The unusual afterglow of GRB 980326: evidence for the gamma-ray burst/supernova connection

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This manuscript was submitted to Nature on March 23, 1999. We are making this m.s. available on astroph given the rapid progress in the field of GRBs. You are free to refer to this paper in your own paper. However, we do place restrictions on any dissemination in the popular media. The article is under embargo until it is published. For further enquiries, please contact Shri Kulkarni (srk@astro.caltech.edu) or Joshua Bloom (jsb@astro.caltech.edu).

Cosmic gamma-ray bursts (GRBs) have been firmly established as one of the most powerful phenomena in the Universe, releasing electromagnetic energy approaching the rest-mass energy of a neutron star in a few seconds. The two currently popular models for GRB progenitors are the coalescence of two compact objects (such as neutron stars or black holes) or collapse of a massive star. An unavoidable consequence of the latter model is that a bright supernovae should accompany the GRB. The emission from this supernova competes with the much brighter afterglow produced by the relativistic shock that gives rise to the GRB itself. Here we present evidence for an unusual light curve for GRB 980326 based on new optical observations. The transient brightened $\sim$ 3 weeks after the burst to a flux sixty times larger than that extrapolated from the rapid decay seen at early time. Furthermore, the spectrum changed dramatically and became extremely red. We argue that the new source is the
underlying supernova. If our hypothesis is true then this would be the first evidence for a supernova connection with GRBs at cosmological distances. We suggest that GRBs with long durations are associated with death of massive stars.

The origin of GRBs remained elusive for a period of nearly three decades after their discovery\(^1\). Beginning in 1997, however, the prompt localization of GRBs by the Italian-Dutch satellite BeppoSAX\(^2\) and the All Sky Monitor\(^3\) on board the X-ray Timing Explorer led to the discovery of the GRB afterglow phenomenon – emission at lower energies: X-ray\(^4\), optical\(^5\), and radio\(^6\).

The persistence of the afterglow emission (days at X-ray wavelengths, weeks to months at optical wavelengths, months to a year at radio wavelengths) enabled astronomers to carry out detailed observations which led to fundamental advances in our understanding of these sources: (1) the demonstration that GRBs are at cosmological distances\(^7\); (2) the proof that these sources expand with relativistic speeds\(^6\); and (3) the realization that the electromagnetic energy released in these objects exceeds that in supernovae\(^8\) and, in some cases, the released energy is comparable to the rest mass energy of a neutron star\(^9,10,11,12\).

Despite these advances, we are still largely in the dark about the nature of the GRB progenitors. Though there are a number of models for their origin, the currently popular models involve the formation of black holes resulting from the coalescence of neutron stars\(^13,14,15\) or the death of massive stars\(^16,17\). The small offsets of GRBs with respect to their host galaxies and the association of GRBs with dusty regions and star-formation regions favors the latter, the so-called hypernova scenario\(^17\). However, this evidence is indirect and also limited by the small number of well-studied GRBs.

The most direct evidence for a massive star origin would be the observation of a supernova coincident with a GRB. Here we present observations of GRB 980326 and argue for the presence of such an underlying supernova. If our conclusions are correct then the implication is that at least some fraction of GRBs, perhaps the entire class of long duration GRBs, represent the end point of the most massive stars. Furthermore, if the association\(^18,19\) of GRB 980425 with a bright supernova in a nearby galaxy holds, then the apparent γ-ray luminosity of GRBs ranges over six orders of magnitude.

**The unusual optical afterglow**

Following the localization of GRB 980326 by BeppoSAX (ref. 20), Groot et al.\(^21\) quickly identified the optical afterglow. Our optical follow-up program began at the Keck Observatory, just 10 hr after the burst. A log of these observations is given in Table 1.

In Figure 2 we present our \(R\)-band photometry along with those reported in the literature. Restricting to data taken within the first month of the burst reported in the literature\(^21,22\) and via the “GRB Coordinates Network” (GCN) (ref. 23), we find a characteristic power law decay in the flux versus time followed by an apparent flattening. The usual interpretation is that the decaying flux is the afterglow emission, while the constant flux reflects the presence of the host galaxy. Indeed, earlier\(^24\) we attributed the entire observed flux on April 17th to the host galaxy.
However, to our surprise, our more recent observations (first carried out nine months after the GRB event) showed no galaxy at the position of the optical transient (OT); see Figure 1. We estimate a 2-σ upper limit of $R > 27.3$ magnitude (see Table 1). This is almost a factor of 10 less flux than that reported from our April 17th detection. A secure conclusion is that the presumed host galaxy of GRB 980326, assuming the GRB was coincident with the host (as appears to be the case for all other well-studied GRBs to date) is fainter than $R \sim 27$ magnitude. This conclusion is not alarming since such faint (or fainter) galaxies are indeed expected from studies\textsuperscript{25,26} of the properties of cosmological GRB host galaxies.

