The Near Infrared and Multiwavelength Afterglow of GRB 000301c

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ABSTRACT

We present near-infrared observations of the proposed counterpart of GRB 000301c. The $K'$ filter (2.1$\mu$m) light curve shows a well-sampled break in the decay slope at $t \approx 3.5$ days post-burst. The early time slope is very shallow ($\sim -0.1$), while the late time slope is steep ($-2.2$). Comparison with the optical (R band) light curve shows significant differences, especially in the early time decay slope (which is steeper in the optical) and the break time (which occurs later in the optical). This is contrary to the general expectation that light curve breaks should either be achromatic (e.g., for breaks due to collimation effects) or should occur later at longer wavelengths (for most other breaks). We discuss some speculative explanations for this behavior. However, it is unclear if any of these can produce the observed contrast in behavior over a factor of only three in wavelength. In addition, by combining the IR-optical-UV data with millimeter and radio fluxes, we are able to constrain the locations of the self-absorption break and cooling break and to infer the location of the spectral peak, $f_\nu \approx 2.3$ mJy at $\nu \approx 5 \times 10^{11}$ Hz.

Subject headings: Gamma rays—bursts

1. Introduction

Infrared observations can be used to improve our understanding of gamma ray burst afterglows in several ways. First, they can be combined with optical measurements to obtain spectral slope measurements with a much wider wavelength baseline, and hence yield a more accurate spectral slope than optical data alone. Second, they can be used to test observed light curve breaks for wavelength dependence, which is an important discriminant between breaks due to ejecta collimation and other possible causes. Finally, if bursts are preferentially located in dusty regions, as suggested under “hypernova” scenarios where bursters are a final evolutionary stage of some class of massive stars, then near-IR observations will detect some afterglows that are obscured at optical wavelengths. At less extreme dust optical depths, near-IR data help to characterize the host
galaxy extinction and so infer both extinction corrected fluxes and properties of dust and gas in high redshift GRB host galaxies.

We present here near-infrared (NIR) photometric observations of the afterglow of the gamma ray burst GRB 000301c. These constitute the best-sampled near infrared light curve for any afterglow to date.

GRB 000301c was detected independently by the All-Sky Monitor on the Rossi X-Ray Timing Explorer and by two spacecraft (Ulysses and NEAR) of the current Interplanetary Network on 2000 March 1.4108 UT. The event was a single peaked GRB lasting approximately 10 seconds (Smith, Hurley, & Cline 2000). Coordinates were available approximately 36 hours after the burst, and an optical counterpart was reported by Fynbo et al (2000) based on observations at March 3.21 UT. The redshift of the burst was measured as $z = 1.95 \pm 0.1$ (Smette et al 2000) using the observed Lyman break in a near-UV spectrum of the GRB afterglow. Subsequent identification of weak metal lines in the afterglow’s optical spectrum refined this redshift to $z = 2.0335 \pm 0.0003$ (Castro et al 2000).

2. Imaging Observations

We present data obtained at the NASA Infrared Telescope Facility (IRTF) on Mauna Kea as part of a service mode Target of Opportunity program for broadband near-IR followup of gamma ray bursts using the NSFCam imager. Observing conditions were good throughout the period, with clear skies and subarcsecond seeing on all nights. All data were taken with a plate scale of 0.3″ per pixel. A log of the observations is given in table 1.

We reduced and analyzed the data following standard near-IR procedures. Raw sky flats were generated for each filter and night using the mean of all available frames after outlier rejection to eliminate the influence of objects on the flatfield. Final flats were generated by subtracting stacked dark frames (taken with the same exposure time, number of coadds, and number of nondestructive reads as the data) from the raw flats and normalizing the result to have mean = 1. Individual frames were then sky-subtracted (using the median of three to six frames taken immediately before and/or after the object frame) and flatfielded. Frames were aligned using bilinear interpolation to implement a simple shift based on the measured centroid of a bright star. Finally, the aligned frames were combined using a clipped mean after removing any sky subtraction residuals through subtraction of the modal pixel value.

