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# DISCOVERY OF EARLY OPTICAL EMISSION FROM GRB 021211

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## ABSTRACT

We report our discovery and early-time optical, near-infrared, and radio wavelength follow-up observations of the afterglow of the gamma-ray burst GRB 021211. Our optical observations, beginning 21 minutes after the burst trigger, demonstrate that the early afterglow of this burst is roughly 3 mag fainter than the afterglow of GRB 990123 at similar epochs, and fainter than almost all known afterglows at an epoch of 1 day after the GRB. Our near-infrared and optical observations indicate that this is not due to extinction. Combining our observations with data reported by other groups, we identify the signature of a reverse shock. This reverse shock is not detected to a 3 $\sigma$ limit of 110 $\mu$Jy in an 8.46 GHz Very Large Array (VLA) observation at $t = 0.10$ days, implying either that the Lorentz factor of the burst $\gamma \lesssim 200$ or that synchrotron self-absorption effects dominate the radio emission at this time. Our early optical observations, near the peak of the optical afterglow (forward shock), allow us to characterize the afterglow in detail. Comparing our model to flux upper limits from the VLA at later times, $t \gtrsim 1$ week, we find that the late-time radio flux is suppressed by a factor of 2 relative to the $\gtrsim$80 $\mu$Jy peak flux at optical wavelengths. This suppression is not likely to be due to synchrotron self-absorption or an early jet break, and we suggest instead that the burst may have suffered substantial radiative corrections.

*Subject headings:* galaxies: high-redshift — gamma rays: bursts

## 1. INTRODUCTION

Gamma-ray burst (GRB) afterglow emission on timescales of hours to days, the historical standard for follow-up observations, can provide a robust measure of the global parameters of the GRB, such as its total explosive yield and the density of the circumburst medium on length scales of $r \gtrsim 10^{17}$ cm (Sari, Piran, & Narayan 1998; Wijers & Galama 1999). Early emission, on a timescale of tens of minutes and less, offers insight into the details of the explosion, including the relativistic Lorentz factor of the burst ejecta (Sari & Piran 1999b) and the distribution of the circumburst medium on length scales $r \gtrsim 10^{15}$ cm. This regime should show a clear signature of any dense stellar wind from the GRB progenitor (Chevalier & Li 2000).

These two unique diagnostics, among others, have motivated searches for early optical emission from GRBs. The first success came with the detection of early optical (Akerlof et al. 1999) and radio (Kulkarni et al. 1999) emission from GRB 990123 (Briggs et al. 1999). This emission has been interpreted in terms of a reverse shock plowing back through the GRB ejecta (Sari & Piran 1999a; Mészáros & Rees 1999).

After nearly 4 years, early emission was recently observed again from GRB 021004 (Fox et al. 2003) and GRB 021211 (Fox & Price 2002). These discoveries were made possible by the prompt alerts of the *High Energy Transient Explorer 2* (*HETE-2*) satellite (Ricker et al. 2002) and the wide field and high sensitivity of the 48 inch (1.2 m) Palomar Oschin telescope (P48) equipped with the Near-Earth Asteroid Tracking (NEAT) camera (Pravdo et al. 1999). The increase in the number of robotic telescopes allowed intensive early-time follow-up of both of these bursts. Here we report the discovery of early optical emission and subsequent multiwavelength follow-up observations of GRB 021211.

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## 2. OBSERVATIONS

GRB 021211 (*HETE* trigger 2493) was detected at UT 11:18:34 on 2002 December 11. With a duration of 6 s and a fluence of $10^{-6}$ ergs cm$^{-2}$ (8–40 keV), the event is a typical long-duration GRB (Crew et al. 2002). The initial *HETE-2* localization, although large (30′ radius), was covered by the 1°.1 × 1°.1 field of view of the NEAT camera. We identified a new source that was not present in the Palomar Sky Survey (Fig. 1) and announced this as a possible optical counterpart of GRB 021211 (Fox & Price 2002). The best *HETE-2* localization at the time of our discovery was 14′ in radius; a subsequent soft X-ray camera (SXC) localization produced the 2′ radius circle shown in Figure 1. The position of the optical transient (OT) with respect to the Guide Star Catalog II is $\alpha = 08^{h}08^{m}59^{s}.858$, $\delta = +06°43'37''.52$ (J2000), with a 0″.1 estimated uncertainty. We continued monitoring with P48, the 40 inch telescope at Siding Spring (SSO-40), and the Palomar Hale 5 m (P200) telescope with JCAM (Bloom et al. 2003). Photometry has been performed using the secondary calibrators of Henden (2002); see Table 1.

