Radio Detection of Old GRB Remnants in the Local Universe

Eric Woods\textsuperscript{1} and Abraham Loeb\textsuperscript{2}

Astronomy Department, Harvard University, 60 Garden St., Cambridge, MA 02138

ABSTRACT

We investigate the hydrodynamic evolution of Gamma–Ray Burst (GRB) remnants at late times, $\gg 1$ yr, by extending the standard fireball model into the nonrelativistic Sedov–Taylor regime. We calculate the associated synchrotron luminosity as a function of remnant age. The radio luminosity of old remnants depends strongly on the power–law index $p \equiv d \log N / d \log e$ of the kinetic energy distribution of shock-accelerated electrons. In addition, the detection probability of remnants in nearby galaxies depends on the GRB rate in the local universe. We predict that if $p \lesssim 2.6$ and the BATSE-calibrated GRB rate per comoving volume is independent of redshift (despite the strong evolution in the cosmic star formation rate) then the VLA can discover a $\sim 10^3$ years-old GRB remnant in the Virgo cluster. Nearby GRB remnants could be searched for and resolved at radio frequencies, and then identified as distinct from supernova remnants based on the detection of the extended emission of high-ionization lines in follow–up optical observations.

Subject headings: gamma rays: bursts

1. Introduction

Since the detection of redshifted spectral features in gamma–ray burst (GRB) afterglows, it has become evident that GRB events do indeed occur at cosmological distances (Metzger et al. 1997; Djorgovski et al. 1998; Kulkarni et al. 1998a; Bloom et al. 1998; Bloom et al. 1999). The enormous energy release $E \sim 10^{51} - 10^{54}$ ergs implied by the observed fluences and the cosmological distance scale could lead to a relativistically–expanding fireball, which produces the prompt ($\lesssim 100$ sec) $\gamma$–ray emission due to collisions between its internal shells (Paczyński & Xu 1994; Rees & Mészáros 1994; Pilla & Loeb 1997; Kobayashi, Piran, & Sari 1997). The fireball then enters the afterglow phase at later times ($\gtrsim 1$ day) when the expanding wind decelerates due to its interaction with the surrounding medium (e.g. Mészáros & Rees 1997; Waxman 1997a, b). During the early afterglow phase, the blastwave is still ultra–relativistic, and is hence well described by the

\textsuperscript{1}email: ewoods@cfa.harvard.edu
\textsuperscript{2}email: aloeb@cfa.harvard.edu
self-similar Blandford–McKee solution (Blandford & McKee 1976). Within a month the expansion is no longer ultra–relativistic. After about a year the expansion becomes nonrelativistic and the gas dynamics is well approximated by the Sedov–Taylor self-similar solution (Taylor 1950; Sedov 1959), similarly to a supernova remnant (SNR). Given the BATSE-calibrated rate of occurrence of GRBs in the universe (Wijers et al. 1998) and the lifetime of their remnants, one infers that there should be hydrodynamic fossils of GRB remnants in any spiral galaxy at any given time (Loeb & Perna 1998). In fact, a subset of the so–called HI supershells observed in the Milky Way and other nearby galaxies might be old GRB remnants (Efremov et al. 1998; Loeb & Perna 1998). Rhode et al. (1999) have identified some HI holes in the nearby galaxy Holmberg II that do not have optical counterparts as expected in alternative models involving multiple SNe or starbursts with a normal stellar mass function.

