the gravitational field of the companion. Note that gravitomagnetic PN of compact objects is analogous to PN of the magnetic moment of a particle around its spin axis in the presence of a magnetic field (Thorne et al. 1986). The PN of the spin axis relative to the fixed stars is then given by

$$d\mathbf{J}_s/dt = (\mathbf{\Omega}_T + \mathbf{\Omega}_J + \mathbf{\Omega}_G) \times \mathbf{J}_s , \quad (9)$$

where $\mathbf{J}_s$ is the PSR angular momentum and $t$ is the time. For a nearly maximally rotating PSR and companion, the main contributions to the three frequencies are then given by (Thorne et al. 1986)

$$\Omega_G \sim [6 \times 10^{-8} \text{ s}^{-1}]\left[\frac{3M_c + M_c M_s/(M_c + M_s)}{1.2\, M_\odot}\right] \times \left(\frac{\Omega_K}{5 \times 10^{-3} \text{ s}^{-1}}\right)\left(\frac{R_B}{2 \times 10^{10} \text{ cm}}\right)^{-1} , \quad (10)$$

$$\Omega_J = 0.5\Omega_G(R_c/10^{10} \text{ cm})^{1/2}(R_B/2 \times 10^{10} \text{ cm})^{-1/2} , \quad (11)$$

$$\Omega_T \sim 10^{-3}\Omega_G(M_s/M_\odot)^{1/2}(R_B/2 \times 10^{10} \text{ cm})^{-1/2} , \quad (12)$$

where $M_s \sim M_\odot$ and $M_c \sim 0.5\, M_\odot$ are characteristic masses of the PSR and companion, and $R_B$ and $R_c$ are the binary and companion radii, which can be further constrained (Yi & Blackman 1996; Martin & Rees 1979). For the typical values shown, $\tau_{\rm dur} \sim \tau_{\rm pn1}/2\pi\gamma = \Omega_G^{-1}/\gamma \sim 100$ s $(\gamma/10^5)^{-1}$ and $\tau_{\rm rep} = \tau_{\rm pn2} = \pi\Omega_T^{-1} \sim 2 \times 10^{11}$ s, so that $\tau_{\rm dur} \ll \tau_{\rm rep}$.

## 4. ROLE OF BLOBS

Although GRBs statistically show asymmetric time profiles, these are not observed for all GRBs (Nemiroff et al. 1994), and it is thus best if a unifying model allows for a myriad of profiles. Toward this end, we note that blob emission is a standard mode by which relativistic motion is often observed in jets (Blandford 1993) and in the present context can allow a sweeping jet to produce asymmetric, symmetric, and multipeaked profiles. The observed GRB time profiles are then characterized by the frequency of blob production $\omega_{\rm prod}$ and the blob decay time $\tau_{\rm dec}$, relative to the timescale for the jet channel to sweep across our line of sight, $\tau_{\rm swp}$. An asymmetric profile would result if $\omega_{\rm prod}^{-1} > \tau_{\rm swp}$ and $\tau_{\rm dec} < \tau_{\rm swp}$. In this case, the rise and fall times would be determined by the rise and decay time of the emitting blob, as the jet would be essentially stationary relative to the blob decay time. A symmetric profile would result if either $\tau_{\rm dec} > \tau_{\rm swp}$ or if $\omega_{\rm prod}$ is sufficiently large that the emission is nearly uniform in a sweep time. In this case, the rise and fall times are simply determined by $\tau_{\rm swp}$. The presence of profiles of all types requires that roughly

$$\tau_{\rm dur} \sim \tau_{\rm dec} \sim \tau_{\rm swp} \sim \omega_{\rm prod}^{-1} , \qquad (13)$$

even if the asymmetric profiles statistically dominate. (In a specific blob production model, the environment of the burst might create multiple blobs in a jet diameter broader than that determined by the solid angle derived from the beaming of any individual blob. This would give multipeaked emission.) Condition (13) is actually consistent with observations of SS 433 (Vermeulen 1993) which we further discuss later.