Our optical source was subsequently identified in images obtained by several robotic telescopes and other ground-based facilities. In particular, RAPTOR (Wozniak et al. 2002), KAIT (Li et al. 2002), and S-LOTIS (Park, Williams, & Barthelmy 2002) detected the source 90, 108, and 143 s after the burst, respectively. In Figure 2, we present the light curve obtained by combining data from these and other GCNs with our data.

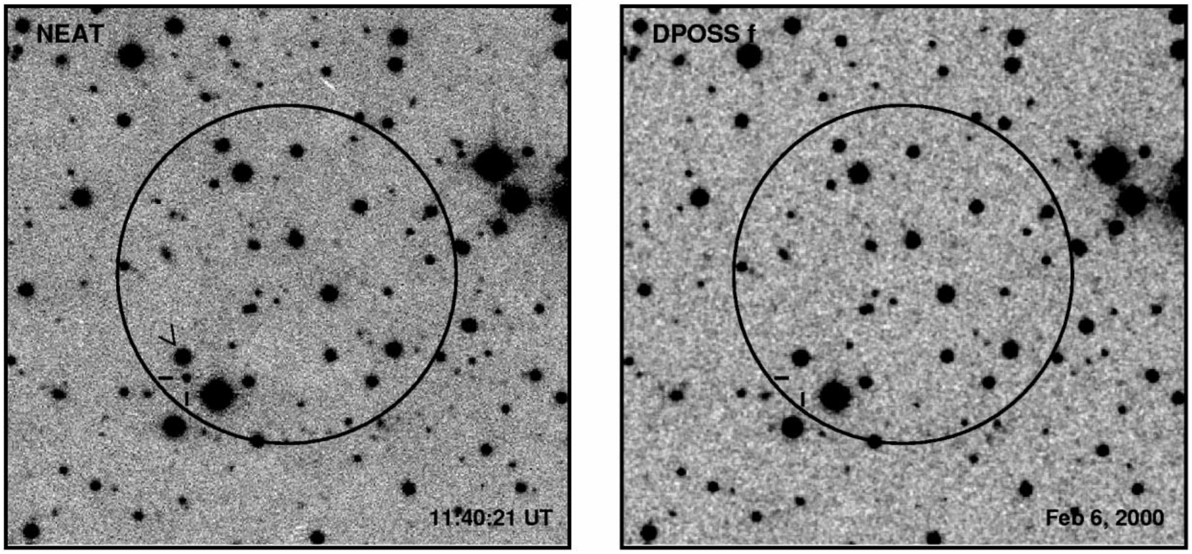


FIG. 1.—Discovery image of the optical afterglow of GRB 021211, as obtained with the NEAT camera on P48, 21 minutes after the burst (*left*). The *R*-band (f-emulsion) Palomar Digital Sky Survey (DPOSS) image of the GRB localization region is shown for comparison (*right*). The afterglow is marked by two dashes. The circle of 2′ radius marks the subsequent SXC localization. The position of S1, one of our secondary standards for NIR photometry (§ 2), is indicated by a carat on the NEAT image; S2 is not visible in either image. Coordinates of S1 are $\alpha = 08^{h}09^{m}00^{s}.0$, $\delta = +06°43'52''$ (J2000), and coordinates of S2 are $\alpha = 08^{h}09^{m}00^{s}.3$, $\delta = +06°43'38''$ (J2000).

*Near-infrared*.—We observed the afterglow in the near-infrared with the Cassegrain f/70 low-background secondary and D-78 infrared camera (Soifer et al. 1991) on P200 on December 11.55 UT ($K_s$ band) and with NIRC (Matthews & Soifer 1994) on the Keck I 10 m telescope on December 18.5 UT ($JHK_s$). NIRC observations were photometered relative to SJ 9116 and SJ 9134 (Persson et al. 1998), and the P200 zero point was determined from the NIRC observations by reference to two secondary calibrators, S1 and S2 (see Fig. 1). Our results are given in Table 1.

