The afterglow of GRB 971214: determination of its physical parameters

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Abstract. The discovery of long-lived X-ray emission[1] that accompanies gamma-ray bursts (GRB) has revolutionized the field of GRBs. This "afterglow" emission is most easily explained by models[2,3,4] similar to supernovae models, but with relativistic ejecta. Afterglow measurements offer us convenient diagnostics of the burst, the energy released, the geometry of the emitting surface and the density of the ambient medium. Here we report infrared (IR) observations of the optical transient[5] (OT) of GRB 971214[6]. We have detected a break in the broad-band spectrum of the OT. Such a break is predicted by afterglow models. From the measurement of the

frequency of the break alone, we constrain the total energy in the GRB to be $> 10^{51}$ erg, independent of the ambient density. Combining the fluence of the afterglow with the redshift reported by Kulkarni et al.,[7] we deduce an energy release in the afterglow alone of 2×10^{51} erg. In all models, the optical and IR afterglow is emitted when the ejecta is moving considerably slower (smaller Lorentz factor) relative to when the gamma-rays are emitted. Consequently, the energetics inferred from the afterglow are subject less to the unknown geometry of the emitting source that plague similar estimates obtained from gamma-ray emission. GRBs may be more energetic than the conventional 10^{51} erg assumed so far.

Our primary goal was to infer fundamental parameters of the burst from observations. As explained in detail below, one of the best diagnostics is a single broad-band spectrum of the OT (optical, near infrared (IR) and radio) at a given time. Consequently we undertook observations in the near infra-red (IR) band and at radio wavelengths. Observations in the optical band began on the Keck II telescope as soon as we were notified of the localization by the Wide Field Camera[6] aboard the X-ray satellite BeppoSAX. These observations are discussed in the companion paper[7].

The near IR observations were initiated on the Keck I telescope only after the receipt of the tighter localization (90% confidence radius of 1 arcminute) resulting from observations of the X-ray afterglow[8] by the Narrow Field Instruments (NFI), also BeppoSAX. We used the Near Infrared Camera[9] (NIRC) with an InSb Hughes-SBRC array (256×256 pixels) and imaged in the K_s band. The log of the observations can be found in Table 1. Despite the tight NFI localization, the small field of view of NIRC (38 arcsecond $\times$ 38 arcsecond) required in a large number of NIRC pointings to cover the error circle.

The OT is quite well detected in the December 15 data (Figure 1). The K-band magnitude of the OT at epoch UT 1997 December 15.58 is found to be 19.4±0.2 mag (see Table 1). The same sequence of NIRC pointings was repeated the next night but with a revised NFI localization which unfortunately did not include the OT[5]. We obtained considerably deeper observations in February (see Table 1). No object was detected at the position of the OT. The 3-σ upper limit to a point source in the obtained by combining the two February datasets is 22.5 mag. The limit for an extended source is weaker. The absence of an IR source is not surprising given the power law decay exhibited by the OT at optical frequencies[10,7]. However, Kulkarni et al.[7] report the detection of a R=25.6 magnitude galaxy at the position of the OT and suggest that this is the host of the GRB. This galaxy is found to have a redshift[7] of 3.4 and a spectrum similar to star-forming galaxies[11] at such redshifts. The R−K color for such galaxies is found to be 2.3 to 3.0 mag (K. L. Adelberger, pers. comm.). This is consistent with our K-band limit.

Observations at 8.46 GHz and centered on the position of the fading X-ray source[8] were conducted with the Very Large Array (VLA) on UT 1997 December 15.67, 16.34, 18.33, 20.28 and UT 1998 January 03.38. The rms noise in the images obtained from each of the observations ranged from 50 μJy beam^{-1} to 11 μJy beam^{-1}. The rms in the summed image is 7.8 μJy beam^{-1}. No radio counterpart to the OT was seen in any of these images.