There are two important physical differences which could in principle lead to ways of observationally distinguishing GRB remnants from SNRs. First, the radiation energy emitted by an isotropic GRB explosion is estimated to be up to 4 orders of magnitude higher than that released in a supernova (Kumar 1999). Hence if a nearby expanding remnant is discovered and the explosion energy (as derived from the expansion speed and the Sedov-Taylor solution) is too great to be attributable to a single supernova, then one must conclude that we are seeing the remnant of either a GRB or multiple supernovae. But a GRB releases its total energy promptly, while the explosion time of multiple supernovae in a star–forming region is not expected to be synchronized to better than \( \sim 10^6 \) years. Hence, GRB remnants should be much more energetic than SN remnants at early times. The existence of energetic X-ray remnants was recently inferred in deep ROSAT X-ray images of M101 (Wang 1999); but future observations with the XMM and Chandra X-ray satellites are necessary in order to identify the nature of these sources conclusively through high-resolution imaging and spectroscopy. Second, GRB afterglows include a strong UV flash, which on the timescale of a few hundreds of years creates an ionized bubble of radius \( \sim 100 \, n_1^{-1/3} \) pc, where \( n_1 \) is the ambient density in units of \( 1 \, \text{cm}^{-3} \) (Perna & Loeb 1998). At ages \( \lesssim 10^4 \) years, the non–relativistic shock wave acquires a much smaller radius than the ionized bubble. This provides a potentially unique signature of young GRB remnants; namely, a relatively compact expanding blastwave embedded in a much larger ionized sphere. The optical-UV recombination lines from highly-ionized species in this region should provide a clear discriminant for recognizing GRB remnants (Perna, Raymond & Loeb 1999). The embedded blast wave emits both thermal and non-thermal radiation; the latter being an extension of the afterglow due to synchrotron emission by shock-accelerated electrons.

In this Letter we calculate the synchrotron radio emission from the expanding GRB shock in old GRB remnants. Our goal is to examine whether a survey in the radio could efficiently identify old GRB remnants. Once a candidate has been identified in the radio, follow-up optical observations could search for the special recombination lines which are generic of GRB remnants. In \( \S 2 \) we review the blastwave hydrodynamics as extrapolated into the Sedov–Taylor regime, and calculate the synchrotron flux as a function of age, as well as the expected source counts in the
Virgo cluster. Finally, we discuss our conclusions in §3.

2. Hydrodynamics and Emission

While the hydrodynamic evolution of GRB remnants through the early afterglow phase is well-described by the ultra–relativistic Blandford-McKee (1976) solution, at times much greater than a year we may to a good approximation use the non-relativistic Sedov-Taylor solution. It has been shown (Huang, Dai, & Lu 1998) that the two regimes may be smoothly matched to one another. We assume that the kinetic energy remaining in the fireball is comparable to the total energy $E_0$ which is radiated away in $\gamma$-rays, and that the energy release is isotropic; the effects of beaming in the initial energy release will be discussed in §3. The mean atomic weight of the surrounding (interstellar) medium is taken to be $1.4m_p$, where $m_p$ is the proton mass. The appropriate scaling laws for the shock radius $r_s$ and velocity $v_s$ in the non-relativistic regime are then

$$r_s = 1.17 \left( \frac{E_0 t^2}{1.4m_p n} \right)^{0.2} = 1.56 \times 10^{18} n_1^{-0.2} E_{52}^{0.2} t_{\text{yr}}^{0.4} \text{ cm},$$

(1)

$$v_s = 0.47 \left( \frac{E_0}{1.4m_p n t^3} \right)^{0.2} = 1.99 \times 10^{10} n_1^{-0.2} E_{52}^{0.2} t_{\text{yr}}^{-0.6} \text{ cm s}^{-1},$$

(2)

where $n = 1 n_1 \text{ cm}^{-3}$ is the pre–shock particle number density, $E_0 = 10^{52} E_{52} \text{ erg}$ is the total burst energy, and $t_{\text{yr}}$ is the age of the remnant in years.

The state of the gas behind the shock is defined by the Rankine-Hugoniot jump conditions. For a strong shock, the post-shock (primed) particle density, bulk velocity, and energy density are, respectively,

$$n' = 4n,$$

(3)

$$v' = \frac{3}{4}v_s,$$

(4)

$$u' = \frac{9}{8}n m_p v_s^2,$$

(5)

where all quantities are measured in the frame of the unshocked material.