*Radio*.—We searched for radio emission with the Very Large Array (VLA)[8]; our initial observation at $t = 2.44$ hr represents the earliest radio observation of any GRB to date. We used PKS 0734+100 for phase calibration and 3C 147 and 3C 286 for flux calibration. No counterpart to the OT is detected in any single observation. Adding the data between 2002 December 20 and 2003 January 6, we measure an 8.46 GHz upper limit of 35 $\mu$Jy at the position of the OT. Peak flux densities at the position of the OT can be found in Table 2.

Separately, on December 12.51 UT, we carried out an ob-

[8] The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

TABLE 1
OPTICAL PHOTOMETRY FOR GRB 021211

| Date (UT) | $\Delta T$ (days) | Telescope | Filter | Magnitude | Error |
|---|---|---|---|---|---|
| Dec 11.4854 ...... | 0.0144 | P48 | *R*[a] | 18.293 | 0.024 |
| Dec 11.4962 ...... | 0.0252 | P48 | *R*[a] | 18.813 | 0.045 |
| Dec 11.4997 ...... | 0.0287 | P48 | *R*[a] | 19.093 | 0.059 |
| Dec 11.5064 ...... | 0.0354 | P48 | *R*[a] | 19.343 | 0.071 |
| Dec 11.5120 ...... | 0.0410 | P48 | *R*[a] | 19.286 | 0.068 |
| Dec 11.5139 ...... | 0.0429 | P48 | *R*[a] | 19.479 | 0.077 |
| Dec 11.5218 ...... | 0.0508 | P48 | *R*[a] | 19.529 | 0.082 |
| Dec 11.5251 ...... | 0.0541 | P48 | *R*[a] | 19.598 | 0.086 |
| Dec 11.5270 ...... | 0.0560 | P48 | *R*[a] | 19.755 | 0.102 |
| Dec 11.5332 ...... | 0.0622 | P48 | *R*[a] | 19.950 | 0.110 |
| Dec 11.5399 ...... | 0.0689 | P48 | *R*[a] | 20.091 | 0.130 |
| Dec 11.5533 ...... | 0.0823 | P200/IRcam | $K_s$ | 18.01 | 0.150 |
| Dec 11.6025 ...... | 0.1310 | SSO-40/WFI | *B* | 21.877 | 0.138 |
| Dec 11.7083 ...... | 0.2370 | SSO-40/WFI | *R* | 21.096 | 0.128 |
| Dec 12.518 ....... | 1.037 | P200/JCAM | $g'$ | 23.398 | 0.047 |
| Dec 12.518 ....... | 1.037 | P200/JCAM | $r'$ | 23.416 | 0.073 |
| Dec 18.49 ......... | 7.019 | Keck I/NIRC | $K_s$ | 22.12 | 0.18 |
| Dec 18.52 ......... | 7.049 | Keck I/NIRC | *J* | 22.77 | 0.11 |
| Dec 18.56 ......... | 7.089 | Keck I/NIRC | *H* | 22.48 | 0.16 |

[a] P48 unfiltered observations have been photometered against the *R*-band calibration of Henden 2002.

