ORPHAN GAMMA-RAY BURST RADIO AFTERGLOWS: CANDIDATES AND CONSTRAINTS ON BEAMING

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Received 2002 March 21; accepted 2002 May 18

ABSTRACT

The number of orphan radio afterglows associated with gamma-ray bursts (GRBs) that should be detected by a flux-limited radio survey is calculated. It is shown that for jetted GRBs, this number is smaller for a smaller jet opening angle \( \theta \), contrary to naive expectation. For a beaming factor \( f_\theta^{-1} \equiv (\theta^2/2)^{-1} \approx 500 \), roughly the value inferred by Frail et al. from analysis of afterglow light curves, we predict that between several hundred to several thousand orphan radio afterglows should be detectable (over all sky) above 1 mJy at GHz frequencies at any given time. This orphan population is dominated by sources lying at distances of a few hundred Mpc and having an age of \( \lesssim 1 \) yr. A search for pointlike radio transients with flux densities greater than 6 mJy was conducted using the FIRST and NVSS surveys, yielding a list of nine orphan candidates. We argue that most of the candidates are unlikely to be radio supernovae. However, the possibility that they are radio-loud active galactic nuclei cannot be ruled out without further observation. Our analysis sets a conservative 95% CL upper limit for the all-sky number of radio orphans, which corresponds to a lower limit \( f_\theta^{-1} > 13 \) on the beaming factor. Rejection of all candidates found in our search would imply \( f_\theta^{-1} > 80 \). This, and the possibility that some candidates may indeed be radio afterglows, strongly motivate further observations of these transients.

Subject heading: gamma rays: bursts

1. INTRODUCTION

Our understanding of gamma-ray bursts (GRBs) has been revolutionized by the discovery of X-ray afterglows by BeppoSAX (e.g., Costa et al. 1997) and the subsequent detections of optical transients (e.g., van Paradijs et al. 1997). These efforts led eventually to a confirmation of the cosmological nature of GRBs through both direct redshift measurements (e.g., Metzger et al. 1997) and imaging of the host galaxies (e.g., Sahu et al. 1997). The enormous power released in the explosion implies extremely large compactness of the source, and therefore, most GRB models involve compact or collapsed objects (e.g., Goodman 1986; Paczyński 1986; Eichler et al. 1989; Woosley 1993; Levinson & Eichler 1993; Paczyński 1999; see Mészáros 2000 for a review). In spite of the impressive successes of expanding relativistic “fireball” models (e.g., Paczyński & Rhoads 1993, Katz 1994, Mészáros & Rees 1997, Vietri 1997, Waxman 1997a, Sari, Piran, & Narayan 1998; see Mészáros 2002 for review), the precise nature of GRB progenitors remains unknown.

The total energy emitted in the GRB explosion and the rate at which such explosions occur in the universe are important keys to the understanding of the progenitors. The determination of these factors is complicated, however, by virtue of relativistic beaming. During the phase of gamma-ray emission, the fireball expands with a large Lorentz factor, \( \Gamma \approx 10^{2-3} \), so that a distant observer receives radiation from a conical section of the fireball of opening angle \( \sim 10^{-2.5} \) around the line of sight. Thus, estimates of total energy and rate based on gamma-ray observations are highly uncertain. The first evidence that the fireball may be jetted was provided by radio observations of GRB 970508 (Waxman, Kulkarni, & Frail 1998). These observations imply a jet of relatively wide opening angle, which expands sideways and approaches subrelativistic, spherical expansion \( \approx 1 \) yr following the GRB (Frail, Waxman, & Kulkarni 2000). The analysis of radio observations during the subrelativistic phase allowed the determination of the total GRB energy to be \( \approx 10^{51} \) ergs.

Jetted GRBs have been widely invoked to explain the optical light curves of the afterglow emission, most notably so for the source GRB 990123 (Stanek et al. 1999; Harrison et al. 1999). Frail et al. (2001) have analyzed a sample of GRB afterglows with known redshifts. They find that most bursts are jetted, with a jet opening angle \( \theta \) and average “beaming factor,” defined as \( f_\theta^{-1} \equiv (\theta^2/2)^{-1} \), of \( f_\theta^{-1} \approx 500 \). They also find that the total gamma-ray energy release, when corrected for beaming as inferred from the afterglow light curves, is narrowly clustered around \( 0.5 \times 10^{51} \) ergs. This result, although somewhat model-dependent, also suggests that the conversion efficiency of fireball kinetic energy to radiation is high, in agreement with the conclusion of Freedman & Waxman (2001), who derived a total fireball energy using early X-ray afterglow data. The energy estimates of Frail et al. are in agreement with those derived by Freedman & Waxman and also with the total energy derived for GRB 970508 (Frail et al. 2000).

Using radio surveys to constrain GRB beaming, rate, and energetics through the search for radio emission from GRBs that were not necessarily detected in gamma-rays has been proposed by Perna & Loeb (1998), Woods & Loeb (1999), and by Paczyński (2001). Perna & Loeb have suggested to search for such “orphan radio afterglow” emission from GRB jets pointing toward us, while Woods & Loeb have suggested to look for \( \sim 10^3 \) yr old, nonrelativistic remnants.

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Paczynski suggested, based on the radio observations of GRB 970508, to search for emission from ~1 yr old nearby GRB remnants, which have undergone the transition from a relativistic jet to spherical subrelativistic expansion, during which emission is isotropic. Given the hints for an association of GRBs with supernovae (Galama et al. 1998; Bloom et al. 1998; Reichart 1999), it was suggested by Paczynski to search for strong radio emitters among nearby supernovae.

In this paper we use the model, proposed in Frail et al. (2000) and Livio & Waxman (2000) for the long-term radio afterglow emission of GRBs, to calculate the expected number of orphan afterglows in radio surveys. We find that the detectable orphan population is dominated by ~1 yr old GRB remnants that have just undergone the transition to subrelativistic, spherical expansion. We determine the dependence of the expected number of sources on uncertain model parameters, derive a lower limit to the expected number of sources, and demonstrate that independent constraints on the beaming factor of early GRB emission can be imposed using radio surveys. We searched for pointlike radio transients, by comparing the FIRST and NVSS wide-field catalog, taken a few years apart, looking for sources present in one catalog and absent in the other. Our approach is different than that proposed by Paczynski, namely, we look directly for radio transients without relying on an association with nearby supernovae, since the link between GRBs and luminous supernovae is not well established; the only clear case, 1998bw, had an atypical (very weak) GRB, while there are three low-redshift, $z \leq 0.45$, GRBs$^4$ with no prominent supernova reported.

