THE ASTROPHYSICAL JOURNAL, 609:L9–L12, 2004 July 1

THE CASE FOR A MISALIGNED RELATIVISTIC JET FROM SN 2001em

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Received 2004 March 18; accepted 2004 May 13; published 2004 May 20

ABSTRACT

SN 2001em, identified as a Type Ic supernova (SN Ic), has recently been detected in the radio and X-rays, $\gtrsim$2 yr after the explosion. The high luminosities at such late times might arise from a relativistic jet viewed substantially off-axis that becomes visible only when it turns mildly relativistic and its emission is no longer strongly beamed away from us. Alternatively, the emission might originate from the interaction of the SN shell with the circumstellar medium. We find that the latter scenario is hard to reconcile with the observed rapid rise in the radio flux and optically thin spectrum, $F_\nu \propto \nu^{-0.36\pm0.16}t^{1.9\pm0.4}$, while these features arise naturally from a misaligned relativistic jet. The high X-ray luminosity provides an independent and more robust constraint; it requires $\sim10^{51}$ ergs in mildly relativistic ejecta. The source should therefore currently have a large angular size (~2 mas), which could be resolved in the radio with the Very Long Baseline Array. It is also expected to be bipolar and is thus likely to exhibit a large degree of linear polarization (~10%–20%). The presence of a relativistic outflow in SN 2001em would have interesting implications. It would suggest that several percent of SNe Ib/c produce mildly relativistic jets, with an initial Lorentz factor $\Gamma_0 \gtrsim 2$, while the fraction that produces gamma-ray burst (GRB) jets (with $\Gamma_0 \gtrsim 100$) is ~100 times smaller. This could considerably increase the expected number of transients similar to orphan GRB afterglows in the radio and to a lesser extent in the optical and X-rays, if there is a continuous distribution in Γ_0. Furthermore, this may give further credence to the idea that core-collapse SNe, and in particular SNe Ib/c, are triggered by bipolar jets.

Subject headings: gamma rays: bursts — ISM: jets and outflows — supernovae: general — supernovae: individual (SN 2001em)

1. INTRODUCTION

SN 2001em was discovered on 2001 September 15 in the nearby galaxy UGC 11794 (Papenkova et al. 2001), at a redshift of $z = 0.019493$. This corresponds to a distance of $D \approx 80$ Mpc (for $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$, and $h = 0.71$). It was classified as a Type Ib/c supernova (SN Ib/c; most likely Ic; Filippenko & Chornock 2001). SNe Ib/c—some of which are thought to arise from the core collapse of a Wolf-Rayet star—have drawn more attention in recent years because of their association with gamma-ray bursts (GRBs). The best and most secure association so far is between GRB 030329 and SN 2003dh (Stanek et al. 2003; Hjorth et al. 2003). A compelling case also exists for SN 1998bw (at $z = 0.0085$) and GRB 980425 (Galama et al. 1998).

This raised interest in the search for signatures of GRB jets in nearby SNe Ib/c (e.g., Paczyński 2001). Typically, the narrow GRB jets point away from us and will not be detectable in gamma rays, but the SN might still be observed. As the off-axis GRB jets become mildly relativistic, months to years after the explosion, their radiation is no longer strongly beamed away from us, and they could become detectable in the radio.

Thus motivated, Stockdale et al. (2004) observed a large sample of SNe Ib/c at late times and detected SN 2001em on 2003 October 17.18 at 8.4 GHz as a 1.151 ± 0.051 mJy radio source. In addition to its high radio luminosity, $L_R \sim 10^{28}$ ergs s^{-1} Hz^{-1} (second only to SN 1998bw; Kulkarni et al. 1998), SN 2001em was also unusual in its subsequent evolution. Its 8.4 GHz flux rapidly increased to 1.480 ± 0.052 mJy on 2004 January 30.90. This corresponds to a temporal index of $\alpha = 1.9 \pm 0.4$, where $F_\nu \propto \nu^\beta t^\alpha$. Interestingly, the source appeared nonthermal, exhibiting a spectral slope of $\beta = -0.36 \pm 0.16$ between 4.9 and 14.9 GHz, at the second epoch. More recently, on 2004 April 4.81, *Chandra* detected SN 2001em in the X-ray (0.5–8 keV) with a luminosity of $L_X \sim 10^{41}$ ergs s^{-1} and $\beta \approx -0.1 \pm 0.35$ (Pooley et al. 2004).