We measured the GRB fluxes on all nights using aperture photometry with an aperture diameter of 1.8″. All afterglow photometry was taken relative to the bright star 5.7″ west and 1″ south of the optical transient. (This is star A of Garnavich et al 2000.) The J and $K'$ band magnitudes of this star were $J = 16.61 \pm 0.01$ and $K' = 15.96 \pm 0.02$. These were calibrated using observations of UKIRT faint standard 27 (Casali & Hawarden 1992) taken immediately before the first IRTF observations of GRB 000301c. The standard star observations were processed in the same way as
the GRB images, and a larger photometry aperture (5.4″ diameter) was used for flux calibration, to reduce sensitivity to any centering errors or seeing variations between the standard star and GRB frames. No correction was made for atmospheric extinction; however, any such correction would be small (≲ 0.01 mag), because the standard was observed at airmass 1.09, and the GRB field at airmass 1.02. The reference star showed no evidence for variability either in our near-IR data or in optical data from two groups (Garnavich, private communication; Halpern, private communication). The aperture photometry included a local sky estimation and subtraction using the mode of pixel values in an annulus around each point source. This step should control any residual sky level or first order gradient in the sky. Moreover, by selecting the annulus to avoid bright objects and using the mode for sky level estimation, we also control the possible influence of other sources on sky level estimates.

Our counts always remained below the nominal linearity limit for NSFCam (Leggett & Denault 1996); we therefore did not apply nonlinearity corrections to our data. A small correction was applied to place the J band magnitude from March 4.652 on the standard CIT photometric system, using $(J - K)_{\text{cit}} = 0.974(J - K)_{\text{nsfcam}} \approx 0.974(J - K')_{\text{nsfcam}}$ (see Leggett & Denault 1996). $K'$ magnitudes are on the NSFCam instrumental system, which should closely approximate CIT K band magnitudes on average.

Errors due to photon counting statistics were computed based on an iteratively clipped variance of each night’s final stacked images, suitably corrected for the correlated noise introduced by bilinear interpolation. Sky subtraction errors arise only from the difference between sky level in the photometry aperture and in the sky annulus. These errors are separated into statistical errors (due to photon noise in the sky annulus) and systematic (due to objects in the sky annulus or any other source of bias in estimating the true background under the transient source). The statistical part is always small compared to statistical errors from the object flux measurement, due to the large number of pixels in the sky annulus (≈ 900) and much smaller number (≈ 28) in the photometric aperture. Systematic errors in sky subtraction are potentially larger, but we believe they are under reasonable control in our data set because the sky level was removed in two steps (globally, during data reduction, and locally, during aperture photometry) accounting for up to first order gradients in both time and space; and because the weather was cooperative, with relatively little temporal variation in sky background (≲ 10% minimum to maximum in any night and filter, and usually less) and subarcsecond seeing (allowing small photometry apertures). Further possible error sources include centroiding of the afterglow and reference star (expected to be systematic-error limited at the 0.1 pixel level) and residual flatfielding difficulties. Neither will be large compared to our photon counting noise. To be conservative, we estimate that sky subtraction and flatfielding errors combined may affect all of our photometry at up to the 4% level. Table 1 lists both pure photon counting errors and error bars including this systematic error added in quadrature.

In addition to the IRTF data, we include in our analysis data from other observatories presented in the literature (primarily the GRB Coordinate Network Circulars). These data are summarized in table 2.
3. Light curve fitting

Both the K’ and R light curves are shown in figure 1. The K’ band light curve shows a smooth rollover from an initially constant flux to a rapid decay at late time. The R band light curve shows a qualitatively similar behavior, but the early time R flux decays more steeply than the early K’ flux, and there are additional irregularities in the R band light curve that are arguably significant.