Having established that the host galaxy of GRB 980326 is faint, we are forced to conclude that the OT did not continue the rapid decay it exhibited initially. Instead, we find two phases of the light curve (Figure 2): a steeply declining initial phase ($t < \sim 5$ d) and a subsequent rebrightening phase ($t \sim 3$–4 weeks). Following the rebrightening, the source appears to have faded away to an undetectable level by the time of our next observation (9 months after the burst).

In previously studied bursts the optical afterglow emission has been modeled by a power law function, flux $\propto t^\alpha$; here, $t$ is time since the burst and $\alpha$ the power law index. In some bursts, at early times ($t$ less than a day or so), significant deviations have been seen, e.g., GRB 970508 (ref. 27). At late times, in some bursts, deviations manifest as steepening (i.e. $\alpha$ becoming smaller) of light curves, e.g., GRB 990123 (ref. 11).

It is against this backdrop of the observed afterglow phenomenology that we now analyze the light curve in Figure 2. The declining phase cannot be fit by a simple power law ($\chi^2 = 72$ for 9 degrees of freedom). From Figure 2 it is clear that the flux already starts flattening by day 3. Restricting the analysis to the first two days, we obtain $\alpha = -2.0 \pm 0.1$, consistent with previous analysis\textsuperscript{21}.

Such power law decays are usually interpreted as arising from electrons shocked by the explosive debris sweeping up the ambient medium\textsuperscript{28,29,30,31}. Assuming that the electrons behind the shock are accelerated to a power-law differential energy distribution with index $-p$, on general grounds\textsuperscript{32} we expect that the afterglow flux, $f_\nu(t) \propto t^\alpha \nu^\beta$; here $f_\nu(t)$ is the flux at frequency $\nu$ and time $t$. The value of $\alpha$ and $\beta$ depend on $p$, the geometry of the emitting surface\textsuperscript{33} (spherical versus collimation) and the radial distribution of the circumburst medium\textsuperscript{34}.

From our spectroscopic observations of March 29th (Figure 3) we find $\beta = -0.8 \pm 0.4$. This combination of $(\alpha, \beta)$ is similar to the $(\alpha = -2.05 \pm 0.04, \beta = -1.20 \pm 0.25)$ seen in GRB 980519 (ref. 35) and can be reasonably interpreted\textsuperscript{36} as arising from a standard $p \sim 2.2$ shock with a jet-like emitting surface. Alternatively, the emission could arise in a $p \sim 3$ shock propagating in a circumburst medium\textsuperscript{34} whose density falls as the inverse square of the distance from the explosion site.

**A new transient source**

We now discuss the bright source seen in the rebrightening phase (corresponding to observations of April 17 and April 23). This source is $\sim 60$ times brighter than that
extrapolated from the rapidly declining afterglow. The magnitude of this excess and the late timescale of rebrightening has never been reported before.

We first establish the reality of the source. As noted in the legend to Figure 1 the source is consistently detected in three separate images of April 17. In the summed image, the source is detected at 4.6-σ (chance probability of $2 \times 10^{-6}$). We note that all other objects in the field at this flux level are reliably detected in our deeper December 18th image. Next, the source is clearly detected in the spectrum obtained on April 23rd (Figure 3) and at the same position as that of the OT. Finally, we note that the source in the April 17th image is coincident with the position of the OT in the image of March 27th to within the expected astrometric error, $0.04 \pm 0.18$ arcsecond.

We conclude that there was indeed a source at the position of the OT which brightened three weeks after the burst and subsequently faded to undetectable levels. We now investigate possible explanations for this source.

The simplest picture is that the rebrightening phase is due to a rebrightening of the optical afterglow itself. As noted earlier, this would be unprecedented in both the magnitude of the rebrightening and the epoch of rebrightening. Piro et al.\textsuperscript{37} have recently suggested that the doubling of the X-ray flux of GRB 970508 three days after the GRB event arises from the relativistic shell running into a dense gas cloud. Such an explanation for the GRB 980326 light curve would require a large dense region, with a size comparable to the timescale of rebrightening, about $\Gamma \times 10$ light days ($\sim 0.1$ pc) and located at a distance $\Gamma^2 c \times 20$ days ($\sim 1$ pc) from the explosion site. Here, $\Gamma$ is the bulk Lorentz factor of the shock and is expected to be order unity three weeks after the burst. Panaitescu et al.\textsuperscript{38} suggest the rebrightening of GRB 970508 may be due to a shock refreshment – delayed energy injection by the extremely long-lived central engine that produced the GRB. In both these models, the expected spectrum would be the typical synchrotron spectrum, flux $f_\nu \propto \nu^{-1}$ (or flatter). The very red spectrum of April 21st (Figure 3) allows us to essentially rule out a synchrotron origin for the rebrightening phase of GRB 980326.