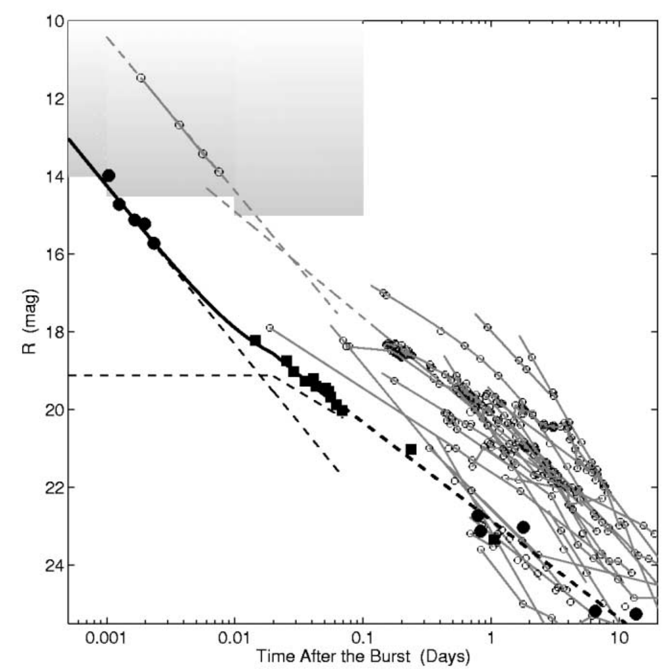


FIG. 2.—Light curve of GRB 021211 and other GRBs, including a two-component flare+afterglow fit for the early optical emission from GRB 021211. The data for GRB 021211 are drawn from the GCN literature (*circles*; see text as well as Levan et al. 2002 and McLeod et al. 2002) and this work (*squares*; Table 1). We fitted the data at $t < 0.1$ days only (see § 3.2 for details); the dotted line at $t > 0.1$ days is merely illustrative. The last two points ($t > 5$ days) are derived from *Hubble Space Telescope* observations (Fruchter et al. 2002) and should be largely free of host contamination. The data for other GRBs are drawn from the literature (see Berger et al. 2002).

TABLE 2
Radio Observations of GRB 021211

| Date (UT) | $\Delta T$ (days) | Telescope | Frequency (GHz) | Flux ($\mu$Jy) | Flux Error ($\mu$Jy) |
|---|---|---|---|---|---|
| 2002 Dec 11.57 ....... | 0.10 | VLA | 8.46 | 12 | 36 |
| 2002 Dec 12.39 ....... | 0.92 | VLA | 8.46 | −36 | 22 |
| 2002 Dec 13.40 ....... | 1.93 | VLA | 8.46 | 9 | 45 |
| 2002 Dec 13.40 ....... | 1.93 | VLA | 22.5 | 48 | 62 |
| 2002 Dec 15.32 ....... | 3.85 | VLA | 8.46 | 45 | 23 |
| 2002 Dec 16.29 ....... | 4.82 | VLA | 8.46 | −6.5 | 19 |
| 2002 Dec 20.32 ....... | 8.85 | VLA | 8.46 | 60 | 28 |
| 2002 Dec 22.26 ....... | 10.79 | VLA | 8.46 | 0.3 | 27 |
| 2002 Dec 26.44 ....... | 14.97 | VLA | 8.46 | −7.3 | 23 |
| 2002 Dec 28.55 ....... | 17.08 | VLA | 8.46 | 33 | 28 |
| 2003 Jan 04.39 ........ | 23.92 | VLA | 8.46 | 2.4 | 24 |
| 2003 Jan 06.28 ........ | 25.81 | VLA | 8.46 | 46 | 24 |
| Dec 20–Jan 06 ...... | | VLA | 8.46 | 15 | 10 |

servation in the 347 GHz band with the Submillimeter Common-User Bolometer Array on the James Clark Maxwell Telescope.[9] We used CRL 618 as the secondary flux standard. At the position of the OT, we measure a 347 GHz flux density of $2.0 \pm 2.5$ mJy.

## 3. A TWO-COMPONENT LIGHT CURVE

Three bursts have had early-time optical detections: GRB 990123 (Akerlof et al. 1999), GRB 021004 (Fox et al. 2003), and GRB 021211. At early epochs, GRB 021211 is more than 3 mag fainter than GRB 990123, and at later epochs ($t \gtrsim 1$ day), it is fainter than the great majority of afterglows (Fig. 2). As we show below, this is not the result of extinction in the host galaxy, so this burst reminds us that many so-called dark bursts may simply be faint (Fynbo et al. 2001; Berger et al. 2002).

Examining Figure 2, we see that the early behavior of GRB 021211 bears a striking resemblance to the light curve of GRB 990123 (see Chornock et al. 2002). The light curve can be considered as composed of two segments: an initial steeply declining "flash," $f \propto t^{-\alpha}$ with $\alpha_{\rm rs} \approx 1.6$, followed by emission declining as a typical afterglow, $\alpha_{\rm fs} \approx 1$.