In this Letter we investigate different explanations for the unusual emission from SN 2001em. The two most natural mechanisms are (1) the interaction between the SN shell and the circumstellar medium (CSM) and (2) off-axis relativistic jets. We examine these two possibilities in detail in §§ 2 and 3, respectively. Our conclusions are discussed in § 4.

2. INTERACTION BETWEEN THE SN SHELL AND THE CSM

The characteristic SN radio light curves are thought to arise from the competing effects of a slowly declining nonthermal radio emission and a more rapidly declining absorption. Under the assumption that the fractions of internal energy in magnetic fields (ϵ_B) and in relativistic electrons (ϵ_e) remain constant with time, the observed radio flux can, to first approximation, be written as $F_\nu \propto \nu^\beta t^\alpha e^{-\tau}$, where $\beta = (1-p)/2$ and p is the power-law index of the electron energy spectrum (Chevalier 1994). The early optically thick phase, $\tau \gtrsim 1$, can be dominated by either free-free absorption or synchrotron self-absorption. The high expansion velocities and low CSM densities found in SNe Ib/c suggest that synchrotron self-absorption is the dominant mechanism in these objects (Chevalier 1998). Synchrotron self-absorption leads to a power law in both time and frequency, $F_\nu \propto \nu^{5/2}$, instead of an exponential form for free-free absorption.

SN 2001em showed both a fast rise in its radio flux and an optically thin spectral slope, $F_\nu \propto \nu^{-0.36\pm0.16}t^{1.9\pm0.4}$. While the former may be similar to that expected from synchrotron self-absorption, the latter is clearly not. The fact that the rapid rise occurs with little absorption implies that it is not because of a reduction in optical depth. The usual models described above therefore fail to reproduce the observed increase in flux. This

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behavior has not been observed previously in radio SNe, although SN 1987A (Type II) has shown a strong rise in its radio flux (Ball et al. 1995) together with an optically thin spectral slope, $\beta \approx -0.95$ (Manchester et al. 2002), that has been attributed to interaction with the dense wind from a previous evolutionary phase (Chevalier 1992).

In order to address the question of whether or not the radio emission seen in SN 2001em is consistent with synchrotron radiation from the interaction of the SN shell with the CSM, we generalize the analysis of Waxman (2004a), which applies to expansion in a $\rho_{\rm ext} \propto r^{-2}$ medium, to $\rho_{\rm ext} = Ar^{-k}$. Let us consider a subrelativistic shell ejected by the SN explosion, with mass M, total energy E, and initial velocity v_0. Denoting, $t_{\rm dec}$, the time at which the SN shell decelerates significantly, we have $t_{\rm dec} = [2(3-k)E/4\pi A v_0^{5-k}]^{1/(3-k)}$ and $v \approx v_0 \min[1, (t/t_{\rm dec})^{(k-3)/(5-k)}]$. The sharp rise, $\alpha = 1.9 \pm 0.4$, and the spectral slope, $\beta = -0.36 \pm 16$, that were observed in SN 2001em cannot be achieved after $t_{\rm dec}$ (Frail et al. 2000). On the other hand, at $t \ll t_{\rm dec}$, the observed spectral slope suggests that we are in the power-law segment of the spectrum where $\beta = (1-p)/2$, which implies $\alpha = 3 - [k(5+p)/4]$. In order to obtain $\alpha \approx 1.9$, one needs $k \lesssim 0.55$–0.63 for $2 < p < 3$. Such a smooth power-law density profile is unlikely in the immediate surroundings of a massive star (Garcia-Segura et al. 1996).