Broken power laws can be empirically fitted by functions of the form

\[ f = f_0 \left[ \left( \frac{t}{t_b} \right)^{\alpha_1} + \left( \frac{t}{t_b} \right)^{\alpha_2} \right]^{-1/\beta}. \]

With \( \alpha_1 < \alpha_2 \) and \( \beta > 0 \), this function describes a light curve falling as \( t^{-\alpha_1} \) at \( t \ll t_b \) and \( t^{-\alpha_2} \) at \( t \gg t_b \). \( \beta \) controls the sharpness of the break, with larger \( \beta \) implying a sharper break. The function that Stanek et al (1999) used to fit the light curve of GRB 990510 is the special case \( \beta = 1 \) of this function. Rewritten in magnitudes, the fitting function becomes

\[ m = m_b + 2.5 \frac{\beta}{\beta} \left\{ \log_{10} \left[ \left( \frac{t}{t_b} \right)^{\alpha_1} + \left( \frac{t}{t_b} \right)^{\alpha_2} \right] - \log_{10}(2) \right\} \]

(1)

where \( m_b \) is the magnitude at time \( t_b \).

The K’ light curve can be well fitted by this model. The best fit values (with \( \chi^2 = 0.422 \) for one degree of freedom) are \( t_b = 3.57 \) days, \( K_b = 17.75 \), \( \alpha_1 = 0.09 \), \( \alpha_2 = 2.26 \), and \( \beta = 4.27 \).

The R band data show significant departures from such a light curve. The best fit to existing R band data has \( \chi^2 \approx 52 \) (for 17 degrees of freedom). The best fit has \( t_b = 6.3 \) days, \( R_b = 21.66 \), \( \alpha_1 = 0.92 \), \( \alpha_2 = 3.11 \), and \( \beta = 2.23 \). However, a fairly wide range of models can achieve comparable \( \chi^2 \), because there is a near degeneracy between the break time, late time slope, and sharpness of the break. Surprisingly, this degeneracy is less severe in fitting the K’ data despite the greater number of R band points. Additional late time optical data will greatly constrain this uncertainty.

4. Spectral Energy Distributions

The long spectral baseline between the K’ band (2.1\( \mu m \)) and the optical/UV bands allows one to obtain accurate spectral slope measurements. We have calculated the burst spectral energy distribution at selected times based on the availability of multiwavelength data. Where necessary, flux measurements were interpolated between adjacent data points at one wavelength in order to determine a contemporaneous flux with another wavelength. For this operation, we always interpolated the light curves with good sampling (R, K’) to match the time of a sparsely sampled wavelength (UV 2825\( \AA \), B). Photometric zero points for the conversion of magnitudes to flux density units were taken from Fukugita, Shimasaku, & Ichikawa (1995) for the optical, and from Campins, Rieke, & Lebofsky (1985) for the near-IR.

The resulting spectral energy distributions are shown in figure 2. The best-fit spectral slopes assuming unbroken power law spectra are given in table 3, first uncorrected for extinction; then with a correction for foreground Galactic extinction (\( E_{B-V} = 0.053 \), Schlegel et al 1998) assuming an \( R_V = A_V / E_{B-V} = 3.1 \) extinction law; and finally with an additional correction for extinction in
Fig. 1.— The light curves of the GRB 000301c afterglow in both $K'$ and $R$ filters. The data are summarized in table 2. Smoothly broken power law fits using the empirical fitting form in equation 1 are shown as solid lines where they interpolate the data, and as dotted lines where they are extrapolations. The fitted parameters are given in the text. Filled circles are $K'$ filter data and open circles are $R$ filter data.
Fig. 2.— The spectral energy distribution of the GRB 000301c afterglow in the observer-frame near-IR to near-UV is plotted for selected epochs. Left panel: Spectral energy distributions corrected for Galactic extinction only. Right panel: An additional correction for $A_B = 0.175$ magnitudes at an assumed host galaxy redshift $z = 2.03$ has been applied. In both panels, the epochs of observation (from top to bottom) are UT 2000 March 3.50, 4.52, 6.375, 9.00, and 14.60. The corresponding times since the GRB are 2.09, 3.11, 4.964, 7.59, and 13.19 days. Solid lines connect flux densities sharing a common epoch, and dotted lines show the best-fit single power law at each epoch.
the GRB host galaxy (see below). Also included are the slopes derived from R and K’ data alone, again corrected for both Galactic and GRB host galaxy extinction.