The optical flash is thought to result from a reverse shock propagating into the GRB ejecta (Sari & Piran 1999a), while the afterglow arises in the shocked ambient material swept up by the ejecta (Sari et al. 1998). A fixed fraction of the energy of each shock is assumed to be partitioned into energetic electrons ($\epsilon_e$) and magnetic fields ($\epsilon_B$). The electrons follow a power-law distribution in energy, $dN/d\gamma \propto \gamma^{-p}$ for $\gamma > \gamma_m$, where $\gamma$ is the electron Lorentz factor, so that their collective emission follows $f_\nu \propto \nu^{-(p-1)/2}$ at frequencies above the synchrotron peak frequency $\nu_m$ and $f_\nu \propto (\nu/\nu_m)^{1/3}$ otherwise. Below the self-absorption frequency $\nu_a$, synchrotron self-absorption becomes important, and above the characteristic cooling frequency $\nu_c$, electrons lose their energy rapidly, on the timescale of the shock evolution.

The forward and reverse shocks evolve differently. Once the reverse shock has passed through the ejecta shell, no new electrons are accelerated and the shocked electrons cool adiabatically: $\nu_m \propto t^{-73/48}$, with the flux at $\nu_m$ (the "peak" flux) decaying as $F_{\nu_m} \propto t^{-47/48}$ (Sari & Piran 1999b); for $\nu > \nu_c$, the emission decreases even more rapidly. In contrast, electrons are continually added to and accelerated at the forward shock; in the case of a uniform circumburst medium, $F_{\nu_m}$ is constant, and even above $\nu_c$, the flux declines only slowly. Since in a stellar wind–type circumburst medium ($\rho \propto r^{-2}$) the reverse shock $\nu_c$ is inevitably below the optical band, detection of long-lived reverse-shock emission for GRB 021211 rules out wind models for this burst (Chevalier & Li 2000).

### 3.1. *The Reverse-Shock Flare*

The optical flux is already declining at the first epoch (Wozniak et al. 2002), when $t = t^* = 90$ s and $R_c = 14$ mag, corresponding to $f = f^* = 7.7$ mJy at a frequency of $\nu_o = 4.7 \times 10^{14}$ Hz; here the asterisk identifies quantities taken at $t = 90$ s. This implies that $\nu_m^* < \nu_o$ and constrains the time when the flare spectral peak $\nu_m$ passes through the optical bandpass to be $t_{m,o} < t^*$. Since the observed decline at $t > t^*$ is not very rapid, $\alpha_{\rm rs} \lesssim 2$, we also have $\nu_c^* > \nu_o$.

The constraint on the time of the optical peak flux can be converted into a constraint on the Lorentz factor $\gamma$ of the GRB ejecta. From Sari & Piran (1999b), we have $t_{\rm peak} = 5 n_0^{-1/3} \gamma_{300}^{-8/3} E_{52}^{1/3}$ s (thin-shell case), where $t_{\rm peak}$ is the time at which the reverse shock crosses the GRB ejecta, $n_0$ is the circumburst particle density per cubic centimeter, $\gamma_{300}$ is $\gamma/300$, and $E_{52}$ is the isotropic-equivalent burst energy in units of $10^{52}$ ergs. Since $t_{\rm peak} < t_{m,o} < t^*$, we find that $\gamma > 100 n_0^{-1/8} E_{52}^{1/8}$.

The prompt emission fluence of $10^{-6}$ ergs cm$^{-2}$ (8–40 keV), together with the proposed redshift, $z = 1.006$ (Vreeswijk et al. 2002), yields an isotropic $\gamma$-ray energy $E_{\rm iso} = 3 \times 10^{51}$ ergs for GRB 021211. Since this fluence is measured over a relatively narrow band, application of a GRB $k$-correction (Bloom, Frail, & Sari 2001) should give $E_{52} \sim 1$.