## 5. POSSIBLE ACCELERATION MECHANISM FOR GAMMA-RAY EMISSION

Avoiding runaway pair production that would make a blob optically thick to gamma rays requires $\gamma > 100$ (see, e.g., Krolik & Pier 1991). Pair plasma blobs moving along the magnetic dipole axis with $\gamma > \sim 10^4$ might be produced in PSR magnetospheres (Usov 1994) by large-amplitude electromagnetic waves (LAEMs). Here, a fraction $f$, used in equation (2), of the LAEM wave energy is absorbed by each blob, which is then accelerated to large $\gamma$ and subsequently emits radiation. We consider here a scenario for which the blobs are observed only along a nearly cylindrical channel, though we do not have a model for formation of this channel. We consider the blobs to be accelerated by the fraction of the nearly spherical wave contained within the channel cross section. Note that the channel is simply that for the gamma-ray blobs; there could be lower energy emission at radii outside that of the gamma-ray blob channel axis. (An alternative scheme for the SBRs is one in which the LAEMs are themselves focused entirely into a narrow beam.) The relevant beaming is simply the beaming of blob emission, as the blobs are accelerated to large Lorentz factors.

The LAEMs propagate outside a radius, $r_{\rm ff}$, where the density drops below that which can sustain a Goldreich-Julian (Goldreich & Julian 1969) charge density, and thus where flux-freezing and force-free conditions are broken. This gives (Usov 1994)

$$r_{\rm ff} \sim 10^{12}\ {\rm cm} (B_{s0}/10^{12}\ {\rm G})^{1/2} (\Omega_s/10^4\ {\rm s}^{-1})^{1/2} , \qquad (14)$$

and the associated pair plasma number density

$$n_{\rm ff} \sim 10^6\ {\rm cm}^{-3} (R_s/10^6\ {\rm cm}) \times (B_{s0}/10^{12}\ {\rm G})^{1/2} (\Omega_s/10^4\ {\rm s}^{-1})^{5/2} . \qquad (15)$$

Electron acceleration at $r_{\rm ff}$ is characterized by the parameter $\sigma_{\rm ff}$, defined by (Usov 1994; Michel 1984)

$$\sigma_{\rm ff} \equiv L_{\rm int}/(mc^2 \dot{N}_{\rm ff}) \sim 5 \times 10^7 (R_s/10^6\ {\rm cm})^5 \times (B_{s0}/10^{12}\ {\rm G})^{1/2} (\Omega_s/10^4\ {\rm s}^{-1})^{1/2} , \qquad (16)$$

where $\dot{N}_{\rm ff} = 4\pi r_{\rm ff}^2 c n_{\rm ff}$ is the electron flux and $m_e$ is the electron mass. By solving the equations of motion for a particle in a pulsar wind zone subject to electromagnetic forces, it has been shown that relativistic electromagnetic waves of frequency $\Omega_s$ can accelerate pair plasma to (Michel 1984; Asseo, Kennel, & Pellat 1978)

$$\gamma \sim \sigma_{\rm ff}^{2/3} \sim 10^5 (R_s/10^6\ {\rm cm})^{10/3} \times (B_{s0}/10^{12}\ {\rm G})^{1/3} (\Omega_s/10^4\ {\rm s}^{-1})^{1/3} , \qquad (17)$$

and the resulting emission is beamed within solid angle $\sim\gamma^{-2}$ from the direction of wave propagation (Asseo et al. 1978). The characteristic emitted frequency of the synchro-Compton radiation is proportional to $\gamma^3$ or $\sigma_{\rm ff}^2$ from equation (17) (like curvature radiation; see, e.g., Beskin, Gurevich, & Istomin 1993, p. 97). In particular (Asseo et al. 1978),

$$\omega_{\rm sc} \sim 10^{20}\ {\rm s}^{-1} (\Omega_s/10^4\ {\rm s}^{-1})(\sigma_{\rm ff}/10^8)^2 \qquad (18)$$

with a tail to

$$\sigma_{\rm ff}^{4/3} [eB_s(r_{\rm ff})/(m_e c)] \sim 10^{24}\ {\rm s}^{-1} (B_{s0}/10^{12}\ {\rm G})^{7/6} \times (R_s/10^6\ {\rm cm})^{23/3} (\Omega_s/10^4\ {\rm s}^{-1})^{1/6} . \qquad (19)$$