A significant deficit of blue flux relative to the best fit power law is observed at UT March 6.375, when the broadest spectral coverage is available. The earlier epochs also show marginal evidence for such a departure. These effects can be interpreted as evidence for a modest amount of host galaxy extinction.

The 2175Å absorption feature falls into the observed R band at the redshift $z = 2.03$ of this burst. Assuming that there is no intrinsic emission feature at this wavelength in the GRB afterglow spectrum, we can place an upper limit of $A_B \lesssim 0.1$ magnitude for Milky Way type dust at $z = 2.03$. However, to make the observed spectral energy distributions consistent with a power laws requires more dust ($A_B \approx 0.25$ for a Milky Way extinction law with $R_V = 3.1$). We therefore favor a Small Magellanic Cloud extinction law with $A_B \approx 0.175$ as the best host-galaxy extinction model for this burst, as this allows both the R band and UV data to fit a single power law reasonably well at any fixed epoch. We have used the analytic extinction law fitting forms of Pei (1992) in deriving these estimates. The apparent absence of a 2175Å feature in the extinction curve of the host galaxy is reminiscent of dust attenuation laws for actively star forming galaxies (e.g., the Magellanic Clouds [Pei 1992 and references therein] and starburst galaxies [Gordon, Calzetti, & Witt 1997]). This may be interpreted as further circumstantial evidence linking GRBs to actively star forming galaxies. Alternatively, such an extinction law might be observed if GRBs preferentially destroy the small carbonaceous particles thought to be carriers of the 2175Å feature, but this explanation would only work if much of the dust optical depth arises near the maximum radius where the burst can destroy grains (cf. Waxman & Draine 1999).

Combining the above spectral slope measurements with the millimeter observation by Bertoldi (1.9±0.3mJy at 1.2mm on March 4.385), we see that a strong spectral break is required between 2µm and 1mm. The spectral slope at radio to millimeter wavelengths is generally expected to be $+1/3$ at these early times. By fitting the slope of the optical-IR data on March 4.385 and extrapolating back towards the millimeter regime, we can estimate the frequency and flux density of the peak in the afterglow spectrum (see figure 3). Using fluxes corrected for both Galactic foreground and host galaxy extinction, we obtain $\log(\nu_{\text{max}}/\text{Hz}) = 11.66\pm0.12$ and $\log(f_{\nu,\text{max}}/\text{mJy}) = 0.37\pm0.05$, where the error bars account only for photometric errors on the data. If we do not apply any correction for host galaxy extinction, we instead obtain $\log(\nu_{\text{max}}/\text{Hz}) = 12.22\pm0.08$ and $\log(f_{\nu,\text{max}}/\text{mJy}) = 0.55\pm0.05$ With the correction for host galaxy extinction, we see that Bertoldi’s millimeter data is very near the spectral peak. Corroborating evidence comes from the 3.5cm observation of $315\pm16\mu Jy$ on March 5.67 UT (Berger, Frail, et al 2000), which lies a factor of $\sim 2$ below the $\nu^{1/3}$ extrapolation from Bertoldi’s data to longer wavelengths. The factor of 1.5 in observer-frame elapsed time between these observations will have a relatively minor effect on this comparison, since the expected time slopes of afterglow light curves are fairly flat at frequencies between the $f_\nu$ peak and the self-absorption frequency (e.g., Rhoads 1999). A larger effect is diffractive scintillation, which introduces a much larger uncertainty in the inferred radio luminosity of the afterglow than
the simple photometric error bar (5%) suggests (Frail 2000, personal communication). The rough agreement of the millimeter and radio fluxes implies that the self-absorption frequency was \( \lesssim 8.46 \text{GHz} \) on March 5.67.