Following Sari & Piran (1999a), in the absence of self-absorption, the radio flux follows $F_r \propto t^{-17/36}$ for times $t < t_{m,r}$ and $F_r \propto t^{-\alpha_{\rm rs}}$ for times $t > t_{m,r}$, where $t_{m,r}$ is the time when $\nu_m$ passes through the radio band, $\nu_r = 8.5$ GHz. The value of $t_{m,r}$ follows from the relation $t_{m,r} = t_{m,o}(\nu_o/\nu_r)^{48/73}$, which gives $t_{m,r} = 1.35$ day in the limiting case $t_{m,o} = t^*$. By this time, the peak flux will have declined as $F_{m,r} = F_{m,o}(t_{m,r}/t_{m,o})^{-47/48}$. Note that we are temporarily ignoring extinction effects, which are discussed in § 3.2.

For $t_{m,o} < t^*$, we extrapolate the observed optical flux decay back in time as $F_{m,o} = f^*(t_{m,o}/t^*)^{-\alpha_{\rm rs}}$. The light curve of the radio flare is thus a direct function of $t_{m,o}$:

$$F_r(t \le t_{m,r}) = 8.9 \times 10^{-4} f^* \left(\frac{t_{m,o}}{t^*}\right)^{-\alpha_{\rm rs}} \left(\frac{t}{t_{m,r}}\right)^{-17/36}, \qquad (1)$$

with the decay past $t_{m,r}$ steepening to $t^{-\alpha_{\rm rs}}$. Our 3 $\sigma$ upper limits at $t = 0.10$ days and $t = 0.92$ days are 110 and 66 $\mu$Jy, respectively. For $\alpha_{\rm rs} \approx 1.6$ (§ 3.2), the radio flux at $t = 0.92$ days is predicted to be ~15 $\mu$Jy, more or less independent of $t_{m,o}$. The radio flux at $t = 0.10$ days is a strong function of $t_{m,o}$, however, and equation (1) gives $t_{m,o} > 20$ s and $F_{m,o} < 135$ mJy.

A lower limit on $t_{m,o}$ implies an upper limit on the Lorentz factor of the ejecta, $\gamma < 180 n_0^{-1/8} E_{52}^{1/8}$. Following the treatment of Sari & Piran (1999a), however, we find that synchrotron self-absorption may be suppressing the radio flux below the level of equation (1), which would render this limit invalid.

### 3.2. *The Forward-Shock Afterglow*

A variety of afterglow light curves are possible (Kobayashi 2000), but the form of sharp rise, plateau, and power-law decay is near universal. Given the bright flare, we cannot constrain the rising portion of the afterglow light curve. We fitted the flare as a power-law decay of index $\alpha_{\rm rs}$ and the afterglow as

[9] The James Clerk Maxwell Telescope is operated by the Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council of the UK, the Netherlands Organization for Scientific Research, and the National Research Council of Canada.

a constant flux $f_m$, which undergoes a power-law decay with index $\alpha_{fs}$ for $t > t_b$ (Fig. 2).

We first examine the constraints on the reverse-shock decay. Published GCN data are sufficient to constrain $\alpha_{rs} = 1.63 \pm 0.13$, and since $\alpha_{rs} = 47/48 + 73/48\,[(p-1)/2]$ (Sari & Piran 1999a), this implies that $p = 1.85 \pm 0.17$.

The gap between the GCN data and our P48 measurements creates fitting degeneracies in the full model, so we fix $\alpha_{rs}$ at three successive values, 1.50, 1.63, and 1.76, and make fits to the full data set. Incorporating the range in parameter uncertainties covered in these three fits, we find that $\alpha_{fs} = 0.80 \pm 0.13$, $f_m = 65 \pm 20$ $\mu$Jy, and $t_b = 1700 \pm 280$ s. Note that because the flare dominates the afterglow emission at early times, our fitted $f_m$ should be considered a lower limit, and our $t_b$ an upper limit.