Explaining the X-ray luminosity, $L_{\rm X} \sim 10^{41}$ ergs s^{-1} at $t \approx 950$ days, is not trivial. We have $L_{\rm X} \sim f_{\rm X}\epsilon_{\rm rad}\epsilon_e(E/t)\min[1, (t/t_{\rm dec})^{3-k}]$, where $f_{\rm X}$ is the fraction of the radiated energy in the 0.5–8 keV *Chandra* range, $\epsilon_{\rm rad} \approx \min[1, (\gamma_m/\gamma_c)^{p-2}]$ is the fraction of the energy in electrons that is radiated away, and $\min[1, (t/t_{\rm dec})^{3-k}]$ is the fraction of the total energy E that is in the shocked CSM. This implies $(3f_{\rm X})(10\epsilon_{\rm rad})(3\epsilon_e)E_{51}\min[1, (t_{\rm dec}/10^3\ {\rm days})^{k-3}] \sim 1$, where $E_{51} = E/(10^{51}$ ergs), which suggests that[2] $E_{51} \gtrsim 1$ and $t_{\rm dec} \lesssim 10^3$ days. The latter condition implies $v_0/c \gtrsim 0.5(E_{51}/A_*)^{1/3}$ for $k = 2$, where $A_* = A/(5 \times 10^{11}\ {\rm g\ cm^{-1}})$. As a consequence, the velocity of the ejecta must be at least mildly relativistic with $E_{51} \sim 1$.[3]

The extrapolated radio flux in 8.4 GHz at the time of the X-ray observation is ∼1.7 mJy, which corresponds to a radio luminosity of $L_R \sim 10^{38}$ ergs s^{-1}. This would lead to $\beta \approx -0.6$ for a single power law in that energy range, which is consistent with $p \approx 2.25$, as long as $\nu_c \gtrsim 10^{18}$ Hz. The ratio $L_R/L_{\rm X}$ requires $p \lesssim 2.25$, where $p < 2.25$ gives $\nu_c < 10^{18}$ Hz and $\nu_c(p=2) \sim 10^{16}$ Hz. Such high values of ν_c favor a low CSM density, $A_* \lesssim 0.03(3\epsilon_B)^{-1}(1+Y)^{-4/3}$, where Y is the Compton y-parameter that satisfies $Y(1+Y) \sim (v/c)\epsilon_{\rm rad}\epsilon_e/\epsilon_B$. Interestingly, a similarly low value of A_* is required in order to explain the lack of detection of an off-axis GRB jet in SN 1998bw (Waxman 2004a, 2004b; Soderberg et al. 2004).[4]

3. EMISSION FROM AN OFF-AXIS RELATIVISTIC JET

We first consider the off-axis emission from a uniform double-sided jet with an initial half-opening angle θ_0 and sharp edges (e.g., Granot et al. 2002). Later, we briefly address “structured” jets, where the energy per solid angle, ϵ, smoothly decreases with the angle θ from the jet symmetry axis, $\epsilon \propto \theta^{-2}$ (Rossi et al. 2002; Zhang & Mészáros 2002).

Following Granot & Loeb (2003) and generalizing their results to a stellar wind external density profile, $\rho_{\rm ext} = Ar^{-2}$, we obtain expressions for the radius R_j where the Lorentz factor γ of the jet drops to θ_0^{-1}, and the radius $R_{\rm NR}$ where the jet becomes subrelativistic,

$$R_j \equiv R_{\rm NR}/f = E/2\pi A c^2 = 3.5 \times 10^{17} E_{51} A_*^{-1}\ {\rm cm}, \quad (1)$$

where $f \approx 1 - \ln\theta_0$ and $E = 10^{51}E_{51}$ ergs is the energy of the jets. The typical angular size of the jet at the nonrelativistic transition time (see Granot & Loeb 2003), $t_{\rm NR} \sim R_{\rm NR}/c$, is

$$\theta_{\rm NR} = \frac{R_{\rm NR}}{D_A} = 0.71\,\frac{f}{3}\frac{E_{51}}{A_*}\left(\frac{D_A}{100\ {\rm Mpc}}\right)^{-1}\ {\rm mas}, \quad (2)$$

where D_A is the angular distance to the source. At the distance of SN 2001em, $\theta_{\rm NR} = 0.88(f/3)E_{51}A_*^{-1}$ mas.