The lower energy emission – X-ray, optical, IR and radio – that follows some of the bursts is referred to as the afterglow emission. The simplest afterglow model[3,2,4] posits an instantaneous release of energy (E_0) and "ejecta" (mass, M_B) in a homogeneous medium (particle density, n_0). The ejecta sweep up the ambient gas and shock-accelerate electrons to a power law energy distribution. The energy fractions in electrons and post-shock magnetic fields are assumed to be close to the equipartition values. These three assumptions are routinely used to explain shocks at other astrophysical sites such as supernovae and jets in active galactic nuclei. The afterglow is due to synchrotron emission by the relativistic electrons. This model appears to explain quite well multi-wavelength observations of GRB 970228 (ref. 12) and 970508 (ref. 13,14,15).

A generic prediction of such models is that the spectrum of the afterglow has the following form:

$$f(\nu) = S_0(\nu/\nu_b)^{-\alpha}, \qquad \nu > \nu_b, \tag{1a}$$

$$= S_0(\nu/\nu_b)^{\beta}, \qquad \nu < \nu_b. \tag{1b}$$

The power law exponent α is related to the power law distribution of the electron energies. The exponent β depends weakly on the low-energy electron tail of the shocked electrons; a robust value is 1/3 (ref. 16). ν_b is the "break" frequency and is expected to evolve as follows[16]:

$$\nu_b = 2 \times 10^{14} (\frac{1+z}{2})^{1/2} (\xi_e/0.2)^2 (\xi_B/0.1)^{1/2} E_{52}^{1/2} t_{\rm day}^{-b} \ \rm Hz, \tag{2}$$

with $b = 3/2$. Here ξ_e and ξ_B are fractions which measure the degree to which the electrons and magnetic fields are in equipartition with respect to the shocked protons. The total energy of the GRB is $E_0 = 10^{52} E_{52}$ erg and z is the redshift of the burst.

Two assumptions are implicit in the above discussion. (1) The shock is non-radiative, i.e. the cooling time for bulk of the synchrotron emitting electrons is larger than the "dynamical" time over which the relativistic blast wave evolves. According to Waxman et al.[17] the radio and the optical observations of GRB 970508 strongly support this assumption. (2) At any given time, electrons producing high frequency radiation cool more rapidly than those producing low frequency radiation. This gives rise to another break at high frequencies. Sari et al.[18] suggest that the late time optical afterglow of GRB 970508 is in this regime. We address this concern below.

From the Equations (1-2) it is straightforward to demonstrate that at a fixed frequency $\nu > \nu_b$, the flux decays as $S_\nu(t) \propto t^{-a}$, where $a = b\alpha$. Thus α can either be measured directly from the spectrum or from observations of the light curve in a fixed band. A measurement of a spectrum across a large range in frequency (broad-band) at an epoch, say t_* (here and below, all times are measured with respect to the GRB event), yields S_0, $\nu_* \equiv \nu_b(t_*)$, α and β. As can be seen from Equations (1-2), once these parameters are known the subsequent evolution of the afterglow emission is fully determined.

In Figure 2 we display the observed fluxes of the OT across the optical[10,19,7] bands, a near-IR band[20] and our own K-band measurement; all these measurements were made around UT 1997 December 15.5. As can be seen from this figure, the broad-band spectrum of the OT has roughly the shape described by Equation (1). However, there is one notable discrepancy. From Equations (1-2) we predict that $\alpha = a/b = 0.8 \pm 0.15$. Instead, the the power law index for the *observed* VRI fluxes is 2.13 ± 0.04 (see Figure 2). This discrepancy has already been noted[10,21] and attributed to extinction by intervening dust. Dust preferentially extinguishes (absorbs and scatters) shorter wavelength light, steepening the curve.