Alternatively, the GRB could have occurred in a dusty region and the afterglow would rebrighten\textsuperscript{39} as the dust is sublimated by the afterglow. However, the observed spectral evolution from a relatively blue spectrum (March 29) to red (April 23) moves in a direction opposite to that expected in this scenario.

**The supernova interpretation**

We advance the hypothesis that the new source is due to an underlying supernova (SN) revealed only after the afterglow emission has vanished. Woosley and collaborators (see ref. 40,16 and references therein) have pioneered the “collapsar” model in which GRBs arise from the death of massive stars – stars which produce black hole remnants rather than neutron stars. In this model, the iron core of a massive star collapses to a black hole and releases up to a few $\times 10^{52}$ erg of kinetic energy. Some fraction of this energy is expected to emerge in the form of a jet with little entrained matter; bursts of gamma-rays result from internal shocks in this jet. The remaining energy is absorbed by the star, causing it to explode and thereby produce an energetic supernova.
Thus in this model, the total light curve has two distinct contributions: a power-law decaying afterglow component and emission from the underlying supernova. In Figure 2 we present the light curve expected in this model and use the light curve of the well observed\textsuperscript{18,41} SN 1998bw as a template for the supernova contribution. We find the $R$-band and $I$-band data consistent with a bright supernova at $z \approx 1$.

The very red spectrum of the source on April 23 finds a natural explanation in the supernova hypothesis. From theoretical\textsuperscript{40} and phenomenological\textsuperscript{19} grounds we expect GRBs to arise from massive stars which have lost their hydrogen envelope, i.e. Type Ibc supernovae. At low redshifts, all Type I supernovae are observed to exhibit a strong UV deficit relative to the blackbody fit to their spectra. This deficit is due to absorption by prominent atomic resonance lines starting below $\approx 3900$ Å. Below $\lambda_c \approx 2900$ Å we expect to see very little flux. In the near UV range (3000–4000 Å) type I SNe spectra have a red appearance. Approximating the flux by a power law ($f_\nu \propto \nu^\beta$), the power law index (depending on the wavelength range chosen) is $-3$ or even smaller; see ref. 42 for a UV spectrum of a type Ia SN. Fitting the spectrum of Figure 3 to a power law we obtain $\beta = -2.8 \pm 0.3$. In this interpretation the redshift of the source is $z \sim 1$. A smaller redshift would lead to a larger $\beta$. A larger redshift would substantially suppress the light in the observed $R$ band (which covers the wavelength range 5800–7380 Å). Indeed, from Figure 1, we can deduce that $z \lesssim 1.6$.

We do not know a priori the spectrum and light curve of a supernova accompanying GRBs. However, we have used the light curve of SN 1998bw because it is a very well studied Type Ibc SN with a possible association with GRB 980425. If SN 1998bw is indeed an appropriate template for a supernova associated with a GRB then, as Figure 2 illustrates, the likely redshift of GRB 980326 is $z \sim 1$ and, as discussed above, the red spectrum of April 23 similarly suggests $z \sim 1$. Given the low signal-to-noise ratio of the April 23rd spectrum and the expected line broadening due to high photospheric velocity we do not, as seems to be the case, expect to see any spectral features.

Independently, from the absence of strong spectral breaks in our spectrum of the OT we can firmly place $z_{\text{OT}} \lesssim 2.3$. This constraint is consistent with our deduction that $z \lesssim 1.6$ (see above). Thus from a variety of accounts we find a plausible redshift of around unity for GRB 980326. Such a redshift is not entirely unexpected. Indeed, we note that five out of eight spectroscopically confirmed redshifts of GRBs lie in the range $0.7 < z < 1.1$.

Implications of the supernova connection

The GRBs localized by BeppoSAX belong to a class of long duration GRBs. The jet in a collapsar model takes many seconds to penetrate the star, and therefore the collapsar model is unlikely to account\textsuperscript{43} for the class of short duration (less than a few seconds) GRBs. If we accept the SN interpretation for GRB 980326, a long duration (5 s) GRB then it is only reasonable to posit that all other long duration GRBs are also associated with SNe. In what way can this assertion be tested observationally?

The evidence for an underlying SN can come in two ways. First, is the direct evidence for an accompanying SN seen in the light curve at timescales comparable to the time for SNe to peak, $\sim 20(1 + z)$ days. However, in our opinion three conditions must be satisfied
in order to see the underlying SN even when one was present. (1) The GRB afterglow should decline rapidly, otherwise the SN will remain overpowered by the afterglow for all epochs. (2) Given the strong UV absorption (discussed above), only GRBs with redshift \( z \lesssim 1.6 \) have an observable SN component in the optical band. (3) The host must be dimmer than the peak magnitude of the SN \( M_V \sim -19.5 \). The last requirement is not needed if the GRB can be resolved from the host (e.g. with HST). Finally one caveat is worth noting: the peak magnitudes of Type Ibc SNe are not constant (unlike those of Type Ia) and can vary from \(-16\) mag to a maximum of \(-19.5\) mag; see ref. 44. We have investigated the small sample of GRBs with adequate long-term follow up and conclude that perhaps only GRB 980519 satisfies the first and the third observational conditions for SN detection; the redshift of this GRB is unfortunately unknown.