In § 2 we provide a brief description of the afterglow model and its main results used in later sections. In § 3 we calculate the number of radio afterglows expected to be detected above a certain flux. In § 4 we present a search for pointlike radio transients using the FIRST and NVSS catalogs, and discuss possible contamination by radio supernovae (RSNe) and active galactic nuclei (AGNs). The implications of our results are discussed in § 5.

2. AN OUTLINE OF THE AFTERGLOW MODEL

The basic model assumes an ultrarelativistic, jetlike ejecta propagating into an ambient medium of density $\rho = 1 n_0$ cm$^{-3}$, slowing down and expanding sideways, ultimately becoming nonrelativistic. As long as the jet Lorentz factor $\Gamma$ is larger than the inverse of the jet’s opening angle $\theta$, it behaves as if it were a conical section of a spherical fireball. Once $\Gamma$ drops below $\theta^{-1}$, the jet expands sideways, and its behavior deviates from that exhibited in the conical phase (Rhoads 1997, 1999). After a transition stage, in which the jet expands sideways, the flow approaches spherical symmetry and becomes subrelativistic (Waxman et al. 1998; Frail et al. 2000). The transition from a jet to a spherical subrelativistic evolution takes place over a timescale,

$$f_{\text{SNT}} \approx 6 \times 10^6 (E_{51}/n_0)^{1/3} \text{ s} \quad (1)$$

(Frail et al. 2000; Livio & Waxman 2000). Here $E_{51}$ is the total energy carried by the jet, in units of $10^{51}$ ergs, corrected for beaming; i.e., it is related to the isotropic equivalent energy $E_{\text{iso}}$ by $E = \theta^2/E_{\text{iso}} = f_b E_{\text{iso}}$, where $\theta$ is the jet opening angle. The subscript SNT refers to the Sedov-von Neumann-Taylor self-similar solution that describes the subrelativistic flow.

After the transition, the power is dominated by synchrotron emission from a subrelativistic fireball (e.g., Frail, Waxman, & Kulkarni 2000). Denoting by $\xi_p (\xi_B)$ the fraction of thermal energy behind the shock that is carried by electrons (magnetic field), and assuming that the electrons are accelerated to a power-law energy distribution, $d\varepsilon_e/d\gamma_e \propto \gamma_e^{-p}$ with $p = 2$, it can be shown (Livio & Waxman 2000) that the observed flux at frequencies above the synchrotron peak frequency at $t = t_{\text{SNT}}$,

$$\nu_{\text{s}} \approx 1 \left( \frac{1 + \frac{z}{2}}{2} \right)^{-1} \left( \frac{\varepsilon_p}{0.3} \right)^2 \left( \frac{\varepsilon_B}{0.3} \right)^{1/2} n_0^{1/2} \text{ GHz} \quad (2)$$

given by (see also Appendix of Frail, Waxman, & Kulkarni 2000)

$$f_{\nu} \approx 2h^2 \left( \frac{1 + z}{2} \right)^{1/2} \left( \frac{\varepsilon_p}{0.3} \right) \left( \frac{\varepsilon_B}{0.3} \right)^{3/4} \frac{d_L}{R_0} \left( \frac{t}{t_{\text{SNT}} (1 + z)} \right)^{-9/10} \text{ mJy} \quad (3)$$

Here $d_L$ is the luminosity distance, $R_0 = c/H_0 = 10^{28}h^{-1}$ cm, and $\nu_0$ is the observed frequency measured in GHz. Analysis of GRB 970508 radio data implies (Frail et al. 2000) $n_0 \approx 1$, $\varepsilon_p \sim \varepsilon_B \sim 1/3$.

3. EXPECTED NUMBER OF ORPHAN AFTERGLOW SOURCES IN RADIO SURVEYS

Consider a survey with a flux threshold denoted by $f_{\nu, \text{min}}$, and denote by $\tau_m$ the time, in units of $t_{\text{SNT}} (1 + z)$, at which the radio flux of a GRB at a given luminosity distance, $d_L$, drops below detection limit. From equation (3) we then obtain

$$\tau_m = \eta (1 + z)^{5/9} (d_L/R_0)^{-20/9} \quad (4)$$

where

$$\eta = h^{20/9} \left( \frac{f_{\nu, \text{min}}}{1 \text{ mJy}} \right)^{-10/9} \left( \frac{\varepsilon_p}{0.3} \right)^{10/9} \left( \frac{\varepsilon_B}{0.3} \right)^{10/12} \left( \frac{\nu_0}{\nu_0} \right)^{5/9} \times n_0^{10/12} E_{51}^{10/9} \quad (5)$$

We shall assume, in what follows, that the total energy output and beaming factor of GRBs are standard and, moreover, that the fraction of total energy release that goes into driving the external blast wave generating the afterglow emission is the same for all GRBs. We make this assumption in order to simplify our analysis and since the distribution of the above parameters is not well known. It is important to emphasize at this point that, as mentioned above, the analysis presented in Frail et al. (2001) indicates that the distribution of GRB true (i.e., corrected for beaming) gamma-ray energies is narrowly clustered around $E_{51} \approx 0.5$, with a corresponding average beaming factor of $f_b^{-1} = (\theta^2/2)^{-1} \approx 500$. These results also imply high-order unity radiative efficiency, consistent with the result obtained by Freedman & Waxman (2001) using a different method, and implying that the true total fireball energy is a

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$^4$ See http://www.aip.de/~jcg/grbgen.html.
few times $E_{\gamma}$, i.e., narrowly peaked around $E_{51} \approx 1$. Thus, we expect corrections to our results, due to deviations of parameters from their standard values, to be small. Moreover, our results, given as explicit functions of the standard parameter values, can easily be generalized to the case where parameter values are drawn from a general distribution, by replacing these values with their corresponding averages.

Let $\tau_i$ be the time at which the radio source just becomes isotropic. Then for a given flux threshold, the maximum luminosity distance below which a substantial number of sources can be detected is obtained from equation (4) for $z_m = \tau_i$:

$$ d_L(\tau_m) = \frac{R_0(\eta/\tau_i)^{9/20}(1 + \frac{z_m}{\tau_i})^{1/4}}{ \Phi(z)} $$

(6) For a given choice of GRB parameters, a flux threshold $f_{\text{min}}$ at the observed frequency $\nu_0$ and the value of $h$, the parameters $\eta$ and $\tau_i$ are fixed. Equation (6) can then be numerically solved for the assumed cosmology to yield the maximum redshift $z_{\text{max}}$ encompassed by the survey.