As usual, we assume that the electrons are injected with a power–law distribution of kinetic energies,

$$f(\epsilon) = (p-1) \epsilon^{p-1} \epsilon^{-p}, \quad \epsilon > \epsilon_m,$$

(6)

where $f(\epsilon)d\epsilon$ is the fraction of shock-accelerated electrons with kinetic energies in the range $(\epsilon, \epsilon + d\epsilon)$. We assume a single power-law index at all energies, for simplicity. The spectral break that might exist at the transition to nonrelativistic electron energies occurs well below the electron energy which is responsible for the relevant radio emission at $\sim 1 \text{ GHz}$. 
The post–shock magnetic and electron energy densities are assumed to be given respectively as fixed fractions $\xi_b$ and $\xi_e$ of the total post–shock energy density:

$$u_b' = \frac{B'^2}{8\pi} = \xi_b u', \quad (7)$$

$$u_e' = n'e_m \frac{p-1}{p-2} = \xi_e u', \quad (8)$$

where $m_e$ is the electron mass. The magnetic field strength and minimum electron energy are thus given by

$$B' = 0.14 \xi_b^{0.5} n_1^{0.3} E_{52}^{0.2} t_{yr}^{-0.6} \text{ G},$$

$$\epsilon_m = 117 \frac{p-2}{p-1} \xi_e n_1^{-0.4} E_{52}^{0.4} t_{yr}^{-1.2} \text{ MeV}. \quad (10)$$

Before calculating the flux, we need to determine whether the Sedov–Taylor remnant is optically thin to synchrotron self–absorption. The shocked region has a thickness $\eta r_s$, with $\eta \sim 0.1$ from particle number conservation. We will adopt the value $\eta = 1/15$, which is consistent with the density profile of the Sedov (1959) solution, and provides a number of shocked electrons which is a fair fraction of the total number swept up by the blast wave. The self–absorption optical depth at a photon frequency $\nu$ is given by (cf. Rybicki & Lightman 1979, p. 190)

$$\tau(\nu) = \frac{\sqrt{3} e^3 n B_\perp \eta r_s}{2\pi m_e \epsilon_m \nu^2} (p-1) \Gamma \left( \frac{p}{4} + \frac{11}{6} \right) \Gamma \left( \frac{p}{4} + \frac{1}{6} \right) \left( \frac{\epsilon_m}{m_e c^2} \right)^p \left( \frac{3eB_\perp}{2\pi m_e c\nu} \right)^{0.5p}. \quad (11)$$

Here, $m_e$ is the electron mass, $\Gamma(x)$ is the gamma function, and $B_\perp \approx B'$ is the component of the magnetic field perpendicular to the electron velocity. Substituting the numerical factors into (11) gives

$$\tau(\nu) = \frac{39.1 \eta}{\nu^9_9} \left( \frac{61.6}{\nu_0^9} \right)^{0.5p} \alpha(p) \xi_b^{0.5+0.25p} \xi_e^{p-1} n_1^{-1.5-0.25p} E_{52}^{0.5p} t_{yr}^{1-1.5p}, \quad (12)$$

where $\nu = 10^9 \nu_9$ Hz, and

$$\alpha(p) \equiv (p-1) \left( \frac{p-2}{p-1} \right)^{p-1} \Gamma \left( \frac{p}{4} + \frac{11}{6} \right) \Gamma \left( \frac{p}{4} + \frac{1}{6} \right). \quad (13)$$

is of order unity. Thus, for typical power–law index values $2.1 < p < 3.2$ (Li & Chevalier 1999), we find that $\tau(\nu) \ll 1$ for $\nu = 1$ GHz at an age of $\gg 1$ yr.