The temporal index $\alpha \sim 2$ is consistent with the rising part of the light curve for a GRB jet viewed off-axis from an angle of $\theta_{\rm obs} \gtrsim$ a few θ_0 with respect to the jet axis (e.g., Fig. 2 of Granot et al. 2002). Therefore, we expect the peak flux to occur at $t_{\rm peak} = 3C$ yr, where $C \gtrsim 1$. The peak flux at $\nu = 8.4$ GHz should be about $F_{\nu,\rm peak} \approx 2C^2$ mJy. Given the late peak time, it is likely that $\theta_{\rm obs} \gtrsim 1$ and therefore $t_{\rm peak} \sim t_{\rm NR} \sim 3$ yr, for which the source angular size is $\sim\theta_{\rm NR}$. According to equations (1) and (2), $\theta_{\rm NR} \sim 2$–3 mas. One can also estimate $\theta_{\rm NR}$ by requiring an apparent velocity of c, $\theta_{\rm NR} \sim ct_{\rm NR}/D_A \sim 2.4(t_{\rm NR}/3\ {\rm yr})$ mas. Such an angular size could be resolved by the Very Long Baseline Array (VLBA).

In order to explain the spectral slope of $\beta \sim -0.4$, we require that $\nu_m < \nu < \nu_c$, for which $\beta = (1-p)/2$. The measured value of β can be somewhat larger than this asymptotic value if $\nu_m \sim 1$ GHz. Following Nakar et al. (2002) and Granot & Sari (2002), we find

$$F_{\nu,\rm peak} = 285\,\frac{g(p)}{g(2.2)}\,a^{-p}\epsilon_{e,-1}^{p-1}\epsilon_{B,-2}^{(p+1)/4}A_*^{3(p+1)/4} \times E_{51}^{(1-p)/2}\nu_{10}^{(1-p)/2}\theta_{\rm obs}^{-2p}\ {\rm mJy}, \quad (3)$$

$$t_{\rm peak} = a\left(\frac{\theta_{\rm obs}}{\theta_0}\right)^2 t_j = 34(1+z)aE_{51}A_*^{-1}\theta_{\rm obs}^2\ {\rm days} \quad (4)$$

(for $\theta_{\rm obs} \gtrsim 2\theta_0$ and at the redshift of SN 2001em), where $g(p) = (p-0.18)e^{-1.66p}(p-2/p-1)^{p-1}$ and a relates t_j to $t_{\rm peak}$. For $\theta_{\rm obs} \sim 1$ we expect $a \sim 4$, while for $\theta_{\rm obs} \ll 1$ we expect $a \sim 1$. For SN 2001em, $F_{\nu,\rm peak}(10\ {\rm GHz}) \approx 2C^2$ mJy, which equals the flux in equation (3) for $a \approx 4$ and $\theta_{\rm obs} \approx C^{-1/p}(\pi/2)$. This suggests a viewing angle $\theta_{\rm obs} \gtrsim C^{-1/p}$ rad. Since for SN 2001em we know that $t_{\rm peak} = 3C$ yr, equation (4) yields $aE_{51}A_*^{-1}\theta_{\rm obs}^2 \sim 30C$, which implies a small CSM density, $A_* \sim 0.1$, similarly to § 2. This relation can also be used to simplify equation (3) and eliminate the dependence on $\theta_{\rm obs}$ and a,

$$F_{\nu,\rm peak} \sim 0.2C^{-p}\epsilon_{e,-1}^{p-1}\epsilon_{B,-2}^{(p+1)/4}A_*^{(3-p)/4}E_{51}^{(p+1)/2}\nu_{10}^{(1-p)/2}\ {\rm mJy}. \quad (5)$$

Thus we obtain that $\epsilon_{e,-1}^{p-1}\epsilon_{B,-2}^{(p+1)/4}A_*^{(3-p)/4}E_{51}^{(p+1)/2} \sim 10C^p$. Assuming a typical energy in GRB jets of $E_{51} \sim 1$ and $A_* \sim 0.1$, this gives $\epsilon_{e,-1}^{p-1}\epsilon_{B,-2}^{(p+1)/4} \sim 6C^p$. As discussed in § 2, the ratio $L_{\rm X}/L_R$ implies $p \lesssim 2.2$. For $C \approx 1$ the above condition can be readily satisfied for a wide range of reasonable parameter values (e.g.,

[2] The bare minimum for the energy content is $E \sim 10^{49}$ ergs for $f_{\rm X}\epsilon_{\rm rad}\epsilon_e = 1$. Such an extreme efficiency is, however, highly unlikely. For more reasonable values of $f_{\rm X}$, $\epsilon_e \sim \frac{1}{3}$ and $\epsilon_{\rm rad} \sim 0.1$, we need $E \sim 10^{51}$ ergs.