We denote by $\bar{n}$ the observed number of GRB events per year per Gpc$^3$ at $z = 0$ (which, assuming that the GRB rate follows the redshift evolution of the star formation, is estimated to be $\bar{n} \approx 0.5$; Schmidt 2001), and by $\Phi(z)$ the redshift evolution factor. The expected number of radio afterglows between $z$ and $z + dz$ can then be expressed as:

$$ \frac{dN_R}{dz} = N_0 dL d\Phi(z_m - \tau_i) $$

(7) where $dL = R_0^{-1} c dt$ is the light distance in units of $R_0$, and

$$ N_0 = f_{\text{b}}^{-1} \pi \nu_0^2 h^3 \bar{n} $$

$$ \approx 3.5 \times 10^4 (500 f_{\text{b}})^{-1} h^{-3} \bar{n} (E_{51} / n_0)^{1/3} $$

(8) The total number expected, can be obtained by integrating equation (7) from $z = 0$ to $z = z_{\text{max}}$, with $z_{\text{max}}(\eta/\tau_i)$ determined from equation (6).

As an example, consider a survey with a flux threshold of 5 mJy. Assuming $\tau_i = 3$, $h = 0.75$, and the above choice for the remaining parameters, we find $dL_{\text{max}} \approx 0.2 R_0 = 0.8$ Gpc, and a corresponding redshift $z_{\text{max}} \approx 0.2$. At such small redshifts, cosmological effects can be neglected to a reasonable approximation, and the luminosity distance can be taken to be equal to the proper distance. In this case, equation (7) can be integrated analytically. One then finds, using $n = 10^{-1} n_{-1}$ cm$^{-3}$

$$ N_R \approx N_0 \eta^{27/20} \tau_i^{-7/20} $$

$$ \approx 18 (500 f_{\text{b}})^{-1} (n/0.5)^{-3/2} \left( \frac{\xi_c}{0.3} \right)^{3/2} \left( \frac{\xi_B}{0.03} \right)^{9/8} $$

$$ \times n_{-1}^{19/36} \frac{E_{51}^{11/6}}{\nu_0^{3/4} (\tau_i/3)^{7/20}} $$

(9) As seen, $N_R$ depends only weakly on $\tau_i$. Consequently, any uncertainty in the time at which the radio emission becomes roughly isotropic should not affect our result considerably.

We have also given the result in terms of the isotropic equivalent energy, $E_{\text{iso}}$, for which we have chosen a normalization of $10^{54}$ ergs, since for the sample of GRBs with known redshifts given in Frail et al. (2001) one finds $(E_{\text{iso}1}) = 3 \times 10^{53}$ ergs and $(E_{\text{iso}2}) = 5 \times 10^{53}$ ergs. Since the true energy inferred from the observations, which is constrained by the isotropic equivalent energy $E_{\text{iso}}$ measured in GRBs with known redshifts, is inversely proportional to the beaming factor, $N_R \propto f_{\text{b}}^2$.

The peak flux of a GRB afterglow, for an observer lying along the jet axis, is proportional to $E_{\text{iso}}(n_{-1})^{1/2}$, and for typical luminosity distance of $3 \times 10^{26}$ cm it is $\approx 10 (\xi_B h_{-1})^{1/2} E_{51}^{20.5} mJy$ (Waxman 1997b; Gruzinov & Waxman 1999; Wijers & Galama 1999). Observed afterglow fluxes generally imply $\xi_B h_{-1} \gtrsim 10^{-3}$ for $E_{51}, n_0 \sim 1$, and values $\xi_B h_{-1} \sim 1$ are obtained in several cases (e.g., Waxman 1997b; Wijers & Galama 1999; Panaitescu & Kumar 2001). Our parameter choice in equation (9), $(\xi_B/0.3) = 0.1$ and $n_0 = 0.1$, is therefore conservative. Even for such a conservative choice of parameters we expect more than a dozen radio afterglows to be detected by an all-sky survey like the NVSS, provided the beaming factor is not much larger than that anticipated from other considerations. Note that our choice $n = 0.5$ is also conservative: if the GRB rate does not evolve with redshift, rather than following the star formation rate, the $z = 0$ rate is about 8 times larger, $n \approx 4$, and the expected number of radio GRB remnants is correspondingly larger by the same factor. The brightest source should have a flux of

$$ f_{\text{v, max}} \approx 30 (500 f_{\text{b}})^{-2/3} (n/0.5)^{2/3} \left( \frac{\xi_c}{0.3} \right)^{2/3} \left( \frac{\xi_B}{0.03} \right)^{11/3} \times n_{-1}^{19/36} \frac{E_{51}^{11/6}}{\nu_0^{3/4} (\tau_i/3)^{-7/20}} mJy. $$

(10)

Since the flux in this phase declines roughly as $(t/t_{\text{SN}})^{-1}$, such a source should remain above 1 mJy for at least several years. This motivates follow-up observations of the brightest transients found in a survey.

The derivation of equation (9) does not take into account the contribution from sources having a lifetime shorter than $t_{\text{SN}}$. These sources are expected to be beamed, and so the fraction that can be observed (those directed along our sight line) should be, of course, correspondingly smaller. On the other hand, the radio flux emitted at times earlier than $t_{\text{SN}}$ is larger, and, consequently, these beamed sources can be seen out to a larger distance. We may estimate the number of beamed radio sources anticipated to be detected by the survey using the following argument. The ratio of the number of sources having an opening angle $\sim \theta$ that are pointing in our direction, to the number of sources that had just become isotropic, is given by $(2 \pi \theta^2 / 4 \pi) T(\theta) / t_{\text{SN}}$ for a two-sided jet, where $T(\theta)$ is the observed expansion time to opening angle $\theta$: $T(\theta) \propto \theta^2$ (e.g., Rhoads 1999). Noting
that the radio flux measured by an observer within the beam drops as \( t^{-1/3} \) during the expansion of the jet (e.g., Rhoads 1999), the flux of a beamed source is higher than that of a source that just became spherical (lying at the same distance) by a factor of \( \theta^{-2/3} \). This implies that beamed sources can be seen out to a distance larger by a factor of \( \theta^{1/3} \) compared to those that just became spherical. Thus, the ratio of the number of beamed sources to those that just became spherical, observed above a certain flux, is 

\[
(\theta^{-1/3})^3 (\pi \theta^2 / 4 \pi) |T(\theta)/S_{\text{NT}}| \propto \theta^2.
\]

Thus, the number of detectable sources is dominated by sources that have already expanded to spherical symmetry.