The location of the cooling break is harder to constrain, not least because it is a relatively modest break of 0.5 in spectral index and because this burst is not very well observed at X-ray wavelengths. If we take the afterglow behavior to be in the spherical regime for a uniform ambient medium at the earliest observed times, then the expected behaviors are

\[
  f_\nu \propto \nu^{-(p-1)/2}
\]

and

\[
  f_\nu \propto t^{-3(p-1)/4}.
\]

Observationally, we have

\[
  f_\nu \propto t^{-0.92} \rightarrow p \approx 2.23.
\]

If we correct for only Galactic extinction, we obtain

\[
  f_\nu \propto \nu^{-0.8} \rightarrow p \approx 2.6,
\]

while if we correct for our estimated host galaxy extinction also, we obtain

\[
  f_\nu \propto \nu^{-0.52} \rightarrow p \approx 2.04.
\]

Within the errors, these estimates for \( p \) are consistent. Other regimes (frequency above the cooling break, or a late time jet solution) yield a much poorer agreement. We therefore infer that the cooling break was in the UV or X-ray regime around UT 2000 March 3.5. If the observed variations in this afterglow’s colors are to be explained by a spectral feature moving through the UV-optical-IR region, then the feature is almost certainly the cooling break. However, neither the variation from blue to red to blue again nor the presence of a strong light curve break in this burst can be explained by the cooling break alone.

5. Discussion

GRB 000301c is the third burst for which a strong break in the light curve is clearly observed. Several classes of breaks are predicted by fireball models. The most basic of these are due to features in the synchrotron spectrum moving through the observed bandpass (e.g., Paczyński & Rhoads 1993; Sari, Piran, & Narayan 1998). However, this class of features predicts relatively modest changes in light curve slope, with the break occurring first at short wavelengths and evolving to longer ones. Jetlike burst ejecta, on the other hand, are expected to give strong breaks that are essentially independent of wavelength (Rhoads 1999), and the observed breaks have generally been interpreted as evidence for collimation of the GRB ejecta (e.g., in GRB 990123, by Castro-Tirado et al 1999, Kulkarni et al 1999, Fruchter et al 1999, and Galama et al 1999; and in GRB 990510, by Stanek et al 1999 and Harrison et al 1999). A difficulty with this model is that the predicted break is quite gradual (Rhoads 1999; Panaitescu & Meszaros 1999; Moderski, Sikora, & Bulik 2000; Kumar & Panaitescu 2000), while observed breaks are rather sharp.

The current burst is no exception. The prediction of Rhoads (1999) for the light curve around the break time for a collimated jet is

\[
  f_\nu \propto \frac{t^{-3(p-1)/4}}{(1 + 3.72 t^{2/5})^{5/2} \times (1 + 2.07 t^{5/12})^{3(p-1)/5}}
\]

(2)

The break in this predicted light curve is extremely broad, and would give \( \chi^2 \) little better than a single power law in fitting the observed break in either \( K' \) or \( R \) band. The model curve is based on numerical integration of the remnant’s dynamical equations, and ignores differences in light travel
Fig. 3.— The spectral energy distribution of the GRB 000301c afterglow from 250GHz to 0.44\(\mu m\)
on UT 2000 March 4.385 (4.974 days post-GRB), and at 8.46GHz on UT 2000 March 5.67 (4.26
days post-GRB). Filled points show the photometric data corrected for both Galactic foreground
and GRB host galaxy extinction (see text). Solid lines show the \(\pm 1\sigma\) fitted power law slopes
through these fully corrected optical/IR data. Open points show the optical/IR data corrected
for only foreground Galactic extinction, and dotted lines show the \(\pm 1\sigma\) fitted power law slopes
through these data points. Finally, dashed lines show the \(f_\nu \propto \nu^{1/3}\) slope expected between the
self-absorption frequency and the peak in \(f_\nu\).
time between the center and edge of the remnant, which will only smooth the break further (e.g., Moderski et al 2000; Panaitescu & Meszaros 1999). We therefore feel that jet collimation is not responsible for the sharp break observed in this burst.