[3] In this case, only a small part of the mass in the SN shell, $M \sim E/c^2 \sim 5 \times 10^{-4}E_{51}\ M_\odot$, would have an initial velocity $v_0 \sim c$.

[4] Waxman (2004b) also derived $v_0 \sim 0.8c$ for SN 1998bw, although with a relatively low energy of $E \sim 10^{49}$ ergs.

$\epsilon_e \sim 0.3$, $\epsilon_B \sim 0.1$). However, since $\epsilon_e, \epsilon_B \lesssim \frac{1}{3}$–$\frac{1}{2}$, we must have $C \lesssim 2$–3, which implies $t_{\rm peak} \lesssim 5$–8 yr.

Finally, we briefly address a structured GRB jet viewed from a large angle $\theta_{\rm obs}$. If the jet has an outer edge at $\theta_{\rm max} < \theta_{\rm obs}$, then the light curve would not be very different from that for a uniform jet viewed at $\theta_{\rm obs} > \theta_0$ (e.g., Wei & Jin 2003). In this case, the above analysis is still approximately valid. If, on the other hand, $\theta_{\rm max} = \pi/2$ or $\theta_{\rm obs} < \theta_{\rm max}$, then the early light curve is dominated by emission from material along the line of sight. In this case, a sharp rise such as the one observed in SN 2001em ($\alpha \approx 2$), together with the observed spectral slope, $\beta \sim -0.4$, cannot be achieved after the time $t_{\rm dec}$ when the material along the line of sight decelerates significantly (Granot & Sari 2002; Kumar & Granot 2003; Granot & Kumar 2003). Therefore, the only way this scenario might still work is if we are before $t_{\rm dec}$. In this case $t_{\rm peak} \gtrsim 3$ yr is given by $t_{\rm dec} \sim t_{\rm NR}\Gamma_0^{-2(4-k)/(3-k)}$. This suggests a mildly relativistic initial Lorentz factor along the line of sight, $\Gamma_0 \lesssim$ a few, which might also explain why no GRB or X-ray flash was observed (e.g., Ramirez-Ruiz & Lloyd-Ronning 2002), despite the very low redshift of SN 2001em. Similarly to the nonrelativistic case discussed in § 2, $\alpha \sim 2$ requires $k \lesssim 0.6$, which is unlikely.

4. DISCUSSION

Different possible explanations for the radio emission from SN 2001em $\gtrsim$2 yr after the SN have been considered. We find that the large temporal index, $\alpha = 1.9 \pm 0.4$, together with the optically thin spectral slope, $\beta = -0.36 \pm 0.16$, cannot be naturally explained as emission from the interaction between the SN shell and the CSM. This would require either an almost uniform external density or a density bump (e.g., Ramirez-Ruiz et al. 2001). On the other hand, we find that a GRB jet, or even a jet with a mildly relativistic initial Lorentz factor, $\Gamma_0 \gtrsim 2$, that points away from us can naturally reproduce the observed temporal and spectral properties.

Since the actual observed rise in the radio luminosity was only ~30%, it might still not be indicative of a long episode of increasing flux and could be only due to a local density bump. However, the measured X-ray luminosity provides a stronger and more robust constraint. It requires $\sim 10^{51}$ ergs in ejecta with a mildly relativistic expansion velocity. Such a system would be physically very similar to an initially relativistic jet that became mildly relativistic at $t \sim t_{\rm NR}$ and began to approach spherical symmetry. It is also reasonable to expect that the mildly relativistic SN ejecta would be somewhat elongated along the rotational axis, similar to a relativistic jet near $t_{\rm NR}$. A high degree of linear polarization might therefore be expected. The polarization from a relativistic jet viewed off-axis is expected to reach its maximum value near the time of the peak in the light curve, $t_{\rm peak}$. For a relativistic jet the peak polarization can reach ~30%–40%, while for a mildly relativistic jet it is probably more modest, ~10%–20%, but still significantly higher than for a typical SN.