The flux from old remnants is therefore given by

$$F_\nu = \left( \frac{4\pi r_s^2 \cdot \eta r_s}{4\pi D^2} \right) \times P_\nu, \quad (14)$$

where $D$ is the distance to the remnant, and $P_\nu$ is the volume emissivity (in erg s$^{-1}$ cm$^{-3}$ Hz$^{-1}$), given by (Rybicki & Lightman 1979, p. 180)

$$P_\nu = 4\sqrt{3} e^3 n B_\perp \frac{p-1}{p+1} \Gamma \left( \frac{p}{4} + \frac{19}{12} \right) \Gamma \left( \frac{p}{4} - \frac{1}{12} \right) \left( \frac{\epsilon_m}{m_e c^2} \right)^{p-1} \left( \frac{3eB_\perp}{2\pi m_e c\nu} \right)^{0.5(p-1)}. \quad (15)$$
Note that we are justified in using the synchrotron formula since the electrons which emit at GHz frequencies are ultra–relativistic:
\[
\frac{\epsilon}{m_e c^2} = \left(\frac{4\pi m_e c \nu}{3eB_\perp}\right)^{0.5} = 41.3 \nu_9^{0.5} \xi_b^{-0.25} n_1^{-0.15} E_{52}^{-0.1} t_{\gamma r}^{0.3}.
\]
(16)

Coulomb collisions thermalize the electrons only at non-relativistic energies, well below the energies of interest for this discussion. Hence, we are justified in using the power–law spectral shape in equation (15). The flux should eventually show a cooling break at high frequencies, due to the fact that electrons with more than a threshold energy \(\epsilon_c\) will radiate away their energy faster than the dynamical time. The synchrotron cooling time is given by
\[
t_c = \frac{6\pi (m_e c^2)^2}{\sigma_T c \epsilon B_\perp^2},
\]
where \(\sigma_T\) is the Thomson cross section. The cooling frequency is thus given by
\[
\nu_c = \left(\frac{3eB_\perp}{4\pi m_e c}\right)^2 \left(\frac{6\pi m_e c}{\sigma_T B_\perp^2 t}\right)^2 = 9.4 \times 10^{11} \xi_b^{-1.5} n_1^{-0.9} E_{52}^{-0.6} t_{\gamma r}^{-0.2} \text{ Hz}.
\]
(17)

For remnant ages \(\lesssim 10^7\) yr, the cooling cutoff occurs well above 1 GHz. Thus, the emission at GHz frequencies should fall on the simple \(P_\nu \propto \nu^{(1-p)/2}\) part of the spectrum.

We may now calculate the numerical value of the expected flux
\[
F_\nu = \frac{5.2 \times 10^6 \eta}{D_{\text{Mpc}}^2} \left(\frac{61.6}{\nu_9}\right)^{0.5(p-1)} \beta(p) \xi_b^{0.25(p+1)} \xi_c^{p-1} n_1^{0.95-0.25p} E_{52}^{0.3+0.5p} t_{\gamma r}^{2.1-1.5p} \text{ Jy},
\]
(18)

where \(D_{\text{Mpc}}\) is the distance to the source in Mpc, and
\[
\beta(p) \equiv \left(\frac{p-1}{p+1}\right) \left(\frac{p-2}{p-1}\right)^{p-1} \Gamma\left(\frac{p}{4} + \frac{19}{12}\right) \Gamma\left(\frac{p}{4} - \frac{1}{12}\right)
\]
(19)
is of order unity.