For deeper surveys, cosmological effects cannot be ignored and must be taken into account. We have solved equations (6) and (7) numerically for different choices of cosmological parameters. For the range of parameters presently favorable we find that \( N_R \) depends only weakly on the assumed cosmology. In the following we present the results obtained for \( h = 0.75, \Omega_M = 0.3, \) and \( \Omega_L = 0.7 \). We also made the popular assumption that the comoving GRB density distribution traces the star formation rate and invoked a strong redshift evolution for the later, as suggested by Madau & Pozetti (2000). Specifically, we take \( \Phi(z) = (1 + z)^3 \) in the following calculations.

The solution of equation (6) is depicted in Figure 1a, where the dependence of the maximum redshift \( z_{\text{max}} \) on \( \eta / \tau_{\text{f}} \) is plotted. Figure 1b shows the dependence of \( N_R / N_0 \) on \( \eta \) for different values of \( \tau_{\text{f}} \).

For the cosmology adopted above, the radio flux of a source at a redshift of \( z = 2 \) is given by

\[
f_\nu \approx 50 \left( \frac{\xi_e}{0.3} \right) \left( \frac{\xi_B}{0.3} \right) \left( \frac{M_{\text{B}}}{3} \right)^{3/4} \left( \frac{E_{51} / 9}{S_{\text{NT}}} \right)^{-9/10} \mu\text{Jy}
\]

and is smaller by a factor of 4 at \( z = 3 \). Thus, for our above (conservative) choice of afterglow parameters, a flux limit of \( \leq 1 \mu\text{Jy} \) is required to see all the orphans if the GRB population is dominated by those at \( z \leq 2 \).

4. A SEARCH FOR NVSS/FIRST RADIO TRANSIENTS

4.1. Analysis

We conducted a search for pointlike radio transients in the FIRST radio catalog (White et al. 1997). We searched for compact FIRST radio sources that do not appear in the NVSS radio catalog (Condon et al. 1998). The sample we obtain this way is incomplete, since it rejects afterglow sources that were detected by the NVSS and were bright enough to remain above 6 mJy during the FIRST observation. We examine this incompleteness factor further below and show that it is smaller than 5\%. As the FIRST and NVSS surveys were obtained in different Very Large Array (VLA) configurations, the comparison was done carefully. We use this comparison to put an upper limit on the number of GRB radio afterglows.

The FIRST is a 20 cm radio survey conducted using the NRAO VLA in B-configuration, with 5" beam-size. The final maps have a typical noise rms of 0.15 mJy. This value allows 5 \( \sigma \) detection of 1 mJy sources. The survey’s resolution enables an astrometric accuracy better than 1" (90\% confidence level [CL]). The FIRST radio survey has begun in 1994, and when completed it will cover 10,000 deg\(^2\), mostly in the north Galactic cap. In the search described below, we used the FIRST 2001 Oct 15 version, covering 8565 deg\(^2\). This catalog has 771,076 sources, hence, a density of about 90 sources per deg\(^2\).

The NVSS 20 cm radio survey (Condon et al. 1998) was conducted between 1993 and 1996 and covers all the sky north of declination \( -40^\circ \). It utilized the VLA D- and DnC-configurations, with a circular beam size of 45". This is significantly larger than the median angular size (~10") of faint extragalactic sources. With this beam size, the faintest NVSS sources have an astrometric accuracy better than 7" (68\% CL). The images have rms brightness fluctuations of \(~0.45\) mJy beam\(^{-1}\) that allows for 5 \( \sigma \) detection of \(~2.5\) mJy sources. The NVSS 99\% completeness level is about 3.4 mJy. With a density of

\[
\tau = 1
\]

\[
\tau = 2
\]

\[
\tau = 3
\]

\[
\tau = 3 \text{ analytic}
\]
Radio sources could be intrinsically variable. Therefore, using the NVSS 99% completeness of 3.4 mJy as our threshold could introduce a large number of variable sources (e.g., sources that were detected in the FIRST survey but were just under detection in the NVSS) into our transients list. In order to compare the two catalogs, we need to choose a flux limit that rejects most of the variable objects. We plot in Figure 2 all FIRST pointlike sources (above 4 mJy) with NVSS counterparts. The solid line shows the location of sources for which the FIRST flux equals the NVSS flux, and the horizontal dashed line shows the NVSS, 99% completeness flux level (i.e., 3.4 mJy). On the basis of this plot we chose a threshold of 6 mJy, for which the scatter around the solid line does not produce large number of false transients sources.

In the following discussion we assume that all the FIRST images were taken after the corresponding NVSS images. This assumption will be examined more carefully later. Unless a GRB afterglow happens in a radio galaxy, it is expected to (1) be a point source and (2) be absent from the NVSS. Since radio galaxies are a tiny fraction of the overall galaxy population, these assumptions hold for most of the afterglow population.

We selected all the FIRST pointlike sources with peak flux above 6 mJy (21.5%). From this subsample, we selected all the unresolved objects (4.3% of the 6 mJy subsample). However, some of the resolved FIRST objects could actually be point sources, classified as resolved due to measurements errors. Adopting the FIRST size error criterion (White et al. 1997), for 9.2% of the FIRST sources above 6 mJy it is not possible to reject the hypothesis that they are pointlike at the 99.7% CL. Therefore, the number of sources above 6 mJy for which the point-source hypothesis could not be rejected at the 3σ level is 2.1 (= 9.2/4.3) times larger than the number of point sources we used in our sample. We ended with a catalog of 7181 FIRST pointlike sources with peak flux above 6 mJy. For these sources, we searched the NVSS for counterpart within 30″ of the FIRST position. Although the NVSS astrometry is better than 7″, the use of such a high threshold was necessary because in cases of two (or more) nearby pointlike radio sources, the NVSS could detect only one elongated source, with its center offset by more than 7″ from one of the FIRST point-source positions. The search yields 110 pointlike FIRST sources with peak flux above 6 mJy for which there is no NVSS counterpart.