The second method is an indirect method to tie GRBs and SNe. The dynamics of the relativistic blast wave is strongly affected by the distribution of circumstellar matter. Chevalier and Li\(^{34}\) note that massive stars, through their active winds, leave a circumstellar medium with density falling as the inverse square of the distance from the star. One expects smaller \( \alpha \) for GRBs exploding such a circumstellar medium. In this framework, GRB afterglows which decline rapidly and are at modest redshifts will again be prime targets to search for the underlying SN.

In conclusion we note that it is not possible to firmly demonstrate on purely observational grounds that all long duration GRBs can be explained by the collapsar model. However, we strongly urge sensitive observations especially at longer wavelengths (to avoid the UV cutoff of SNe) for GRBs satisfying the above three conditions. If the proposed hypothesis is correct then the light curves and the spectra would show the behavior shown and discussed in Figure 2 and Figure 3.

We end with a discussion of one interesting point. The total energy release in \( \gamma \)-rays of GRB 980326 was \( E_\gamma = 3 \times 10^{51} f_J \) erg where \( f_J \) is the fractional solid angle of the jet (if any); here we have used the measured fluence\(^{21}\) and assumed \( z \sim 1 \) \( (H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_0 = 0.2, \Lambda_0 = 0) \). If this GRB was beamed then \( E_\gamma \sim 10^{49} \) erg. Curiously enough, this rather small energy requirement places GRB 980326 as close in energetics to GRB 980425 \( (E_\gamma = 6 \times 10^{46} \) erg, ref. 18) as to the classic gamma-ray bursts \( (E_\gamma \gtrsim 6 \times 10^{51} \) erg).
Table 1. Keck II Optical Observations† of GRB 980326∗

| Date (UT) | Band/ Int. Time | Seeing (FWHM) | Magnitude | Observers |
|-----------|-----------------|---------------|-----------|-----------|
| Mar 27.35 | R 240           | 0′′.74        | 21.25 ± 0.03 | AVF, DCL, AGR |
| Mar 28.25 | R 240           | 0′′.66        | 23.58 ± 0.07 | HS, AD, DS, SAS |
| Mar 29.27 | 300 3600        | 0′′.74        | 24.45 ± 0.3 | HS, AD, DS, SAS |
| Mar 30.24 | R 900           | 0′′.66        | 24.80 ± 0.15 | SP, BG, RK, IH |
| Apr 17.25 | R 900           | 0′′.82        | 25.34 ± 0.33 | PC, JB |
| Apr 23.83 | 300 5400        | 0′′.74        | > 27.3     | SGD, SCO |
| Dec 18.50 | R 2400          | 0′′.74        | > 27.3     | SRK, JSB, MvK |
| Dec 18.54 | I 2100          | 0′′.74        | > 25.3     | SRK, JSB, MvK |
| Mar 24    | I 5450          | 0′′.80        | > 26.6     | SRK, JSB |

Notes:

† We used the Keck II 10-m Telescope 2,048 × 2,048 pixel CCD (charged coupled device) Low-Resolution Imaging Spectrometer (LRIS) for imaging and spectroscopy of the GRB field.

* The epoch of GRB 980326 is March 26.888, 1998 (ref. 20).

(a) Mean epoch of the image. The year is 1998 for all images except for that on March 24 for which it is 1999.

(b) Photometric Calibration. The absolute zero-point of the $R$ (effective wavelength of $\lambda_{\text{eff}} \approx 6588$ Å) and $I$-bands ($\lambda_{\text{eff}} \approx 8060$ Å) were calibrated to the standard Cousins bandpass using standard-stars in the field SA98 (ref. 47) and assuming the standard atmospheric correction on Mauna Kea (0.1 mag and 0.06 mag per unit airmass, respectively). The estimated statistical error on the absolute zero-point is 0.01 mag. We estimate the systematic error (due to lack of inclusion of color term) to be less than 0.1 mag. We propagated all photometry to the absolute zero-point derived in the first epoch of observation using 8 “secondary” stars which were detected with high signal-to-noise ratio, unsaturated, near to the transient, and common to every epoch; the typical uncertainty in the zero-point propagation is 0.01 mag. Thus any systematic error in our absolute zero-point will not affect the conclusions based on relative flux. The uncertainties quoted in the Table contain all known sources of error (aperture correction, etc.) The calibrated magnitudes of the secondary stars reported in Groot et al.21 agree to within the measurement errors.

(c) Spectrophotometric measurement. The flux in $\mu$Jy is determined at 6588 Å, the central wavelength of the $R_c$ band; the conversion to magnitude assumes 0 mag equal to 3020 Jy (ref. 46). The spectrophotometric magnitudes are relative to a bright star that was on the slit (for which we have obtained independent photometry from our images).