For GRBs, $\gamma$ is important in determining $\omega_c$ of equation (18) and also in providing a fundamental reduction in the source energy requirements. This reduces the required magnitude of the magnetic field through equation (1). Specifically, given the observed $\tau_{\rm dur}$, $L_{\rm obs}$, and $\omega_{\rm sc}$, the quantities $B_{s0}$, $\Omega_s$, and $R_s$ can be estimated for a given $f$ and for $\tau_{\rm dur} \sim \tau_{\rm swp}$. Spin-orbit synchronization gives $\Omega_s = 10^6 \Omega_K$ from equation (5) so the PN frequency (eq. [10]) depends on $\Omega_s$. We take $M_s = 5M_c = M_\odot$, $f \sim 0.01$, $L_{\rm obs} \sim 10^{51}$ ergs s$^{-1}$, $\omega_{\rm sc} \sim 10^{20}$ s$^{-1}$, and $\tau_{\rm dur} \sim 100$ s. Then equations (1), (8), and (18), using (10), are fitted well by $B_{s0} \sim 10^{12}$ G, $\Omega_s \sim 10^4$ s, and $R_s \sim 0.9 \times 10^6$ cm. In this case, from equation (17), $\gamma \sim 10^5$, and $\tau_{\rm life} \sim 10^3$ yr from equation (7).

If the SPRs dim[2] on a timescale $\tau_{\rm SPR}$, PN is irrelevant. The equations to consider are then equations (1), (18), and (6) since for these particular SPRs, $\tau_{\rm dur} = \tau_{\rm life}$. For $f \sim 0.01$, $L_{\rm obs} \sim 10^{51}$ ergs s$^{-1}$, $\omega_{\rm sc} \sim 10^{20}$ s$^{-1}$, and $\tau_{\rm dur} \sim 0.05$ s, the equations are well fitted by $B_{s0} \sim 10^{11}$ G, $\Omega_s \sim 1.3 \times 10^4$ s, and $R_s \sim 1.3 \times 10^6$ cm for the unstable PSRs. For such SPRs, $\gamma \sim 10^5$. The smaller $B_{s0}$ and larger $\Omega_s$ for SPRs compared to SBRs are consistent with accretion-induced collapse. A reduced magnetic torque correlates a smaller field with a larger $\Omega_{\rm wd}$ and $\Omega_s$ (see, e.g. Narayan & Popham 1989).

[2] Because of the short timescale of SPRs, the physics of the gamma-ray emission may be complicated by neutrino emission (Thompson 1994).

Whether the differences between SPRs and SBRs can be related to the observed bimodal distribution in GRB durations (Koveliotou et al. 1994) might warrant further study.

## 6. PRODUCTION RATE AND COMPARISON TO GALACTIC SOURCES

The observed number of GRBs is given by $N_{\rm obs} \sim 10^{-6}$ yr$^{-1}$ galaxy$^{-1}$ (Piran 1994). Because $\tau_{\rm life} \gg 1$ yr $\gg \tau_{\rm dur}$ for the precessing jet GRBs, the required production rate of the objects is much reduced from a model for which $\tau_{\rm life} \sim \tau_{\rm dur}$ even though the emission is strongly beamed. The reason is that an object would account for an event in a given year if the line of sight is within the solid angle swept out during that year by the beam, instead of having to fall strictly within a solid angle $\sim\gamma^{-2}$. Since the repetition time is the timescale for which the beam fills the full $4\pi$ solid angle, in 1 yr, the beam would sweep through a solid angle $4\pi(1\ {\rm yr}/\tau_{\rm rep})$ in this time. Thus the required production rate is

$$N_{\rm pro} \sim N_{\rm obs}(\tau_{\rm rep}/1\ {\rm yr})/4\pi \sim 10^{-4}(\tau_{\rm rep}/10^3\ {\rm yr}). \qquad (20)$$

In a model for which $\tau_{\rm life} \sim \tau_{\rm dur}$, then $N_{\rm pro} \sim \gamma^2 N_{\rm obs}$, which is much larger and excessive.

Though the jets require blob-forming instabilities and jet collimation that are poorly understood phenomena, such features are definitively observed in active galactic nuclei (AGNs) and microquasar jets GRS 1915−105 and SS 433 (Blandford 1993; Vermeulen 1993; Mirabel & Rodríguez 1994). In particular, the SS 433 jets precess with $\tau_{\rm pn1} \sim 10^7$ s, with a secondary modulation of $\tau_{\rm pn2} \sim 10^8$ s. Bullets and blobs of emission are seen distinctively, with equation (13) satisfied, namely that $\tau_{\rm dec} \sim \omega_{\rm prod}^{-1} \sim \tau_{\rm swp} \sim 10^5$ s. Beamed emission with $\gamma > 10^4$ would be visible only for $\tau_{\rm swp} < 10^3$ s. Any secondary PN of the jet that moved it even $6 \times 10^{-4}$ rad would render it invisible for a timescale longer than the lifetime of the rotational decay of the source. Note also that the SS 433 blobs flow out from channels through either side of a thick disk that may aid in the jet collimation (Vermeulen 1993).