We examined the POSS-II E images and the FIRST and NVSS radio maps of all these transient candidates. We found that 2% result from holes in the NVSS maps, 14% are clearly artifacts due to uncleaned aliases in the radio maps (an additional 16 artifacts are identified based on association with bright radio sources; see below), and 61% are multiple sources for which the NVSS found an elongated source centered more than 30″ from one of the FIRST radio positions; for the rest (23%, 25 sources) we could not reject the hypothesis that these are radio transients or variable radio sources of some kind (e.g., AGNs, SNe, GRBs, pulsars). A large fraction of these “sources” are possibly radio artifacts, NVSS nondetections due to locally high background, e.g., in the vicinity of a bright radio source (or physical phenomena other than GRBs, e.g., AGNs, SNe, pulsars). In order to minimize the number of artifacts, we further searched for bright (S₂₁ > 2.5 Jy) sources within a radius of 1″ of our candidates. We find that an additional 16 of the 25 sources are concentrated near bright radio sources and are, therefore, likely to be spurious. Since there are only 38 FIRST radio sources with S₂₁ > 2.5 Jy, and assuming there is no angular correlation between bright radio sources and radio-transients, we remove 38π deg² from our survey. This cut changes our survey area by only 1.4%. In what follows we ignore this correction factor. We are left with nine sources that could be radio transients of some kind. If we change the flux limit from 6 to 10 mJy, the number of candidates drops from 9 to 0.

Table 1 lists the 9 candidates along with their basic properties. For each of these objects, we conducted a search for known counterparts within a radius of 5″ in the NED database within 1″ in the HEASARC database. Our findings are listed in the table.

### Table 1: A List of Radio-transient Candidates

| R.A. | Decl. | FIRST Flux (mJy) | Optical Counterparts and Comments |
|------|-------|------------------|---------------------------------|
| 08 21 50.18 .... | +17 46 16.3 | 6.0 | No optical source |
| 10 48 48.92 .... | +55 15 08.7 | 6.1 | Blue point source with B ~ 21 |
| 11 43 55.34 .... | +22 10 20.4 | 6.2 | No optical source |
| 12 15 50.24 .... | +13 06 54.0 | 9.7 | Located in an NGC 4216 galactic arm |
| 12 25 32.62 .... | +12 25 00.5 | 7.2 | Nucleus of an R ~ 16 galaxy |
| 13 07 13.39 .... | −05 27 09.4 | 6.6 | No optical source |
| 15 22 48.69 .... | +54 26 44.1 | 6.6 | Point source with R ~ 19 |
| 16 52 03.08 .... | +26 31 39.9 | 6.3 | Coincident with the PSR J1652−2651 |
| 17 20 59.90 .... | +38 52 26.6 | 8.2 | No optical source |

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds (J2000).
There were 2575 deg$^2$ of the FIRST survey taken before the completion of the NVSS survey. Therefore, we reject all the sources in this area (i.e., $22.7^\circ < \delta < 42.5^\circ$). Omitting this strip (PSR J1652+2651 is in this strip), the area covered by our search is therefore 5990 deg$^2$, and the number of sources is seven and zero for the 6 and 10 mJy flux thresholds, respectively. The upper 95% Poisson CL on these numbers are 13.2 and 3.0, respectively. We consider these numbers to be conservative upper limits on the number of possible GRB afterglows.

Finally, we have to correct our upper limits for the various completeness factors involved:

1. Missing point sources due to FIRST measurements errors. As we showed above, a very conservative estimate for this number is $C_{\text{miss}} = 9.2/4.33 = 2.1$.
2. Area completeness (e.g., the fraction of the sky covered by our survey) $C_{\text{area}} = 41252/5990 = 6.8868$.
3. Given the crude NVSS resolution, the probability that a transient source will be detected up to $r = 90''$ (twice the NVSS FWHM) from a known unrelated NVSS source and therefore could be confused with it, is $P(< r) = 1 - \exp(-\pi r^2) = 11\%$. Therefore, the source confusion completeness factor is: $C_{\text{conf}} = 1.11$.
4. NVSS completeness—for about 2% of the FIRST sources there are no corresponding NVSS images (holes in the catalog), hence we set $C_{\text{comp}} = 1.02$.
5. Incompleteness due to our search criteria—afterglo sources detected by the NVSS that were bright enough to remain above 6 mJy during the FIRST observation are rejected by our search.

The number of such sources depends on the average time separation between the NVSS and FIRST observations. Denoting by $t_{\text{sep}}$ the time interval between two consecutive observations of a typical afterglow source, equation (3) implies that the flux during the first observation was larger than during the second observation by a factor of $(t_{\text{sep}}/SNT)^{9/10}$, assuming the source was near maximum flux during the first detection (i.e., its age was roughly $t_{\text{SNT}}$). Consequently, the fraction of bright afterglow sources in the NVSS catalog that may be detected above 6 mJy by the FIRST at time $t_{\text{sep}}$ after 1996 must be smaller than $\delta(t_{\text{sep}}) = (t_{\text{sep}}/SNT + 1)^{-27/20}$. The smallest time separation between the catalogs in the strips we consider is about $t_{\text{min}} = 6$ months, and the largest is about $t_{\text{max}} = 4.5$ yr. Taking the FIRST detections to be uniformly distributed in time, integrating the fraction $\delta(t_{\text{sep}})$ from $t_{\text{min}}$ to $t_{\text{max}}$ yields a total fraction of less than 5% that our search rejected. Thus, we set $C_{\text{search}} = 1.05$. Taking together all these factors, we can put a conservative 95% CL upper limit of 13.2 $\times$ $C_{\text{area}} \times C_{\text{miss}} \times C_{\text{conf}} \times C_{\text{comp}} \times C_{\text{search}} = 227$ for the all-sky number of GRB afterglows with peak specific flux above 6 mJy (or 52 for the 10 mJy threshold).

To summarize the results, based on the FIRST and NVSS surveys, we have put a conservative 95% CL upper limit on the all-sky number of GRB radio-afterglows. Nine of the sources found in our search are potential radio transients of some kind. In the following sections, we discuss the possibility that these sources are associated with radio supernovae and/or AGNs. We note that pulsars occasionally show long-term variations in their mean pulse energies by a factor of 10 or more (Huguenin, Taylor, & Helfand 1973; Rankin, Payne, & Campbell 1974; Lyne & Thorne 1975), and indeed one of our candidates coincides with PSR J1652+2651.