The transition to the nonrelativistic regime has been proposed as another mechanism for light curve breaks (Dai & Lu 1999). However, we do not know of a detailed calculation of the sharpness of this break, making a fair evaluation of this possibility difficult.

A final possible cause for sharp breaks in GRB afterglow light curves is discontinuities in the ambient density distribution. Assuming that the density is a function of radius alone, the timescale for breaks due to such discontinuities is $\Delta t \gtrsim t$, where $t$ is the time elapsed in the observer’s frame since the burst and $\Delta t$ the characteristic duration of a light curve feature. This duration is set by differential light travel time effects between material moving along the line of sight and off-axis material moving in direction $1/\Gamma$, and is a rough minimum for any afterglow light curve feature provided the ambient medium density is roughly independent of angle from the line of sight.

Perhaps the greatest difficulty posed by the observations of GRB 000301c is in finding a model whose light curve steepens in $K'$ before it steepens in $R$. For most mechanisms, breaks will occur either first at short wavelengths (e.g. the cooling break), or simultaneously at all wavelengths (e.g. “beaming” breaks). One speculative way out is to suppose that a discontinuity in the ambient density is encountered while the cooling break is between the R and K’ filters. The predicted appearance of an afterglow at frequencies above and below this break is expected to differ qualitatively: A high frequency image would show an annular structure and a low frequency image a more nearly filled disk. This is caused by the difference in the apparent dynamical age of the remnant along the line of sight (where we see things changing quickly) and near the edge of the observed afterglow (where light travel time is larger, and we see material at an earlier and hotter stage of its evolution). (E.g., Granot, Piran, & Sari 1999.) Now, the same variation of “lookback time” from the center to edge of the afterglow implies that we see the effect of an ambient density drop first in the middle of the afterglow, and that the fractional effect of such a discontinuity on the afterglow flux will initially be larger at long wavelengths than short ones. This mechanism can reproduce the sign of the observed effect. Detailed calculations will be necessary to see if it can approach the observed magnitude, given that the two filters are separated by only a factor of 3 in wavelength.

An additional “irregularity” in the GRB 000301c light curve is the plateau in optical brightness from March 6.1 to 8.1 UT (Bernabei et al 2000). This feature comprises five data points from three groups, of which three points deviate from the broken power law fit by $2\sigma$, so that the feature is significant although not highly so. This period coincides with a continued steep decay of the K’ light, so that the R–K’ color of the afterglow shifts considerably to the blue. A similar feature is observed in the GRB 970228 light curve (Fruchter et al 1999), and has been interpreted as evidence for a supernova underlying the GRB light curve (Galama et al 2000). However, in GRB 000301c, such an explanation is ruled out, because the plateau is too early for the peak of a supernova (at 2 days in the burster frame for $z = 2.03$). The required flux also exceeds that available from
a supernova, and the color shift (to the blue) is contrary to expectations for supernova light at high $z$. The color shift likewise rules out dust emission as a relevant factor. Refreshed shock effects (Panaitescu, Meszaros, & Rees 1998) are a more viable explanation, though the contrasting behavior at wavelengths only a factor of 3 apart again poses potential difficulties.

6. Conclusions

By combining our near-infrared observations of GRB 000301c with other observations in the literature, we show a strong and unexpected contrast between the behaviors at R band ($0.7\mu m$ observed, $0.218\mu m$ emitted) and $K'$ band ($2.1\mu m$ observed, $0.7\mu m$ emitted). In particular, the early time light curve slopes are 0.92 (R) versus 0.09 ($K'$) and the break times are 6.3 days (R) and 3.6 days ($K'$). In addition, the R band light curve shows significant short-term departures from its best-fitting smoothly broken power law, while the $K'$ light curve does not. The late time slopes are roughly consistent between the two filters, and are quite steep, comparable to the late time behavior of GRB 990510.