Correction for extinction by dust requires knowledge of the wavelength dependence of extinction by dust (the extinction law) in the host galaxy of the OT. The data for other galaxies, even the two nearest (the Large and the Small Magellanic Cloud) are scanty. We assume a simple dust extinction law (extinction optical depth proportional to inverse wavelength) and deduce the extinction from the observed VRI measurements (see Figure 2). As can be seen from Figure 2, the observed as well as the extinction-corrected J and K fluxes are well below the extrapolation of the model. One interpretation is that extinction correction has a more complicated frequency dependence. We prefer the simpler interpretation that the optical-IR broad-band spectrum exhibits the two component structure described by Equation 1. This interpretation is fully consistent with our 3-σ upper limit on the 8.46-GHz flux discussed earlier. Accepting this interpretation, we find that the break frequency is $\nu_* \sim 3 \times 10^{14}$ Hz (corresponding to a wavelength of 1 μm) at a post-burst time of $t_* = 0.58$ d. We remark that the significant change in slope across 1 μm is inconsistent with the idea that this break is due to electron cooling discussed above[18].

The determination of ν_* allows us to determine the energy of the GRB in an elegant manner. Substituting ν_* and t_* into Equation (2) we find

$$E_{52} = 0.44\Big(\frac{2}{1+z}\Big)\Big(\frac{\xi_e}{0.2}\Big)^{-4}\Big(\frac{\xi_B}{0.1}\Big)^{-1} \tag{3}$$

In this equation the equipartion factors are set close to their maximum value (their sum clearly cannot exceed the contribution from protons). Thus, *independent of the ambient density,* n_0, we note that $E_{52} > 0.1$. The dependence on the red-shift is weak and curiously enough is stronger for smaller values of z.

A notable prediction of this hypothesis is that the OT should be detected in the radio with a flux of about 13 μJy. For GRB 970508 the radio flux rose rapidly and reached the peak value within a few weeks[22,17]. Thus transparency at radio wavelengths is probably not an issue. We eagerly look forward to further radio observations of GRB 971214.

The fluence in the afterglow, integrated up to photon energy $E_m = h\nu_m$, can be shown to be $F_A = [a/(a-1)][b/(b-1)]S_0 t_* \nu_* (\nu_m/\nu_*)^{(b-1)/b}$. We obtain $F_A = 7 \times 10^{-8}(E_m/10\,\mathrm{eV})^{1/3}$ erg cm^{-2}. The X-ray emission dominates the energy budget of the afterglow. However, at early times (when the aftgerglow is mainly X-ray emission) our assumption of non-radiative shock may not be valid. For this reason we restrict the estimation of the fluence to lower photon energies.

Kulkarni et al.[7] have proposed that the OT lies in a galaxy with red-shift $z = 3.418$. The luminosity distance (d_L) for a Hubble constant, $H_0 = 65$ km s^{-1} Mpc^{-1} and $\Omega = 0.3$ is 9.7×10^{28} cm. The luminosity in the afterglow, assuming spherical symmetry, is $E_A(E_m < 10\,\mathrm{eV}) = 4\pi d_L^2 (1+z)^{-1} F_A = 1.9 \times 10^{51}$ erg. The gamma-ray fluence as observed by the Gamma-ray Burst Monitor (GRBM) aboard BeppoSAX is $(0.9 \pm 0.09) \times 10^{-5}$ erg cm^{-2} s^{-1} (above 40 keV); the fluence[23] as measured by the Compton Gamma-ray Observatory (above 20 keV) is $(1.09 \pm 0.07) \times 10^{-5}$ erg $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. Thus the inferred isotropic energy loss is $\sim 3 \times 10^{53}$ erg. This is remarkably coincident with the gravitational binding energy released during the merger of two neutron stars[24].