The best way to test our conclusion of a mildly relativistic expansion velocity is via the angular size of the image, which should be $\gtrsim$2 mas and could be resolved with VLBA. For a double-sided relativistic jet, we might observe both jets, if the viewing angle is large enough, $\theta_{\rm obs} \gtrsim 1$, so that the difference in brightness between the two jets would not be very large (Granot & Loeb 2003). In this case, their brightness ratio and its temporal evolution can help determine our viewing angle, $\theta_{\rm obs}$.

If indeed the radio and X-ray emission observed in SN 2001em are from an off-axis relativistic jet, then this has several interesting implications. This could provide an estimate for the fraction $f_{\rm RJ}$ of SNe Ib/c that produce relativistic jets. In order to account for the observed emission, we only need an initial Lorentz factor of $\Gamma_0 \gtrsim 2$. Such jets would generally not produce a GRB, which typically requires $\Gamma_0 \gtrsim 100$. In this case, if we use a conservative estimate, combining the 33 SNe from the sample of Berger et al. (2003) and the additional seven (including 2001em) from the sample of Soderberg et al. (2004), then SN 2001em would be one out of 40 nearby SNe Ib/c that produced relativistic jets. This implies $f_{\rm RJ} \gtrsim 2.5\%$. Following Soderberg et al. (2004) and using only nearby SNe Ib/c for which there are late-time (>100 days) observations, we obtain $f_{\rm RJ} \sim 1/15 \approx 6.7\%$. Since the observations are sparse (and in most cases consist of a single upper limit), the actual value of $f_{\rm RJ}$ might even be larger.

It is interesting to compare $f_{\rm RJ}$ to the fraction $f_{\rm GRB}$ of SNe Ib/c that produce GRBs. There are various estimates for $f_{\rm GRB}$. Assuming a uniform jet with sharp edges, Frail et al. (2001) found a beaming correction of $\langle f_b^{-1} \rangle \sim 500$ between the observed and the true GRB rates (where $f_b \approx \theta_0^2/2$) that results in $f_{\rm GRB} \approx 0.4\%$. Perna et al. (2003) estimated $f_{\rm GRB}$ for the universal structured jet (USJ) model and found $f_{\rm GRB} \sim 8 \times 10^{-6}$. Guetta et al. (2004) found that the USJ model is not consistent with the observed log N–log S distribution and did a more thorough analysis for the uniform jet model, which resulted in $\langle f_b^{-1} \rangle \approx 75 \pm 25$ and $f_{\rm GRB} \approx (5.5 \pm 1.8) \times 10^{-4}$. Therefore, if indeed $f_{\rm RJ} \gtrsim$ a few percent, then $f_{\rm RJ}/f_{\rm GRB} \sim 10^2$, implying that SNe Ib/c produce ~100 times more mildly relativistic jets (with $\Gamma_0 \gtrsim 2$) than highly relativistic ones (with $\Gamma_0 \gtrsim 100$), as suggested by several authors (MacFadyen et al. 2001; Ramirez-Ruiz et al. 2002; Granot & Loeb 2003).

If this is the case, one might expect a smooth and continuous distribution $P(\Gamma_0)$ of initial Lorentz factors for the jets produced by SNe Ib/c, where $\Gamma_0 \gtrsim 100$ would produce a GRB, $\Gamma_0 \gtrsim 10$–20 could result in X-ray orphan afterglows and possibly also X-ray flashes, $\Gamma_0 \gtrsim 5$–10 may give rise to optical orphan afterglows, and $\Gamma_0 \gtrsim 2$ could be responsible for radio orphan afterglows. If, for example, we parameterize this distribution as a power law, $P(\Gamma_0) = K\Gamma_0^{-\eta}$ for $\Gamma_{\rm min} < \Gamma_0 < \Gamma_{\rm max}$, where $\Gamma_{\rm min} \approx 1$, $\Gamma_{\rm max} > 100$, and[5] $K = f_{\rm RJ}(\eta - 1)\Gamma_{\rm min}^{1-\eta}$, then we need $\eta \sim 2$ in order to get $f_{\rm RJ}/f_{\rm GRB} \sim 10^2$. However, this is still highly speculative at this stage.