Fitting a standard synchrotron spectral energy distribution to the burst, we place the peak of $f_\nu$ around 2.3mJy at about $5 \times 10^{11}$Hz (600$\mu m$). The dominant uncertainty in this measurement is the correction for extinction in the GRB host galaxy. Random errors are $\approx 0.12$ dex in $\nu_{\text{max}}$ and $0.05$ dex in $f_{\nu,\text{max}}$, while the correction for host galaxy extinction is uncertain at perhaps twice this level. These strong constraints on the $f_\nu$ peak are possible because of the precise optical-IR spectral slope measurements afforded by $K'$ observations.

The rapid and steep break in this burst’s light curve, together with its unusual color variations, pose a challenge for afterglow modelling.

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Table 1: Log of the IRTF data. $t$ is the observed time elapsed since the GRB. “Exposure” is the sum of the exposure times for all GRB images in that filter and night. The “photometric” error is due to poisson statistics of received photons. The “total” error combines the photometric error in quadrature with an estimated 0.04 magnitudes error due to sky subtraction and flatfielding uncertainties.
| UT Date | t   | Filter | Magnitude       | Authors          | Reference                          |
|---------|-----|--------|-----------------|------------------|------------------------------------|
| 3.215   | 1.804 | K'     | 17.51 ± 0.06    | Stecklum et al   | GCNC 572 & private communication   |
| 3.55    | 2.14 | K'     | 17.52 ± 0.02    | Kobayashi et al  | GCNC 577, 587                      |
| 4.640   | 3.229 | K'     | 17.65 ± 0.04    | Rhoads & Fruchter| This work                          |
| 5.610   | 4.199 | K'     | 18.00 ± 0.07    | Rhoads & Fruchter| This work                          |
| 6.595   | 5.184 | K'     | 18.56 ± 0.12    | Rhoads & Fruchter| This work                          |
| 8.590   | 7.179 | K'     | 19.28 ± 0.09    | Rhoads & Fruchter| This work                          |
| 3.55    | 2.14 | J      | 18.88 ± 0.02    | Kobayashi et al  | GCNC 577, 587                      |
| 4.652   | 3.241 | J      | 19.06 ± 0.05    | Rhoads & Fruchter| This work                          |
| 3.17    | 1.76  | R      | 19.94 ± 0.04    | Fynbo et al      | GCNC 570, 576                      |
| 3.191   | 1.780 | R      | 20.11 ± 0.05    | Bernabei et al   | GCNC 599                           |
| 3.51    | 2.10  | R      | 20.28 ± 0.05    | Garnavich et al  | GCNC 573                           |
| 3.51    | 2.10  | R      | 20.27 ± 0.04    | Veillet et al    | GCNC 575, 588                      |
| 3.51    | 2.10  | R      | 20.24 ± 0.05    | Halpern et al    | GCNC 578                           |
| 3.93    | 2.52  | R      | 20.53 ± 0.05    | Mohan et al      | GCNC 595                           |
| 4.057   | 2.646 | R      | 20.46 ± 0.09    | Castro-Tirado et al| GCNC 579                        |
| 4.080   | 2.669 | R      | 20.573 ± 0.06   | Gal-Yam et al    | GCNC 593                           |
| 4.178   | 2.767 | R      | 20.22 ± 0.2     | Bernabei et al   | GCNC 599                           |
| 4.38    | 2.97  | R      | 20.56 ± 0.05    | Garnavich et al  | GCNC 581                           |
| 4.458   | 3.047 | R      | 20.54 ± 0.06    | Mujica et al     | GCNC 597                           |
| 4.50    | 3.09  | R      | 20.61 ± 0.04    | Halpern et al    | GCNC 582                           |
| 5.63    | 4.22  | R      | 20.86 ± 0.04    | Veillet et al    | GCNC 588                           |
| 5.96    | 4.55  | R      | 21.18 ± 0.05    | Mohan et al      | GCNC 595                           |
| 6.145   | 4.734 | R      | 21.60 ± 0.2     | Bernabei et al   | GCNC 599                           |
| 6.22    | 4.81  | “R”    | 21.5 ± 0.15     | Fruchter et al   | GCNC 602                           |
| 7.135   | 5.724 | R      | 21.63 ± 0.15    | Bernabei et al   | GCNC 599                           |
| 7.65    | 6.24  | R      | 21.70 ± 0.07    | Veillet et al    | GCNC 598                           |
| 8.157   | 6.746 | R      | 21.63 ± 0.1     | Bernabei et al   | GCNC 599                           |
| 9.52    | 8.11  | R      | 22.28 ± 0.09    | Halpern & Kemp   | GCNC 604                           |
| 11.63   | 10.22 | R      | 23.02 ± 0.10    | Veillet et al    | GCNC 610                           |
| 14.60   | 13.19 | R      | 23.82 ± 0.10    | Veillet et al    | GCNC 611                           |
| 3.50    | 2.09  | B      | 21.11 ± 0.04    | Veillet et al    | GCNC 575, 588                      |
| 4.52    | 3.11  | B      | 21.41 ± 0.04    | Halpern et al    | GCNC 585                           |
| 14.60   | 13.19 | B      | 24.83 ± 0.12    | Veillet et al    | GCNC 611                           |
| 4.385   | 2.974 | 1.2mm  | 1.9 ± 0.3mJy    | Bertoldi         | GCNC 580                           |
| 5.67    | 4.26  | 3.54cm | 315 ± 16μJy     | Berger & Frail   | GCNC 589 & private communication   |