Even though E_G is much greater than E_A, the afterglow measurements pose a clear problem to GRB models. At the time the gamma-rays are emitted, the shocked gas is moving with very large Lorentz factor (Γ). The initial Γ is assumed to be 10^2 to 10^3 and expected to evolve as $t^{-3/8}$. Due to relativistic beaming only a small portion, solid angle $\sim \Gamma^{-2}$, of the fireball is visible to us. Hence we remain ignorant of the true shape of the fireball. The estimate of E_G can be reduced by positing the emitting surface to be a narrow jet directed towards the observer. However, Γ is smaller during the optical afterglow emission as compared to that during the gamma-ray emission. Relativistic beaming is less of a limitation and the full extent of the fireball is gradually revealed to the observer. The monotonic power law decay at optical wavelengths seen in the OTs of previous transients[13,14,15] is not consistent with the narrow jet-like emitting surfaces. However, we recognize that more complicated models (in which energy is injected non-spherically) could account for such monotonic decays whilst having non-spherical geometry. However, the main issue that we discuss here is the inferred energetics. It is by no means clear that the energy requirements inferred from afterglow observations (when the Lorentz factor is small) is any lower than the simplest case considered here.

According to the afterglow models discussed here, the afterglow emission is supposed to arise from non-radiative shocks i.e. the efficiency of the shock in converting E_0 (the total energy in the GRB event) to afterglow radiation is low. Thus, E_0 is significantly larger than the E_A reported above. This finding is in direct contrast to the assumptions made by most practitioners in this field, viz. $E_0 = 10^{51}$ erg. As as aside we note that Equation 1 predicts that the break frequency should evolve with time as $t^{-3/2}$. Measurement of the break frequency at successive epochs for future bursts offers the possibility of directly confirming or refuting the non-radiative shock assumption.

The evidence presented here favors GRB models which produce energy vastly in excess of 10^{51} erg; see for example, ref. 24,14,25. The afterglow emission is similar in nature to the emission from supernovae but more energetic by two orders of magnitude. Following the naming sequence, nova and supernova, it is only appropriate to refer to GRB afterglow as hypernova[14].

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Table 1. Log of K band observations

UT	Date	Band	Integration (s)	Magnitude	Seeing (")	Observer
1997 December	15.61	K_s	9×20	19.4	0.7	C. Koresko
1997 December	16.66	K_s	9×20	(a)	0.7	C. Koresko
1998 February	07.46	K	1200	> 21.5 (b)	0.4	G. Neugebauer
1998 February	10.56	K	4320 (c)	> 22.1 (c)	0.5	R. Goodrich

Notes: The K_s band covers the range 1.99–2.32 μm. The K band filter covers the range 2.00–2.427 μm. All quoted magnitudes have been transformed to the K band. The K band magnitude of the OT was measured with respect to stars H1 and H2 (Figure 1). One of us (GN) observed the field of OT on UT 1998 February 7, 1998 and the standard star SC 9139 (E. Persson, pers. comm.) and derived K=16.26±0.03 for H2. This set the zero point for all of our K and K_s observations. The derived K magnitude for H1 is 15.31 ± 0.03 which agrees very well with that expected from its BVR (ref. 26) and I (ref. 10) colors.

(a) The mosaic did not include the position of the OT. See text.

(b) The 1-σ limit for a bema of 1.5 arcsecond diameter is K = 23.5 mag. The limit quoted in the Table is the 3σ limit for a point source. This was obtained by injecting fake point sources with a similar point spread function as H2 and then using IRAF task DAOFIND to detect the object.

(c) We employed a 9-position dither pattern with exposure time of 30 seconds at each position. Sixteen of these dither patterns were summed together for a total exposure time of 72 minutes. Each individual frame within a dither pattern was shifted and added according to the commanded telescope offsets; the scarcity of stars in the field precluded using stars for this "shift-and-add" procedure. The sixteen mosaics thus formed were shifted and added using the bright star at the edge of the field. The 3-σ upper limit that is quoted was derived in a manner similar to that in note (b).

Figure 1. K_s-band image of the field of the optical transient (OT) of GRB 971214 obtained using NIRC. The figure on the left is a single 3×3 mosaic. The mosaic was formed by offsetting each NIRC frame by 30 arcseconds in either one or both of the cardinal coordinates so as to form a square of size 98 arcsecond. Nine such mosaics were obtained with their centers on a 3×3 grid with a grid spacing of 10 arcseconds. Two nearby bright reference stars (H1 and H2) are marked. The OT's position is at the center of the inset $15'' \times 15''$ square. It is not visible in a single mosaic but is readily detected when all the nine mosaics are summed; see inset on the right side. The data were analyzed in the usual manner: a "super-sky" frame was obtained by combining all the frames. This super-skyflat frame was subsequently used to flat-correct each of the mosaics. The software package IRAF (Image Reduction and Analysis Facility; distributed by the National Optical Astronomy Observatories) was used to process the data.