We can measure the power-law slope of the spectrum, $\beta_{obs} = -0.98$, using our $B$ and $K_s$ photometry near $t = 0.1$ days (correcting first for Galactic extinction of $A_R = 0.07$ mag; Schlegel, Finkbeiner, & Davis 1998). If $\nu_c < \nu_o$ at this time, then $\alpha_{fs} = \frac{3}{4}(p-1) + \frac{1}{4}$, $p = 1.7 \pm 0.2$, and $\beta = -p/2 = -0.85 \pm 0.1$, implying little extinction in the host, $A_R = 0.15 \pm 0.18$ mag in the observer frame. On the other hand, if $\nu_c > \nu_o$ at this time, then $\alpha_{fs} = \frac{3}{4}(p-1)$, $p = 2.1 \pm 0.2$, and $\beta = -(p-1)/2 = -0.55 \pm 0.1$, corresponding to an intrinsic reddening of $A_R = 0.48 \pm 0.18$ mag (observer frame). In either case, extinction within the host cannot explain the ~2 mag gap between the $R$-band light curve and those of most afterglows.

Since we do not know the location of $\nu_c$ relative to the optical band, we adopt an average extinction correction of $A_R = 0.3$ mag. This corrects our limiting peak flux of $f_m \gtrsim 65$ $\mu$Jy to an unextinguished flux of $F_m \gtrsim 85$ $\mu$Jy.

From our model fits, $\alpha_{fs} = 0.80 \pm 0.13$, so that $F_m \approx 85(t_{m,o}/t_b)^{-0.8}$ $\mu$Jy. We can use this relation along with equations (4.3) and (4.5) of Sari & Esin (2001) to estimate the circumburst density on length scales of $r \sim 2\gamma^2 t_b c \lesssim 10^{18}$ cm. We find that $n_0 = 0.1\epsilon_{B,-2}^{-23/15}\epsilon_{e,-1}^{-32/15}E_{52}^{-38/15}$, where $\epsilon_e = 0.1\epsilon_{e,-1}$. Since we have $E_{52} \sim 1$ (§ 3.1), this implies either a low-density circumburst medium or abnormally low values of $\epsilon_B$ or $\epsilon_e$.

In the absence of self-absorption, the radio afterglow can be expected to peak at time $t \lesssim t_b(\nu_o/\nu_r)^{48/73} \lesssim 25$ days. In the standard model, the synchrotron peak flux $F_m$ remains constant as the peak frequency decreases, so we expect a radio peak flux of roughly 85 $\mu$Jy. Prior to the peak time, $\nu_r < \nu_m$, and $F_r \sim t^{0.5}$. At the mean epoch of our summed image, $t = 17.3$ days, we expect $F_r \sim 70$ $\mu$Jy, and our 2 $\sigma$ upper limit is $F_r < 35$ $\mu$Jy, a factor of 2 below the predicted level.

We can estimate the self-absorption frequency (eq. [4.1] of Sari & Esin 2001) in terms of the peak flux, $\nu_a = 0.7E_{52}^{-9/20}n_0^{3/20}(F_m/85\ \mu\mathrm{Jy})^{1.86}$ GHz. Self-absorption will be effective in the case of a high circumburst density—unlikely on the basis of our $n_0$ estimate—or if $F_m$ is sufficiently large. In the latter case, at fixed frequency, the effects of increasing self-absorption win out over the raw increase in flux. Suppressing the radio flux by a factor of 2, however, requires $F_m \gtrsim 800$ $\mu$Jy ($t_{m,o} \lesssim 100$ s), which seems unlikely.

The discrepancy between the observed and expected fluxes can be due to an early jet break, $t_{jet} < t_{m,r}$ (Rhoads 1999; Sari, Piran, & Halpern 1999). The optical light curve, however, shows no sharp steepening out to $t \gtrsim 10$ days (Fig. 2). Moreover, the measured fluence and proposed redshift $z = 1.006$ for GRB 021211 are consistent with minimal beaming for a "standard candle" burst ($E_{iso} \sim 5 \times 10^{50}$ ergs; Frail et al. 2001), so that an early jet break seems an unlikely scenario.

Alternatively, the afterglow radiative corrections (Sari 1997; Cohen, Piran, & Sari 1998) may be significant. In the slow-cooling regime ($\nu_c > \nu_m$), radiative corrections can be substantial if $\epsilon_e$ is large ($\epsilon_e \gtrsim 0.1$), $\nu_c$ is close to $\nu_m$, or $p$ is close or equal to 2. We have not derived an estimate for $\epsilon_e$, but $p \approx 2$ for our models, so this scenario remains an attractive candidate for future modeling.

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