Table 2: Data from the literature. The estimated error on Kobayashi et al data has been increased from their 0.01 magnitude statistical error to 0.02 mag to allow for possible color terms in conversion between their photometric system and ours.
| UT date | $t$ | Filters | Slope (none) | Slope (MW) | Slope (MW + host) | Slope (R-K) |
|---------|-----|---------|--------------|------------|------------------|-------------|
| 3.50    | 2.09| B,R,J,K’ | $-0.916 \pm 0.026$ | $-0.800 \pm 0.026$ | $-0.519 \pm 0.026$ | $-0.511 \pm 0.037$ |
| 4.385   | 2.974| B,R,J,K’ | $-1.039 \pm 0.032$ | $-0.918 \pm 0.032$ | $-0.624 \pm 0.033$ | $-0.657 \pm 0.052$ |
| 4.52    | 3.11| B,R,J,K’ | $-1.054 \pm 0.035$ | $-0.934 \pm 0.034$ | $-0.643 \pm 0.035$ | $-0.687 \pm 0.049$ |
| 6.375   | 4.964| UV,R,K’ | $-1.49 \pm 0.061$ | $-1.33 \pm 0.061$ | $-0.930 \pm 0.061$ | $-0.77 \pm 0.15$ |
| 9.00    | 7.59| R,K’ | $-0.82 \pm 0.11$ | $-0.73 \pm 0.11$ | $-0.51 \pm 0.11$ | $-0.51 \pm 0.11$ |
| 14.60   | 13.19| B,R | $-1.64 \pm 0.36$ | $-1.44 \pm 0.37$ | $-0.91 \pm 0.37$ | n/a |

Table 3: Spectral slopes $d \log f_\nu/d \log (\nu)$ of the GRB 000301c afterglow at selected epochs. Column sub-headings indicate the type of extinction correction applied, starting with none, then correcting for Milky Way extinction only, and finally for both Milky Way extinction and host galaxy extinction. The last column gives the slope measured using the R and K’ filters alone, again corrected for both Milky Way and host galaxy extinction, to isolate the time evolution of the burst from possible systematic differences among filters. Host galaxy extinction corrections assume $A_B = 0.175$ at $z = 2.03$ with a Small Magellanic Cloud extinction law (Pei 1992).