Figure 2. The optical/near-infrared broad-band spectrum of GRB 971214 at epoch UT 1997 December 15.58. The crosses with no error bars are the original data taken from the literature and this paper with V=22.65±0.1 (0.55 μm; ref. 10) at UT 1997 December 15.51, R=22.1±0.1 (0.65 μm; ref. 19) at UT 1997 December 15.51, I=21.3±0.04 (0.8 μm; ref. 10) at UT 1997 December 15.50, J=20.27±0.03 (1.22 μm; ref. 20) at UT 1997 December 15.44, K=19.4±0.2 (2.19 μm, this paper) at UT 1997 December 15.58 UT. The observed magnitudes were converted to spectral flux densities assuming the following fluxes for zero mag: 3590 Jy (V; ref. 27), 3020 Jy (R; ref. 27), 2380 Jy (I; ref. 27), 1570 Jy (J; ref. 28) and 636 Jy (K; ref. 28). The observed fluxes were extrapolated to the same epoch as the K-band measurement, UT 1997 December 15.58, using the same temporal slope as the I-band light curve[7]: $I(t) = 22.22 + 3.09 \log(t - t_\circ)$, where $t_\circ$= UT 1997 December 14.9727. A power-law model fitted to these extrapolated VRI points (open points) yields a power law index of 2.13 ± 0.04; the power-law fit is displayed by the dashed line. As explained in the text, in the framework of the afterglow models the spectrum of the decaying afterglow is expected to be a power law with index $\alpha = a/b$; here a is the power law index of the afterglow observed at any one frequency and $b = 3/2$ (see Equation 2). From I-band observations discussed in ref. 7 we note $a = 1.2 \pm 0.2$ and thus the expected α is 0.8 ± 0.13. In order to reconcile the observations with theory we invoke extinction by dust between us and the OT. To this end we used a two-component model consisting of a power law, $S_\circ(\lambda/\lambda_\circ)^\alpha$, and an exponential absorption, $\exp(-\lambda_\circ\tau_\circ/\lambda)$. The first component is the expected spectral behavior of the afterglow from GRB 971214; $\alpha = 0.8$. The second component is the "extinction law"; we assume the optical depth from extinction is $\propto \lambda^{-1}$. The parameters τ_0 and λ_0 are degenerate but are displayed as such for physical clarity. Only the VRI fluxes were used in the model fit since the OT is known to undergo a power-law decay in these bands and thus we have every expectation that the underlying spectrum is a power-law (see above). The best fit parameters (solid line) are $\alpha = 0.8$ (by fiat), $\tau_\circ\lambda_\circ = 0.7$ μm and $S_\circ \sim 13\,\mu$Jy. A final

set of points (filled circles) shows the flux density when data are corrected for the extinction law derived above. The corrected J and K fluxes do depend on the extrapolation of the extinction law to these wavelengths. Nonetheless, as can be seen from the figure, Note that the VRI fluxes are well fit by the power law dependence (solid line) expected for the afterglow but there is clear evidence of a spectral turnover or flattening in the J and K bands, indicating that the νF_ν spectrum peaked at around 1 μm at the epoch of the K-band observations.

Figure 3. K band image of the field of the optical transient of GRB 971214, taken on UT February 10, 1998. The field is about 50 across. North is up and East is to the left in the image. The image shown is the sum of nine 450s exposures. The reference star H2 as well the position at which the OT is expected, are marked. However, neither the OT nor the host galaxy (see text) was detected in this observation. The three sigma detection limit for point sources is estimated to be K=22.1.