In figure 1 we plot the flux at 1.6 GHz from equation (18) as a function of remnant age \(t_{\gamma r}\) for \(p = 2.1\) (\(F_\nu \propto t^{-1.05}\)) and \(p = 3.2\) (\(F_\nu \propto t^{-2.7}\)), the two values which bracket the range of power–law indices seen in radio supernovae (Li & Chevalier 1999). We have assumed that the sources reside in the Virgo cluster, at a distance of \(D_{\text{Mpc}} = 16\). We also assumed sub-equipartition energy density of the magnetic fields and nonthermal electrons in the post-shock gas with \(\xi_b = 0.1\), \(\xi_e = 0.1\); a typical interstellar medium density, \(n_1 = 1\); and \(\eta = 1/15\). In panel (a), we take \(E_{52} = 0.7\), derived from the BATSE catalog for a source population with a redshift–independent burst rate per comoving volume, while in panel (b) we use \(E_{52} = 14\), which applies for population which traces the star formation rate in galaxies. For comparison, the horizontal line shows the 5\(\sigma\) sensitivity threshold, \(F_{\text{VLA}} = 70\mu\text{Jy}\), for the Very Large Array (VLA) in the 1.6 GHz band, using a one–hour integration in the VLA’s most extended configuration (L. Greenhill 1999, private communication). Clearly the maximum age for a detectable remnant, and hence the number of detectable remnants, depends strongly on \(p\). The vertical line, at \(t = 600\) yr and \(10^5\) yr in panels (a) and (b) respectively, indicates the age at which we expect to detect at least one remnant in
the Virgo cluster. The intermediate plots of $F_\nu(t)$ in panels (a) and (b) are for $p = 2.6$ and 2.3, the respective maximum electron slopes for which a 600 or $10^5$–year–old Virgo remnant would be detectable by the VLA.

To calculate the expected source counts, we note that the local GRB rate per $L_\star$ (where $L_\star$ is the characteristic stellar luminosity per galaxy in the local universe), assuming no beaming, is estimated to be $\Gamma \approx 2.5 \times 10^{-8} L_\star^{-1}$ yr$^{-1}$ (Wijers et al. 1998). This value is derived assuming that the GRB rate traces the star formation history of galaxies; for a non–evolving burst rate, the inferred value is 150 times higher. The number of remnants per $L_\star$ younger than $t_{yr}$ [and hence brighter than $F_\nu(t_{yr})$] at a given time is then $\Gamma t_{yr}$. The best place to search for optical emission from old GRB remnants is in the Virgo cluster (Perna, Raymond, & Loeb 1999). There are $\sim 2500$ galaxies brighter than $B = 19$ in this cluster; at a distance of 16 Mpc, this limit corresponds to an absolute magnitude magnitude $M_B = -12$. For typical Schechter (1976) function parameters, $\alpha = -1$ and $M_\star = -19$ (Loveday et al. 1992; Marzke et al. 1994), this yields a total luminosity for the Virgo cluster of $L_{Vir} = 430 L_\star$. Thus, for a non-evolving GRB population, we need to look for remnants as old as $t = (\Gamma \cdot L_{Vir})^{-1} = 600$ yr to be reasonably confident of seeing at least one remnant in the Virgo cluster. For a GRB population which traces the cosmic star formation history, we need $t = 10^5$ yr. As illustrated in Figure 1, for the burst parameters we have assumed, remnants this old could be detected by the VLA only for an electron power–law index $p < 2.6$ in the non–evolving case and $p < 2.3$ in the evolving case.

For deeper volume–limited searches, e.g. of volumes probed by the Sloan Digital Sky Survey (SDSS; Gunn & Weinberg 1995), the increase in the number of galaxies surveyed $N \propto D^3$ dominates over the decrease in detectable ages $t \propto D^{2/(2.1-1.5p)}$, obtained by solving equation (18) for $t_{yr}$. Thus, although at a distance of 250 Mpc we need to look for remnants which are younger than $10^2$ years, the galaxy luminosity within this volume is $\sim 10^5 L_\star$, leading to the prediction of at least one detectable young remnant for $p = 3.2$ and many more for lower $p$ values.