(d) Photometry of the faint source. Since the transient was not detected to significantly fainter levels in later epochs it is safe to assume that the April 17 detection was that of a point-source (and not an extended galaxy as we had earlier believed). To maximize the signal-to-noise ratio we choose to measure the photometry in an aperture radius equal to the FWHM of the seeing and correct for the missing flux outside the aperture by using
the radial flux profiles of bright isolated stars in the image. The determination of the optimum sky level (from which we subtract the total flux in the aperture) is not well-defined. We estimate the systematic uncertainty introduced by the uncertainty in the sky level as 0.25 mag. The statistical uncertainty (weighted mean over different background determinations) of the flux was 0.22 mag. Thus we quote the quadrature sum of the statistical and systematic uncertainty of 0.33 mag.

(e) Upper-limits. On 1998 Dec 18 UT and 1999 March 24 UT there was no detectable flux above the background at the position of the optical transient. We centered 1000 apertures randomly in our image (approximately 1800 × 2048 pixels in size) and performed weighted aperture photometry with a local determination of sky background and recorded the counts (“DN”) above background at each location. The flux contribution from an individual pixel, some radius \( r \) from the center of the aperture, to the total flux was weighted by a Gaussian with a radial width FWHM equal to the seeing. A histogram of the resulting flux was constructed. This histogram was decomposed into two components—a Gaussian with median near zero DN and a long tail of positive DN corresponding to actual source detections. We fit a Gaussian to the zero-median component, iteratively rejecting outlier aperture fluxes. Based on the photometric zero-point and using isolated point sources in the image for aperture corrections, we computed the relationship between DN within the weighted aperture and the total magnitude. In the Table we quote an upper limit (95%-confidence level corresponding to 2-\( \sigma \) of the Gaussian fit) at the position of the optical transient.
Figure 1.

Images of the field of GRB 980326 at three epochs. Each image shows a 54″×54″ region centered on the optical transient (labeled “OT”). In all the images, the local background has been subtracted by a median filter and the resulting image smoothed (with a two-dimensional Gaussian with $\sigma = 0''.23$). An unrelated faint source “f” in the field is noted for comparison of the relative limiting flux between the three epochs: it is marginally detected (at the $\sim 2-$σ level) on March 27 and April 17 but well detected on December 18. In contrast the OT is brighter and better detected (at the 4.6-σ level, see text) on April 17 but clearly not detected to fainter levels on December 18 ($R > 27.3$; see Table 1).

Methodology. In keeping with standard practice, our April 17th observations consisted of three separate 300-s observations (dithered by 5 arcseconds). Visual inspection of the three frames reveals a faint source near the position of the optical transient. In no frames was did a diffraction spike of the nearby bright star “A” overlap the OT position. Also, there were no apparent cosmic-ray hits at the transient position nor were there any strong gain variations (i.e. no apparent problem with the flat-fielding) at the three positions on the CCD. In both the sum and mode-scaled median of the three shifted images, we detect a faint source consistent with the centroid location (angular offset $0.04 \pm 0.18$ arcsec) of the optical transient on 1998 March 27. Lastly, we computed the point source sensitivity in the April 17th image by computing Gaussian-weighted photometry in 1000 random apertures (see discussion accompanying Table 1). Relative to this distribution, the flux at the location of the transient is positive and equal to 4.6-σ; the probability that the measured flux is due to noise is $2 \times 10^{-6}$. All objects at the flux level of the transient are reliably detected in the deeper image from December, thereby providing an independent validation of our methodology. We conclude that indeed the transient was significantly detected on April 17th. We discuss the photometric calibration of the detection in Table 1.
The $R$-band light curve of the afterglow of GRB 980326. Overlaid is a power-law afterglow decline summed with a bright supernova light curve at different redshifts. (Although we use as as a template the multi-band light curve of SN 1998bw (refs. 18,41), the bright supernova potentially associated with GRB 980425, we emphasize that the exact light-curve shapes of a supernova accompanying a GRB is not known a priori.) The GRB+SN model at redshift of about unity provides an adequate description of the data.

**Transient Light curve.** From ref. 48 we estimate the Galactic extinction in the direction of the optical transient ($l, b = 242.36, 13.04$) to be $E(B-V) = 0.08$. Thus, assuming the average Galactic extinction curve ($R_V = 3.1$), the extinction measure is $A_R = 0.22$, $A_I = 0.16$ mag. Plotted are the extinction corrected magnitudes (see Table 1) of the transient converted to the standard flux zero-point of the Cousins $R$ filter from ref. 46. In addition to our data, we include photometric detections from Groot et al.\textsuperscript{21} and an upper-limit from Valdes et al.\textsuperscript{22} (KPNO). The GRB transient flux dominates at early times, but with a power-law decline slope $\alpha = -2$ (straight solid line).