4.2. Radio Supernovae

The characteristic behavior of RSNe (see Weiler et al. 2002 for a recent review) appears to be similar to the expected behavior of radio afterglows (RGRBs). In particular, the radio light curve of Type II RSNe rises on a characteristic timescale of ~100 days (Weiler et al. 1998), comparable to $S_{\text{NT}}$ (see eq. [1]), and has an overall similar shape to that of RGRBs following the peak. This is not at all surprising since both are produced by the same mechanism, namely, a blast wave, albeit under somewhat different conditions. This similarity would render any attempt to distinguish RGRBs from RSNe difficult and, therefore, motivates a careful examination of potential differences between these two classes of objects.

We identify two features that may allow one to distinguish RGRBs from RSNe. First, the radio flux is anticipated to decline smoothly with a $r^{-1}$ dependence during the subrelativistic phase in RGRBs, while the radio light curves seen in RSNe are often much more complex. However, some RSNe do show a smooth decline, and those may be confused with RGRBs. Second, the absolute peak radio luminosity of RSNe may differ considerably from the radio luminosity of the brightest RGRBs. For a typical GRB the energy injected into the blast wave is $E \approx 10^{50}$ ergs, and with the above choice of parameters, $n = 0.1$ cm$^{-3}$, $\tau_1 = 3$, $\tau_2 = 0.03$, and $\zeta_3 = 0.3$, the RGRB luminosity density at 5 GHz is $7 \times 10^{28}$ ergs s$^{-1}$ Hz$^{-1}$ at a time of $\approx 0.5$ yr after the explosion. This luminosity is ~100 times larger than the typical peak luminosity (of detected) RSNe, on the order of $10^{27}$ ergs s$^{-1}$ Hz$^{-1}$ (Weiler et al. 1998) and several times brighter than the brightest known RSNe, SN1988z, which had a peak flux density of $2 \times 10^{28}$ ergs s$^{-1}$ Hz$^{-1}$. This suggests that in a flux-limited survey, RSNe and RGRBs should have a distinct redshift distribution, with RSNe having preferentially smaller redshifts.

We estimate below the number of RSNe expected to be detected in a search of the type described in this paper for RGRBs and compare their expected redshift distribution to that calculated for RGRBs. In order to make an accurate prediction for RSNe, their (peak) luminosity function and the shape of the corresponding light curves must be known. Unfortunately, because of the small sample of RSNe presently available (12 Type II and four Type I), and the lack of a supernova model that is capable of predicting the distribution of RSN properties, the determination of the peak luminosity function is highly uncertain. We therefore provide below a crude estimate based on the Weiler et al. (1998) compilation of RSN radio data. On the basis of Figure 3 from Weiler et al., we adopt an RSN peak luminosity function with equal number of RSNe per logarithmic peak luminosity interval over the 5 GHz peak luminosity range $L_1 = 10^{23}$ ergs s$^{-1}$ Hz$^{-1}$ to $L_2 = 10^{28}$ ergs s$^{-1}$ Hz$^{-1}$. In addition, we invoke a correlation between 5 GHz peak luminosity $L_p$ and peak time $t_p$ of the form $L_p = 10^{28}(t_p/10^3 $days$)^{1/2}$ ergs s$^{-1}$ Hz$^{-1}$, as demonstrated in Weiler et al. (1998). These assumptions hold, based on the available data, for Type II RSNe. The properties of Type I RSNe are less certain. However, since Type II RSNe dominate the (detected) RSN population, and since the Type I RSN peak luminosities are close to the typical Type II peak luminosities, we expect our estimate below of the Type II RSN “background” rate to provide a (crude) estimate for the total RSN background.
Assuming that the RSN flux drops as $T_p/t$ for $t > T_p$, the number of 5 GHz sources on the sky above a certain flux density $f_{\nu, \text{min}}$ at any given time can be readily computed:

$$N_{\text{RSNe}} = \frac{112\pi}{93\ln(L_2/L_1)} R_{\text{RSNe}}^3 \bar{h}_{\text{RSNe}} T_2 \cdot$$  

(12)

Here $\bar{h}_{\text{RSNe}}$ is the RSN rate per unit volume, $T_2$ is the peak time corresponding to peak luminosity $L_2$, and $R_{\text{RSNe}}$ is the maximum distance at which an RSN can be observed,

$$R_{\text{RSNe}} = \left( \frac{L_2}{4\pi f_{\nu, \text{min}}} \right)^{1/2} = 41 \left( \frac{L_2/10^{28} \text{ ergs s}^{-1} \text{ Hz}^{-1}}{f_{\nu, \text{min}}/5 \text{ mJy}} \right)^{1/2} \text{ Mpc} \cdot$$  

(13)

Since the typical distances of detectable RSNe are $\sim 10$ Mpc, we have assumed Euclidean geometry for the calculation above. It is also straightforward to calculate the average distance of detected RSNe,

$$\langle R \rangle_{\text{RSNe}} = \frac{93}{304} R_{\text{RSNe}}$$

$$= 13 \left( \frac{L_2/10^{28} \text{ ergs s}^{-1} \text{ Hz}^{-1}}{f_{\nu, \text{min}}/5 \text{ mJy}} \right)^{1/2} \text{ Mpc} \cdot$$  

(14)

These distances should be compared with those obtained for RGRBs: for the conservative GRB parameters quoted above, the maximum and average distances of RGRBs detectable above 5 mJy at 5 GHz are $R_{\text{GRB}} = 140$ Mpc and $\langle R \rangle_{\text{GRB}} = R_{\text{GRB}}/3 = 46$ Mpc, respectively.

Using the above equations, and taking $\bar{h}_{\text{RSNe}} = 1.2 \times 10^5 \text{ Gpc}^{-3} \text{ yr}^{-1}$, corresponding to the total rate of core-collapse SNe (Filippenko 2001), we find $N_{\text{RSNe}} = 3(f_{\nu, \text{min}}/5 \text{ mJy})^{-3/2}$. Comparing this result with the estimates for RGRBs given in $\S$ 2, we find that the number of RGRBs detected in a survey of the type described here should be at least comparable to, and most likely significantly larger, than the number of detected RSNe. The characteristic distances of detectable RGRBs should be $\geq 4$ times larger than those expected for RSNe.