3. Discussion and Conclusions

We have calculated the expected synchrotron flux from $\lesssim 10^5$–year–old GRB remnants in the Virgo cluster. Although the most revealing signature of a GRB remnant may be the presence of optical-UV recombination lines from high-ionization states of metals (Perna, Raymond, & Loeb 1999), it might be easier to search for nearby GRB remnants in the radio due to the lower background noise (from the sky plus the host galaxy) at radio frequencies. For a non–evolving GRB population, we find that if the spectral index of the shock-accelerated electrons $p < 2.6$, then one could find at least one $\sim 600$–year–old remnant in the Virgo cluster at the VLA detection threshold. Such a remnant should be characterized by a synchrotron spectrum $F_\nu \propto \nu^{-0.8}$ or
flatter.

Perhaps the most poorly constrained parameter of the GRB sources is the beaming fraction $f_b$, the fraction of $4\pi$ steradians into which the initial $\gamma$–ray emission is emitted; the actual event rate may then be enhanced to $f_b^{-1}\Gamma$. However, the total energy released in an event scales as $f_b E_0$, and so the synchrotron flux from the remnant is proportional to $f_b^{0.3+0.5p}$. The decrease in the required energy due to beaming may be counteracted by the fact that the efficiency for producing $\gamma$–rays in the initial event is very low (Kumar 1999). We note that even if the initial (impulsive) energy release is beamed, the deposited energy, $f_b E_0$, will be isotropized at the onset of the non-relativistic expansion phase. In addition, for a uniform distribution of sources in Euclidean space, the number of detectable remnants younger than a given age should decline with decreasing $f_b$ as $\propto f_b^{-1/2} = f_b^{0.75-0.65}$.

Due to the as–yet uncertain nature of the progenitors, it is not clear whether we should expect the GRB rate to directly trace the star formation history. Hence we considered both the SFR–tracing and non–evolving cases in Figure 1. We summarize these results in Figure 2, which shows the upper bound on $p$ as a function of explosion energy for the two cases. The factor of 150 enhancement in the rate for a non–evolving population allows for a greater probability of seeing younger bursts with steeper spectral slopes. It is important to note that if a young ($\lesssim 10^3$ yr) remnant is detected in the Virgo cluster, our results will strongly suggest that the local GRB rate is consistent with the non–evolving scenario, but not with the star–formation–tracing scenario. This is the only immediate way to constrain the local burst rate (short of monitoring the $\sim 10^6$ SDSS galaxies over one year and searching for a GRB explosion). The young radio remnants detected in this case should be well–embedded in the bubble that was ionized by the initial UV flash, and should be detectable in optical recombination lines. If GRBs follow the global star formation history, however, we only expect to see a $\sim 10^5$–year–old remnant in Virgo, which is large and not well-embedded, and will also not be easily detectable at optical wavelengths (Perna, Raymond, & Loeb 1999).

Is it justified to assume that the only significant flux at 1.6 GHz comes from the freshly shocked electrons within a distance $\eta r_s$ behind the shock? Might the electrons which were shocked at $t \sim 1$ yr contribute a substantial amount of flux when the remnant is $10^4$ years old? The Sedov-Taylor similarity solution implies that the volume occupied by the material behind the shock front is increasing with time as $r_s^2$. Hence, the relativistic energy densities of the electrons and magnetic fields scale adiabatically as $u_e' \propto u_b' \propto r_s^{-4}$. The flux at a fixed frequency $\nu$ due to the old electrons is then $F_{\nu}^{\text{old}} \propto t^{-0.8p_{\text{old}}}$, where $p_{\text{old}}$ is the power–law index measured for afterglows at $t \sim 1$ yr; typically $p_{\text{old}} \approx 3$. Using this value, a comparison with equation (18) yields a ratio $F_{\nu}^{\text{old}} / F_{\nu}^{\text{new}} = t^{1.5p_{\text{new}}-4.5}$, where $F_{\nu}^{\text{new}}$ is the flux from newly–shocked electrons. Thus, if $p_{\text{new}} > 3$, the flux from the old electrons will dominate at times $t \gg 1$ yr. For values in the range observed

\footnote{Although it appears that the energy flux $\nu F_\nu \propto \nu^{0.2}$ diverges at high frequencies, recall (cf. Eq. 13) that there is a break in the spectrum at the cooling frequency $\nu_c$, above which, $F_\nu \propto \nu^{-0.3}$.}
in radio SNRs (Li & Chevalier 1999), we are justified in neglecting the contribution from the old electrons.