**Supernova light curve.** The supernova light curve template was constructed by spline-fitting the broadband spectrum measured by Galama et al.\textsuperscript{18} of the bright supernova 1998bw at various epochs (augmented with late-time observations of SN 1998bw by McKenzie and Schaefer\textsuperscript{41}) and transforming back to the restframe of SN 1998bw ($z = 0.0088$). As discussed in the text, we expect the rest-frame UV emission (below 3900 Å) to be suppressed due to absorption by resonance lines. We assume that the UV flux declines as $f_\nu \propto \nu^{-3}$. Theoretical light curves are then constructed by red-shifting the template to various redshifts and determining the flux in the $R$ (observer frame) by interpolating (or extrapolating, for $z \gtrsim 1$). The flux normalization of the redshifted SN 1998bw curves are independent of the Hubble constant but are dependent upon the value of $\Omega_0$ and $\Lambda_0$ (here we show the curves for $\Omega_0 = 0.2$ and $\Lambda_0 = 0$). Beyond $z \approx 1.3$ the observed $R$-band corresponds to restframe $\lambda \lesssim 2900$ Å. As stated in the text, the spectrum in this range has been modeled along simple lines. Qualitatively, the peak flux derived from the SN model as a function of redshift and shown here agrees with the theoretical peak flux-redshift relation for type Type Ia\textsuperscript{49}. This suggests that our adopted model for the UV spectrum is reasonable.
Figure 3

The spectra of the transient on March 29.27 and April 23.83 1998 UT. The two spectra are shown at two different spectral resolutions. Starting from the top, panels 1 and 3 show the spectra at the two epochs at the full spectral resolution (see below for details) and panels 2 and 4 show the same two spectra but binned in groups of 51 channels. Panel 5 is the spectrum of the sky. The best-fit power law models ($f_{\nu} \propto \nu^{\beta}$) to the binned spectra are shown by dashed lines; the fits were restricted the wavelength range 4500-8500 Å. The scatter of individual channel values within each bin was used to assign relative weights to the median fluxes in each bin when performing the fits.

Results. On March 29.27, we obtain $\beta = -0.8 \pm 0.4$ and $\beta = -2.8 \pm 0.3$ on April 23.83. The derived power-law indices include the correction of Galactic extinction. From the absence of continuum breaks in the spectrum of March 29, we can place an upper limit to the redshift, $z_{OT} < 2.3$.

Observing Details. Spectroscopic observations of the OT were obtained on 29 March 1998 UT, using the Low Resolution Imaging Spectrometer (LRIS) at the Keck-II 10-m telescope on Mauna Kea, Hawaii. We used a grating with 300 lines mm$^{-1}$ blazed at $\lambda_{\text{blaze}} \approx 5000$ Å and a 1.0 arcsec wide slit. The effective wavelength coverage was $\lambda \sim 4000 - 9000$ Å and the instrumental resolution was $\sim 12$ Å. Two exposures of 1800 s each were obtained. We used Feige 34 (ref. 50) for flux calibration. The estimated uncertainty of the flux zero point is about 20%. Additional spectra were obtained on 23 April 1998 UT, in photometric conditions, using the same instrument, except that the spectrograph slit was 1.5 arcsec wide. The effective spectral resolution for this observations was $\sim 16$ Å. Three exposures of 1800 s each were obtained. For these observations we used HD 84937 (ref. 51) for flux calibration. The estimated zero-point uncertainty is about 10%. On both epochs, exposures of arc lamps were used for primary wavelength calibration. Night sky lines were used to correct for calibration changes due to flexure. In both cases, slit position angles were close to be close to the parallactic angles. Thus the differential slit losses were negligible.

The spectra shown were convolved with a Gaussian with $\sigma = 5$ Å (i.e., less than the instrumental resolution) and rebinned to a common 5 Å sampling. None of the apparent features in the spectra are real, on the basis of a careful examination of two-dimensional, sky-subtracted spectroscopic images: apparent emission of absorption features are all due to an imperfect sky subtraction noise. A sky spectrum from the April 23 observation, extracted in the same aperture, is shown for the comparison. These spectra are shown before the correction for the Galactic foreground extinction.

Spectrophotometry. In both epoch, we chose a slit position angle close to parallactic so that the slit would cover both the transient and a relatively bright star ($R \sim 19$). The spectroscopic $R$-band magnitudes reported in table 1 were derived relative to the calibrated $R$-band magnitude of these stars. This calibration serves to eliminate most of the systematics and calibration errors; that is, the spectrophotometric magnitudes were put on the direct CCD system, and are not based on the flux calibration of the spectra (which do, nevertheless, agree to twenty percent). This procedure bypasses most of the systematic errors in comparing our spectroscopic magnitudes with those from direct CCD images.
References

1. Klebesadel, R. W., Strong, I. B., & Olson, R. A. Observations of gamma-ray bursts of cosmic origin. *Astrophys. J.* **182**, L85–L88 (1973).