The anticipated proximity of RSNe in the FIRST survey implies that the host galaxy should be easily detectable. In fact, even very faint galaxies should be detectable above the POSS-II limit out to a distance of 100 Mpc. This means that all the radio transients listed in Table 1 for which no optical counterpart is detected are unlikely to be RSNe, as even dwarf hosts should be clearly evident.

4.3. Radio-loud AGNs

Radio-loud AGNs are known to exhibit large-amplitude variations over a broad range of timescale and frequencies, with flare durations ranging from minutes to years. The characteristic durations of radio outbursts (with the exception of ID variability) are between weeks to years (Valtaoja et al. 1999; Venturi et al. 2001), with amplitudes that occasionally exceed a factor of 10. Thus, it is conceivable that some of the transients in our selected sample are radio-loud AGNs. Indeed, our initial list of 110 transients contains a number of such sources.

Most of the candidates in Table 1 have no optical counterpart brighter than $M_R = 21$. What is the likelihood that some or most of them are, in fact, AGNs? One way to characterize the radio loudness is in terms of the radio-to-optical luminosity ratio, $R$, which is commonly defined using radio and optical luminosities at some fiducial rest-frame wavelengths. Existing samples of AGNs exhibit a distribution in radio loudness that depends on selection criteria. The distribution of $R$ in the FIRST Bright Quasar Survey (White et al. 2000), for example, peaks at $R \sim 10$, with very few sources ($0.3 \%$) having $R > 10^4$. The distribution of radio-selected quasars has a median at $R \sim 10^3$ (Wadadekar & Kembhavi 1999). It is not clear at present whether this is a result of a selection effect, and whether there exists a population of extremely radio-loud AGNs. However, based on our current knowledge, we would naively expect that deep enough observations at optical wavelengths would be able to ultimately reveal the underlying AGN. Future X-ray detections of some of our candidates will also imply that these are likely AGNs. A precise determination of the minimum value of $R$ for the objects in Table 1 requires a knowledge of their redshifts, which are not available. If $R$ is defined as in Wadadekar & Kembhavi (1999), then a rough estimate yields $R > 300$ for those objects. In addition, they should have no extended structure above $\sim 1$ mJy on scales larger than a few arcseconds.

Another potential difficulty for future surveys may arise due to the presence of faint, BL Lac–type sources. If a population of radio BL Lac objects exist for which the continuum flux associated with the nuclear activity drops below that of the host galaxy during quiescent periods, then a radio transient associated with such an object may be confused with an RSN or orphan afterglow if optical observations were made when the AGN was in a low state. An example is the source SDSS J124602.54, which has been proposed as a candidate optical orphan afterglow (Vanden Berk et al. 2002) and later confirmed to be a BL Lac (Gal-Yam et al. 2002). In order to select out such sources in future surveys, monitoring in the radio and/or optical bands may be necessary.

5. DISCUSSION

We have calculated the number of orphan radio afterglows expected to be detected in a flux-limited survey. For the GRB parameters derived by Frail et al. (2001), total jet energy $E \simeq 10^{51}$ ergs and average beaming factor $(f_{\nu, \text{min}}^{-1}) = (\theta^2/2)^{-1} \simeq 500$, the number of sources expected to be present over all sky at any given time with flux exceeding $f_{\nu, \text{min}}$ is (see eq. [9])

$$N_R \simeq 20 \left( \frac{n}{0.5 \text{ Gpc}^{-3} \text{ yr}^{-1}} \right) \left( f_{\nu, \text{min}}^{-1} \right)^{-3/2} \left( \frac{\xi_B}{0.03} \right)^{9/8} n_{-1}^{19/24} .$$  

(15)

Here $n$ is the GRB rate at redshift $z = 0$, $n = 0.1n_{-1} \text{ cm}^{-3}$ is the number density of the ambient medium into which the blast wave expands, and $\xi_B$ is the energy density of the magnetic field behind the shock in units of the equipartition value; $n$ is normalized in equation (15) to the value obtained under the assumption that the GRB rate follows the redshift evolution of the star formation rate (Schmidt 2001). If the GRB rate does not evolve with redshift, $n$ is a factor of 8 larger than the value used in equation (15). Since afterglow observations generally imply $\xi_B \eta_B \gtrsim 10^{-3}$ cm$^{-3}$, and values $\xi_B n \sim 1$ cm$^{-3}$ are obtained in several cases (see the discussion in the paragraphs following eq. [9]), our choice of $n$ and...
\( \xi_B \) values are conservative. Even for such a conservative choice of parameters we expect \( \approx 20 \) radio afterglows to be detected by an all-sky survey with \( f_{\nu, \text{min}} \approx 5 \text{ mJy} \). These sources are detected out to a distance

\[
d_{\text{max}} \approx 200 \left( \frac{\xi_B}{0.03} \right)^{3/8} \left( \frac{f_{\nu, \text{min}}}{5 \text{ mJy}} \right)^{-1/2} \text{ Mpc} . \tag{16}
\]

We conducted a search for pointlike radio transients with flux densities larger than 6 mJy using the FIRST and NVSS surveys and discovered nine radio afterglow candidates, listed in Table 1. The two main types of sources that may produce radio transients, which may be confused in our analysis with a radio afterglow, are RSNe and radio-loud AGNs. While we have shown that our candidate sources are unlikely to be RSNe (see § 4.2), the possibility that most of them are radio-loud AGNs cannot be ruled out (see § 4.3).

Thus, our detected sources allow us to set an upper limit to the number of orphan radio afterglows. Correcting for various completeness factors (see § 4.1), we obtained an upper limit of 227 all-sky radio afterglows above 6 mJy, and 52 above 10 mJy.