There would be about 100 jetted objects of this type in the Galaxy at any one time (cf. eqs. [7] and [20]), which may not look significantly different from normal pulsars from angles not pointed favorably to see their gamma emission. The gamma-ray–emitting blobs in the GRB pulsars of the Galaxy must have a minimum Lorentz factor such that the probability of the beam solid angle of passing through our line of sight is less than 1/100. This gives an angle $\sim 1/(\pi\gamma_{\rm min}^2) < 1/100$ so that $\gamma_{\rm min} \gtrsim 5.6$. Finally, we note that a fraction of the objects, those associated with SPRs, would be necessarily accompanied by a burst of gravitational radiation from the stellar collapse and the unstable rotation. The fraction of these objects requires determination of what kind of PSRs form from accretion-induced collapse (Yi & Blackman 1996). Stellar mass micro-quasars may occur in classes similar to AGNs. GRBs may be a signature of one such class.

We thank R. Narayan for references, C. Thompson and E. T. Vishniac for comments, and M. J. Rees for discussion.

## REFERENCES

Asseo, E., Kennel, C. F., & Pellat, R. 1978, A&A, 65, 401
Beskin, V. S., Gurevich, A. V., & Istomin, Ya. N. 1993, Physics of the Pulsar Magnetosphere (Cambridge: Cambridge Univ. Press)
Blackman, E. G. 1995, Ph.D. thesis, Dept. of Astronomy, Harvard Univ.
Blandford, R. D. 1993, in Astrophysical Jets, ed. D. Burgarella, M. Livio, & C. O'Dea (Cambridge: Cambridge Univ. Press), 15
Chandrasekhar, S. 1987, Ellipsoidal Figures of Equilibrium (New York: Dover)
Chiueh, T., Li, Z., & Begelman, M. C. 1991, ApJ, 377, 462
Fargion, D., & Salis, A. 1996, astro-ph SISSA preprint 9605166
Fatuzzo, M., & Melia, F. 1993, ApJ, 414, L89
Friedman, J. 1983, Phys. Rev. Lett., 51, 11
Goldreich, P., & Julian, W. H. 1969, ApJ, 157, 869
Heyverts, J., & Norman, C. A. 1989, ApJ, 347, 1055
Kouveliotou, C., et al. 1994, in AIP Conf. Proc. 307, Gamma-Ray Bursts, ed. G. J. Fishman, J. J. Brainerd, & K. Hurley (New York: AIP), 167
Krolik, J. H., & Pier, E. A. 1991, ApJ, 373, 277
Martin, P. G., & Rees, M. J. 1979, MNRAS, 189, 19P
Meegan, C., et al. 1994, in AIP Conf. Proc. 307, Gamma-Ray Bursts, ed. G. J. Fishman, J. J. Brainerd, & K. Hurley (New York: AIP), 3
Michel, F. C. 1984, ApJ, 284, 384
Mirabel, I. F., & Rodríguez, L. F. 1994, Nature, 371, 46
Narayan, R., & Popham, R. 1989, ApJ, 346, L25
Nemiroff, R. J., et al. 1994, in AIP Conf. Proc. 307, Gamma-Ray Bursts, ed. G. J. Fishman, J. J. Brainerd, & K. Hurley (New York: AIP), 257
Ostriker, J. P., & Gunn, J. E. 1969, ApJ, 157, 1395
Piran, T. 1994, in AIP Conf. Proc. 307, Gamma-Ray Bursts, ed. G. J. Fishman, J. J. Brainerd, & K. Hurley (New York: AIP), 543
Thompson, C. 1994, MNRAS, 270, 480
Thorne, K. S., Price, R. H., & MacDonald, D. A. 1986, Black Holes: The Membrane Paradigm (New Haven: Yale Univ. Press)
Usov, V. V. 1992, Nature, 357, 452
———. 1994, in AIP Conf. Proc. 307, Gamma-Ray Bursts, ed. G. J. Fishman, J. J. Brainerd, & K. Hurley (New York: AIP), 552
van den Heuvel, E. P. J. 1986, in The Evolution of Galactic X-Ray Binaries, ed. J. Trümper, W. H. G. Lewin, & W. Brinkmann (NATO ASI Ser. 167) (Dordrecht: Reidel), 107
Vermeulen, R. 1993, in Astrophysical Jets, ed. D. Burgarella, M. Livio, & C. O'Dea (Cambridge: Cambridge Univ. Press), 241
Yi, I., & Blackman, E. G. 1996, preprint