Our extrapolation to the non-relativistic regime may be tested by continuing to monitor the event GRB 970508, which is at $z = 0.835$ and had a 1.4 GHz flux of $249 \pm 60 \mu$Jy at an age of 354 days (Frail et al. 1999, in preparation).

Our discussion assumed that GRB sources release their energy impulsively in the form of the ultra-relativistic wind that produces the early $\gamma$-ray and afterglow emission. It is possible that more energy is released in the form of non-relativistic ejecta that catches up with the decelerating shock and re-energizes it at late times. In this case, if $f_b = 1$ then the total hydrodynamic energy (and the associated synchrotron flux) may be much larger than we estimated based on the GRB energetics alone. However, the situation might be different if $f_b \ll 1$. Recently, there have been several claims for a potential detection of supernova emission in the light curves of rapidly declining afterglows (Kulkarni et al. 1998b; Bloom et al. 1999; Reichart 1999). We emphasize that any association between supernova and GRB events could be explored more directly in the local Universe by examining the ionization and hydrodynamic structure of SN–like remnants in the interstellar medium of nearby galaxies. For example, one could search for extended ionization cones in young supernova remnants, as expected if the intense UV emission from the associated GRB afterglows is collimated. Complementary information about the shock structure and temperature can be obtained by observations in the radio band (probing the synchrotron emission) or the X-ray regime (probing thermal emission from the hot post-shock gas). In particular, follow-up observations of the energetic X-ray remnants discovered by Wang (1999) in M101 or the optically-faint HI holes discovered by Rhode et al. (1999) in Holmberg II, would be revealing as to the nature of these peculiar objects.

The expanding spherical shock front will typically acquire a diameter of $\sim 1''$ after $10^4$ years at the distance of the Virgo cluster. With VLBI, one can achieve up to sub milli-arcsecond resolution and hence easily resolve the radio-emitting shock. Since the shocked gas occupies a thin shell, the source should be strongly limb-brightened and possibly highly polarized at the limb (Medvedev & Loeb 1999). In the simplest case of an isotropic point explosion, the radio-emitting region will appear embedded inside a much larger region which was ionized by the prompt UV emission from the GRB and which emits optical-UV recombination lines (Perna, Raymond, & Loeb 1999). This distinct structure of a shock embedded in an HII region with high ionization states of heavy elements, is unique to GRB remnants since only the optically-thin wind of a relativistic GRB fireball can give rise to the intense hard radiation which produces a highly-ionized bubble out to large distances $\sim 100$ pc, in front of the shock. This is to be contrasted with ordinary supernovae, in which the UV emission from the optically-thick envelope is suppressed above the thermal cutoff.

We thank Lincoln Greenhill for useful discussions. This work was supported in part by NASA grants NAG 5-7039 and NAG 5-7768.
REFERENCES

Blandford, R. D., & McKee, C. F. 1976, Phys. Fluids, 19, 1130

Bloom, J. S., Fenimore, E. E., & in’t Zand, J. 1996, in Proc. of the Huntsville Symposium on GRBs (New York: AIP), 321

Bloom, J. S., et al. 1999, ApJ, 518, L1

Bloom, J. S., et al. 1999, Nature, in press, astro-ph/9905301

Djorgovski, S. G., et al. 1998, ApJ, 508, L17

Efremov, Y. N., Elmegreen, B. G., Hodge, P. W. 1998, ApJ, 501, L163

Gunn, J. E., & Weinberg, D. H. 1995, in Wide Field Spectroscopy and the Distant Universe, eds. S. Maddox & A. Aragón–Salamanca (Singapore: World Scientific), p. 3