We have shown that for a given isotropic equivalent burst energy, \( E_{\text{iso}} = f_{h}^{-1} E \), the number of afterglows detected in a flux-limited survey is smaller for a larger beaming factor \( f_{h}^{-1} \), i.e., for a smaller jet opening angle \( \theta \) (see eq. [9]). The upper limit we derived on the number of radio afterglow sources therefore implies a lower limit for the beaming factor,

\[
f_{h}^{-1} \geq 13 \left( \frac{\xi_B}{0.03} \right)^{6/5} \left( \frac{n}{0.5 \text{ Gpc}^{-3} \text{ yr}^{-1}} \right)^{27/20} \left( \frac{n_{1-1}}{1} \right)^{19/20} . \tag{17}
\]

Here we have used equation (9) with \( \langle E_{\text{iso}} \rangle^{11/6}, \langle f_{\nu, \text{min}} \rangle^{11} = 5 \times 10^{53} \text{ ergs} \) based on GRBs with known redshifts (Frail et al. 2001). This result is consistent with the value \( \langle f_{h}^{-1} \rangle = 500 \) inferred by Frail et al. (2001). Better determination of the distribution of \( n \) and \( \xi_B \), based on afterglow observations of identified GRBs, will improve the constraint on beaming. Alternatively, if the beaming factor is determined independently using other methods, then equation (17) can be used to constrain the afterglow parameters. For instance, invoking \( \langle f_{h}^{-1} \rangle = 500 \) implies

\[
\left( \frac{\xi_B}{0.03} \right)^{27/19} \left( \frac{n}{0.5 \text{ Gpc}^{-3} \text{ yr}^{-1}} \right)^{-24/19} < 4 \text{ cm}^{-3} . \tag{18}
\]

In reality, the afterglow parameters in a sample of radio GRBs should have a spread, and so the above condition may be taken as a constraint on the mean.

Additional observational efforts aimed at identifying the candidates in Table 1 are strongly motivated by two arguments. First, some of the candidates may turn out to be orphan afterglows. The fact that most candidates in Table 1 have no optical counterparts brighter than the POSS-II limit implies that if some of them are indeed GRB radio orphans, then their host galaxies are not as bright as would have been expected under the assumption that GRBs are associated with star-forming regions, given the distances estimated in equation (16) for the conservative values of \( n \) and \( \xi_B \). Nevertheless, the observed number of orphan candidates is consistent with larger values of these parameters, as shown in equation (18), for which the distances are larger and the absence of optical counterparts is not surprising.

Second, further observations are also motivated by the fact that rejection of sources from our list in Table 1 as possible candidates would impose a more stringent constraint for the beaming factor. Rejection of all the sources in Table 1 would imply an all-sky 95% CL upper limit of 52 sources, and a corresponding beaming factor \( f_{h}^{-1} > 80 \).

Future radio surveys may go deeper than FIRST and would be of comparable or better quality. The Allen Telescope Array (formerly the “1 hectare radio telescope”) will provide even better sensitivity. A search for pointlike radio transients similar to that outlined in § 4.1 would probably yield a large number of candidates. The analysis presented in § 3 predicts that the number of all-sky radio GRBs above 1 mJy is likely to lie in the range between a few hundreds and a few thousands, depending on afterglow parameters (see eq. [15]), provided that the average beaming factor of GRBs is not significantly larger than currently estimated from other considerations. Since the detectable orphan population is dominated by \( \approx 1 \) yr old GRB remnants, which have just undergone the transition to subrelativistic expansion, these sources should be transient, exhibiting \( \approx 1/r \) flux decline on timescale of months. Expansion at the speed of light over \( \approx 1 \) yr implies that the angular size of the nearby remnants, lying at a distance \( \approx 100 \text{ Mpc} \), is \( \approx 1 \text{ mas} \). The nearby remnants may therefore be resolved using the Very Long Baseline Array (VLBA), and, moreover, since they have just undergone the transition to spherical expansion, their structure may show significant anisotropy (see Paczyński 2001).

RSNe and radio-loud AGNs would probably contribute a large number of transients and may render the identification of radio afterglows difficult. As shown in § 4.2, RSNe and RGRBs can, in principle, be distinguished statistically by their redshift distributions. At the mJy level, the average distance of the radio afterglows is expected to lie between 0.1 and 1 Gpc, depending on afterglow parameters (see eq. [16]), so it should be possible to detect the host galaxies and obtain their redshifts. RSNe should typically lie at significantly shorter distances (see § 4.2). Detection of such bimodality in redshift distribution will greatly assist in identifying radio GRBs. Furthermore, the relativistic expansion of the GRB remnants also implies, as explained above, that unlike RSNe, they may be resolved with the VLBA, possibly revealing anisotropic structure. Efficient rejection of flaring blazars would require follow-up observations in the radio, optical, and X-ray bands. In particular, the orphan radio afterglows should exhibit a \( r^{-3} \) decay of the radio flux.

Finally, it is conceivable that GRBs emit substantial amounts of energy in the form of gravitational waves and high-energy neutrinos (Waxman & Bahcall 1997; Rachen & Mészáros 1998; Waxman & Bahcall 1999, 2000; Mészáros & Waxman 2001; see Waxman 2001 for review). Association of orphan radio afterglows with potential signals in gravitational wave and neutrino detectors may help by increasing the signal-to-noise ratio. In a model proposed recently (Van Putten 2001; Van Putten & Levinson 2002), the GRB results from extraction of the rotational energy of

\[ 5 \text{ See http://astron.berkeley.edu/ral/}. \]

\[ 6 \text{ See http://www.nfra.nl/skai/}. \]
a Kerr black hole through its interaction with a magnetized torus. This model predicts that the major fraction of the rotational energy available will be emitted in the form of gravitational waves in the band 0.5–1.5 KHz, for a reasonable range of black hole masses. It further proposes that measuring the product of the total energy carried by the gravitational waves and the corresponding frequency, which reflects the compactness of the system, can provide an existence test for Kerr black holes. However, such a measurement requires a knowledge of the distance to the source. Since the gravitational wave emission is isotropic, the chance of associating a LIGO source with a GRB event is small if GRBs have a beaming factor as large as currently believed. Nevertheless, if this model is correct, then LIGO sources should be associated with the orphan radio afterglows that should appear several months after the burst of gravitational radiation. At the distance within which LIGO can detect the predicted signal (≈100 Mpc), the radio source is expected to be very bright (see eq. [10]) and can be monitored for at least several years. Even though the angular resolution of the gravitational wave telescopes is expected to be quite poor, the chance that such a bright transient would coincide with a LIGO source should still be very small, and so such an association would be statistically significant. Our analysis, for instance, yielded an upper limit of about 10⁻³ transients per deg² above 10 mJy. The association of a radio afterglow with a LIGO source would also provide a means to identify the host galaxy, given the superior resolution of the radio telescopes and, hence, a distance measurement for the LIGO source.

We thank K. Weiler, A. Loeb, B. Paczyński, A. Laor, and R. D. Blandford for useful discussions. We thank the referee for useful comments. E. W. is partially supported by AEC grant and a Minerva grant, and is an incumbent of the Beracha Career development Chair.