2. Boella, G. et al. BeppoSAX, the wide band mission for x-ray astronomy. *Astron. Astrophys. Suppl. Ser.* **122**, 299–399 (1997).

3. Levine, A. M., Bradt, H., Cui, W., Jernigan, J. G., Morgan, E. H., Remillard, R., Shirey, R. E. & Smith, D. A. First Results from the All-Sky Monitor on the Rossi X-ray Timing Explorer. *Astrophys. J.* **469**, L33-L36 (1996).

4. Costa, E. et al. Discovery of an X-ray afterglow associated with the gamma-ray burst of 28 February 1997. *Nature* **387**, 783–785 (1997).

5. van Paradijs, J. et al. Transient optical emission from the error box of the \( \gamma \)-ray burst of 28 February 1997. *Nature* **386**, 686–689 (1997).

6. Frail, D. A., Kulkarni, S. R., Nicastro, L., Feroci, M. & Taylor, G. B. The radio afterglow from the gamma-ray burst of 8 May 1997. *Nature* **389**, 261–263 (1997).

7. Metzger, M. R., Djorgovski, S. G., Kulkarni, S. R., Steidel, C. C., Adelberger, K. L., Frail, D. A., Costa, E. & Frontera, F. Spectral Constraints on the redshift of the optical counterpart to the gamma-ray burst of May 8, 1997. *Nature* **387**, 878–879 (1997).

8. Waxman, E., Kulkarni, S. R. & Frail, D. A. Implications of the Radio Afterglow from the Gamma-ray Burst of 1997 May 8. *Astrophys. J.* **502**, L119–L122 (1998).

9. Kulkarni, S. R. et al. Identification of a host galaxy at redshift \( z = 3.42 \) for the \( \gamma \)-ray burst of 14 Dec 1997. *Nature* **393**, 35–39 (1998).

10. Djorgovski, S. G., Kulkarni, S. R., Bloom, J. S., Goodrich, R., Frail, D. A., Piro, L., & Palazzi, E. Spectroscopy of the Host Galaxy of the Gamma–Ray Burst 980703. *Astrophys. J.* **508**, L17–L20 (1998).

11. Kulkarni, S. R. et al. The afterglow, the redshift, and the extreme energetics of the gamma-ray burst 990123. *Nature* **398**, 389–394 (1999).

12. Andersen, M. I. et al. Spectroscopic limits on the distance and energy release of GRB 990123. *Science* **283**, 2075–2077 (1999).

13. Paczyński, B. Gamma-ray bursters at cosmological distances. *Astrophys. J.*, **308**, L43–L46 (1986).

14. Goodman, J. Are Gamma-Ray Bursts Optically Thick? *Astrophys. J.*, **308**, L47–L50 (1986).

15. Narayan, R., Paczyński, B., Piran, T. Gamma-ray bursts as the death throes of massive binary stars. *Astrophys. J.*, **95**, L83–L86 (1992).