Huang, Y. F., Dai, Z. G., & Lu, T. 1998, A&A, 336, L69

Kobayashi, S., Piran, T., & Sari, R. 1997, ApJ, 490, 92

Kulkarni, S. R., et al. 1998a, Nature, 393, 35

Kulkarni, S. R., et al. 1998b, Nature, 395, 663

Kumar, P. 1999, ApJL, in press, astro-ph/9907096

Li, Z., & Chevalier, R. A. 1999, ApJ, in press, astro-ph/9903483

Loeb, A., & Perna, R. 1998, ApJ, 503, L35

Loveday, J., Peterson, B. A., Efstathiou, G., & Maddox, S. J. 1992, ApJ, 390, 338

Mahadevan, R., Narayan, R., & Yi, I. 1996, ApJ, 465, 327

Marzke, R. O., Geller, M. J., Huchra, J. P., & Corwin, H. G. 1994, AJ, 108, 437

Medvedev, M. V., & Loeb, A. 1999, ApJ, in press, astro-ph/9904363

Mészáros, P., & Rees, M. J. 1997, ApJ, 476, 232

Metzger, M. R., et al. 1997, Nature, 387, 879

Ostriker, J. P, & McKee, C. F. 1988, Rev. Mod. Phys., 60, 1

Paczyński, B., & Xu, G. 1994, ApJ, 427, 708

Perna, R., & Loeb, A. 1998, ApJ, 501, 467

Perna, R., Raymond, J., & Loeb, A. 1999, ApJ, submitted, astro-ph/9904181

Pilla, R. P., & Shaham, J. 1997, ApJ, 486, 903

Pilla, R. P., & Loeb, A. 1998, ApJ, 494, L167

Rees, M. J., & Mészáros, P. 1994, ApJ, 430, L93

Reichart, D. E. 1999, ApJL, in press, astro-ph/9906079

Rhode, K. L., Salzer, J. J., Westfahl, D. J., & Radic, L. 1999, AJ, in press, astro-ph/9904063
Rybicki, G. B., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York: Wiley–Interscience)

Schechter, P. 1976, ApJ, 203, 297

Sedov, L. I. 1959, Similarity and Dimensional Methods in Mechanics (New York: Academic)

Taylor, G. I. 1950, Proc. Roy. Soc. London A, 201, 159

Wang, D. 1999, ApJL, in press, astro-ph/9903246

Waxman, E. 1997a, ApJ, 485, L5

Waxman, E. 1997b, ApJ, 489, L33

Wijers, R. A. M. J., Bloom, J. S., Bagla, J. S., & Natarajan, P. 1998, MNRAS, 294, 13
Fig. 1.— Observed remnant 1.6 GHz flux as a function of age (solid lines) at the Virgo cluster distance $D = 16$ Mpc, for (a) a non–evolving GRB population and (b) a star–formation–tracing GRB population. We show three different power–law indices; the upper and lower values correspond to the range of observed slopes in radio SNRs, while the middle value is such that one remnant should be visible in the Virgo cluster. Shown for comparison is the VLA $5\sigma$ sensitivity level, $F_{\text{VLA}} = 70$ $\mu$Jy (horizontal dotted line), and the corresponding age limit [$t = 600$ yr in panel (a) and $t = 10^5$ yr in panel (b)], such that there should be at least one younger remnant in Virgo. We assume $\xi_b = \xi_e = 0.1$, and $\eta = 1/15$. 
Fig. 2.— Maximum values of the electron power-law slope $p$, such that one remnant will be detectable in the Virgo cluster (assuming $f_b = 1$). We show best-fit results for a non-evolving source population (upper left) and a population which traces the star formation history of galaxies (lower right). The widths of the horizontal line segments reflect the 1σ uncertainty in the burst energy, from Wijers et al. (1998).