We now compare $f_{\rm RJ}/f_{\rm GRB} \sim 10^2$ to current observational limits. Levinson et al. (2002) have used the Faint Images of the Radio Sky at Twenty cm survey and the NRAO VLA Sky Survey to place limits on orphan radio GRB afterglows. They estimated the number of candidates for such events over the whole sky above 6 mJy to be 227 and obtained a lower limit on $f_b^{-1} \sim E_{\gamma,\rm iso}/E$, of $\langle f_b^{-1} \rangle > 13$. However, this was derived assuming a fixed value for the isotropic equivalent energy output in gamma rays, $E_{\gamma,\rm iso}$, while allowing the true energy E to vary. If instead we fix the true energy to be $E \approx 10^{51}$ ergs, as suggested by Frail et al. (2001) and Bloom et al. (2003), the same analysis would result in an upper limit of $\langle f_b^{-1} \rangle \lesssim 6300$. Following Guetta et al. (2004), $f_{\rm RJ}/f_{\rm GRB} \sim 10^2$ and $\langle f_b^{-1} \rangle = 75 \pm 25$, which is consistent with the revised limit of $\langle f_b^{-1} \rangle \lesssim 63$ that is obtained by scaling up the expected number of such transients by a factor of $f_{\rm RJ}/f_{\rm GRB}$. This gives roughly the right number of radio transients found by Levinson et al. (2002), if most of them are caused by $\Gamma_0 \gtrsim 2$ jets produced in SNe Ib/c.

[5] Here $\int P(\Gamma_0)\, d\Gamma_0 = f_{\rm RJ}$ is normalized to the total fraction of SNe Ib/c that produce relativistic jets.

Nakar & Piran (2003) estimated the ratio of on-axis orphan X-ray afterglows ($\Gamma_0 \gtrsim 10$–20) and GRBs ($\Gamma_0 \gtrsim 100$) to be less than 8, using the *ROSAT* all sky survey. This is marginally consistent with $\eta \sim 2$ and suggests $\eta \lesssim 2$. Finally, we note that even if the radio emission from SN 2001em arises from the deceleration of a relativistic jet, then there is still a large statistical uncertainty on the value of $f_{\rm RJ}$, since it is estimated on the basis of one event. For example, $f_{\rm RJ}/f_{\rm GRB}$ might still be ∼10, which would imply $\eta \sim 1.5$.

A relatively large value of $f_{\rm RJ}$ might support the idea that at least some core-collapse SNe, and in particular SNe Ib/c, may be triggered by bipolar jets (Khokhlov et al. 1999). Even if only ∼1% of the core energy is channeled into such jets, they would still have enough kinetic energy to provide most of the power in the explosion and substantially alter the structure of the expanding SN shell. While most rotating magnetized proto–neutron stars with low power are expected to produce broad slowly collimating jets, a few high power ones should produce narrow rapidly collimating jets (Usov 1992; Thompson 1994). Although carrying more power, these highly collimated jets will be much less efficient than the broad jets in imparting energy and momentum to the outer layers (Khokhlov et al. 1999). They may then act similarly to the failed SNe (MacFadyen et al. 2001; Izzard et al. 2004), continuing to accrete much of the surrounding stellar layers and collapse to a black hole, potentially resulting in even faster and narrower jets. Observational estimates of the ratio $f_{\rm RJ}/f_{\rm GRB}$ will be valuable for constraining the different stellar evolution routes involved in producing relativistic bipolar jets in core-collapse SNe.

We thank B. Paczyński and S. D. Van Dyk for helpful discussions that initiated this work. We are grateful to E. Waxman and D. Pooley for useful comments. This work is supported by the W. M. Keck foundation, NSF grant PHY-0070928 (J. G.), and NASA through a Chandra Postdoctoral Fellowship award PF3-40028 (E. R.-R.).

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