16. Woosley, S. E. Gamma-Ray Bursts from Stellar Collapse to a Black Hole? *Astrophys. J.*, **405**, 273–277 (1993).

17. Paczyński, B. Are Gamma-Ray bursts in Star-Forming Regions? *Astrophys. J.* **494**, L45–L48 (1998).
18. Galama, T. J. et al. An unusual supernova in the error box of the gamma-ray burst of 25 April 1998. *Nature*, **395**, 670–672 (1998).
19. Kulkarni, S. R. et al. 1998, Radio emission from the unusual supernova 1998bw and its association with the \( \gamma \)-ray burst of 25 April 1998. *Nature* **395**, 663–669.
20. Celidonio, G., Coletta, A., Feroci, M., Piro, L., Soffitta, P., in ’t Zand, J., Muller, J., Palazzi, E. GRB 980326. *I.A.U.C.* **6851** (1998).
21. Groot, P. J. et al. The Rapid Decay of the Optical Emission from GRB 980326 and Its Possible Implications. *Astrophys. J.* **502**, L123–127 (1998).
22. Valdes, F., Jannuzi, B., & Rhoads, J. GRB980326, optical observations. *G.C.N.* **156**, (1998).
23. The GRB Coordinates Network. [http://gcn.gsfc.nasa.gov/gcn/](http://gcn.gsfc.nasa.gov/gcn/)
24. Djorgovski, S. G., Kulkarni, S. R., Côté, P., Blakeslee, J. Bloom, J. S., Odewahn, S. C. GRB980326, Optical Observations. *G.C.N.* **189**, (1999).
25. Mao, S. & Mo, H. J. The nature of the host galaxies for gamma-ray bursts. *Astron. Astrophys.* **339**, L1–L4 (1998).
26. Hogg, D. W., Fruchter, A. S. The faint galaxy hosts of Gamma-Ray bursts. *Astrophys. J.* in press (1999).
27. Djorgovski, S. G. et al. The optical counterpart to the gamma-ray burst GRB 970508 *Nature*, **387**, 876–878 (1997).
28. Katz, J.I. Low-frequency spectra of gamma-ray bursts. *Astrophys. J.* **432**, L110–113 (1994).
29. Mészáros, P., & Rees, M.J. Optical and Long-Wavelength Afterglow from Gamma-Ray Bursts. *Astrophys. J.* **476**, 232–240, (1997).
30. Vietri, M. The Soft X-Ray Afterglow of Gamma-Ray Bursts, A Stringent Test for the Fireball Model. *Astrophys. J.* **478**, L9–12. (1997).
31. Waxman, E. Gamma-ray-burst afterglow: supporting the cosmological fireball model, constraining parameters, and making prediction. *Astrophys. J.* **485**, L5–L8 (1997).
32. Sari, R., Piran, T., Narayan, R. Spectra and Light Curves of Gamma-Ray Burst Afterglows. *Astrophys. J.* **497**, L17–L20 (1998).
33. Mészáros, P., Rees, M. J. & Wijers, R. A. M. J. Viewing Angle and Environment Effects in Gamma-ray Bursts: Source of Afterglow. *Astrophys. J.* **499**, 301–308 (1998).
34. Chevalier, R. & Li, Z.-Y. Gamma-ray Burst Environments and Progenitors. [astro-ph/9904417](http://xxx.lanl.gov/), (1999).
35. Halpern, J. P., Kemp, J., Piran, T., & Bershady, M. A. The Rapidly Fading Optical Afterglow of GRB 980519. [astro-ph/9903418](http://xxx.lanl.gov/) [http://xxx.lanl.gov](http://xxx.lanl.gov) (1999).
36. Sari, R. & Piran, T. Jets in GRBs. [astro-ph/9903339](http://xxx.lanl.gov/) [http://xxx.lanl.gov](http://xxx.lanl.gov) (1999).
37. Piro, L. et al. The X-Ray Afterglow of the Gamma-Ray Burst of 1997 May 8: Spectral Variability and Possible Evidence of an Iron Line. *Astrophys. J.* **514**, L73–L77, (1999).
38. Panaitescu, A., Mészáros, P., & Rees, M.J. Multiwavelength Afterglows in Gamma-Ray Bursts: Refreshed Shock and Jet Effects *Astrophys. J.* **503**, 314–324 (1998).
39. Loeb, A. Talk given at the Institute for Theoretical Physics, University of California, Santa Barbara, March 1999.
40. MacFadyen, A. & Woosley, S. E. Collapsars – Gamma-Ray Bursts and Explosions in “Failed Supernovae”. astro-ph/9810274, http://xxx.lanl.gov, (1999).
41. McKenzie, E. H. & Schaefer, B. E. The Late Time Light Curve of SN 1998bw Associated with GRB980425 astro-ph/9904397, http://xxx.lanl.gov, (1999).
42. Kirshner, R. P., et al. SN 1992A: Ultraviolet and Optical Studies Based on HST, IUE, and CTIO Observations Astrophys. J. 415, 589–615 (1993).
43. Woosley, A. Talk given at Rome Conference on Gamma-Ray Bursts, Rome, Italy, November 1998.
44. Iwamoto, K. et al. A hypernova model for the supernova associated with the gamma-ray burst of 25 April 1998. Nature 395, 672–674.
45. Oke, J. B., Cohen, J. L., Carr, M., Cromer, J., Dingizian, A., Harris, F. H., Labrecque, S., Lucinio, R. Schaal, W., Epps, H. & Miller, J. The Keck Low-Resolution Imaging Spectrometer. Publ. Astr. Soc. Pacific 107, 375-385 (1995).
46. Fukugita, M., Shimasaku, K., & Ichikawa, T. Galaxy Colors in Various Photometric Band Systems. Publ. Astr. Soc. Pacific 107, 945–958 (1995).
47. Landolt, A. UBVRI photometric standard stars in the magnitude range 11.5–16.0 around the celestial equator. Astron. J. 104, 340–376 (1992).
48. Schlegel, D. J., Finkbeiner, D. P., & Davis, M. Maps of Dust Infrared Emission for Use in Estimation of Reddening and Cosmic Microwave Background Radiation Foregrounds. Astrophys. J., 500, 525–553 (1998).
49. Schmidt, B. P. et al. The High-z supernova search: Measuring cosmic deceleration and global curvature of the universe using type Ia supernovae. Astrophys. J. 507, 46–63 (1998).
50. Massey, P., Strobel, K., Barnes, J. V., Anderson, E. Spectrophotometric standards Astrophys. J. 328, 315–333 (1988).
51. Oke, J. B., & Gunn, J. E. Secondary standard stars for absolute spectrophotometry Astrophys. J. 266, 713–717 (1983).