The host galaxy and the high redshift (z=3.42) of the gamma-ray burst 971214

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The nature of gamma-ray bursts (GRBs) still remains one of the major unresolved mysteries of astrophysics. Recently the discovery of the "afterglow" phenomenon – long-lived fading emission at lower energies, from X-ray to optical and radio – has dramatically increased our understanding of these mysterious bursts. The third such optical afterglow known was associated with the burst of 14 December 1997 UT. We report on the discovery of a faint

galaxy coincident with the fading optical source. The redshift of the galaxy is measured to be z = 3.42, placing it at a cosmological distance corresponding to the look-back time of about 85% of the present age of the universe. The properties of the galaxy are typical for the young galaxy population at such redshifts. The large distance, coupled with the measured γ-ray flux from the burst, implies an energy release of $\sim 3 \times 10^{53}$ erg in the γ-rays alone, if the emission was isotropic. This is considerably larger than the energies heretofore believed to be involved in GRBs, presenting a challenge for theoretical models.

Ever since their discovery nearly three decades ago[1], it was understood that the progress in solving the puzzle of γ-ray bursts depends on their identification at other wavelengths, preferably at optical wavelength, so that the distances can be measured using standard spectroscopic techniques. From distances and flux measurements one can then infer luminosities and other physical parameters, which can then be used to motivate and test theoretical models for the bursts and their origins.

A recent breakthrough in this field was the precise localisation of bursts by the BeppoSAX satellite[2], which has lead to the first identifications of GRBs at other wavelengths: x-rays[3], optical[4] and radio[5]. This has further lead to the determination of the distance scale of GRBs, with the detection of intergalactic absorption lines[6] in the optical transient[7,8] of GRB 970508 (ref. 9,10). Apparent host galaxies have been detected for the first two optical afterglows found[11,12,13,14].

Here we report follow-up studies of the optical transient[15] (OT) of a relatively bright burst, GRB 971214 (ref. 16,17,18). As the OT faded away, we found an extended object with a red magnitude R=25.6 ± 0.15 at the position of the OT. Based on the excellent positional coincidence, 0.06 ± 0.06 arcsecond, we argue that this is the host galaxy of GRB971214. Spectroscopic observations show that the host is a typical star-forming galaxy[19,20,21] at a redshift $z = 3.418$.

Given this high redshift, the γ-ray energy release of this burst is unexpectedly large, about 3×10^{53} erg, assuming isotropic emission, corresponding to about 16% of the rest mass energy of our Sun. Energy released in other forms of radiation, e.g., neutrinos or gravity waves, is not included in this energy budget. Nonetheless, the inferred energy release in gamma-rays alone is so substantial that it may present difficulties for some of the currently popular theoretical models for the origin of the bursts (coalescence of neutron stars). We may be forced to consider even more energetic possibilities[22,23] or find ways of extracting more electromagnetic energy in coalescence models.

The optical transient

Our follow-up at the Keck Observatory began on the night of UT 1997 December 15, approximately 13 h after the burst. The only available imager was a "guide" camera with a small field-of-view and relatively low sensitivity; consequently, these data were not used in the analysis described below. For the subsequent nights we used the Low Resolution Imaging Spectrograph[24] (LRIS) mounted at the Cassegrain focus of the Keck II 10-m telescope. Our early observations were made in the I-band. This choice was driven by the presence of bright moon in the sky. Later observations were done under darker sky conditions and with a R-band filter (OG570+KG3). See Table 1 for an observational summary as well as measurements reported in the literature[25,26,27,28,29].

In Figure 1 we display an I-band image obtained on UT 1997 December 16.52, when the optical transient[25] (OT) was still bright. I and R magnitudes of the OT are presented in Table 1 and displayed in Figure 2. In order to establish consistency between our measurements and the early time measurements reported by others, we measured instrumental magnitudes of a number of "secondary" stars in the general vicinity of the OT and then used them to define the zero-point of our instrumental magnitudes for all of our data sets. We calibrated the instrumental magnitudes by using observations of the standard star PG 0231+051 (for which we assume I=16.639 mag; ref. ref. 31) obtained on UT 1997 December 22. We then derived the magnitudes for stars H1 and H2 (identified in Figure 1), respectively, 16.1 ± 0.1 mag and 18.6 ± 0.2 mag. For these two stars, Halpern et al.[15] obtained 15.93 mag and 18.46 mag. Within errors, these two sets of measurements agree and thus allow us to link our I-band magnitudes to those of Halpern et al.[25]. The zero point for our R-band magnitudes was set by assuming $R = 20.1 \pm 0.1$ for object 2 of Henden et al.[29]; see also Figure 1. Our R-band magnitude is in excellent agreement with that obtained by Diercks et al.[27] at about the same epoch.

The decay of previous OTs associated with GRBs appears to be well characterized by a power law: $S(t) \propto t^{-\alpha}$, where $S(t)$ is the flux of the OT and t is the time since the gamma-ray burst. Accepting this parametric form and restricting to the time interval December 15–17 we obtain $\mathrm{I(t)} = (22.22 \pm 0.18) + (3.09 \pm 0.52) \log(\mathrm{t/day})$. Since magnitudes are defined to be $-2.5\log(S) + \text{constant}$, the value of α is 1.22 ± 0.2 — remarkably similar to those reported for previous OTs[32,33,34].

From Figure 2 we note that initially the R flux appears to decrease in approximately the same fashion as the I flux. Such broad-band decay has been noted in previous OTs[33,34] and indeed is an expectation of simple fireball models[32,35]. Accepting that all optical bands decay with the same α, we obtain, $\mathrm{R(t)} = (23.0 \pm 0.22) + (3.09 \pm 0.52)\log(\mathrm{t})$. In arriving at this equation we have used our 16 December R-band measurement (Table 1) to set the zero point.

Identifying the host galaxy

Using the above decay formula we predict $\mathrm{R} = 27.4 \pm 0.8$ mag on UT 1998 January 10. In contrast, we find at the same epoch an object at the position of the OT with $\mathrm{R}{=}25.6 \pm 0.17$ mag (see Figure 1). Furthermore, this object, henceforth "K", is extended in comparison to stars in the same field. We suggest that K is the host galaxy of the GRB and has become apparent now that the OT has dimmed.

It is of considerable importance to assess how well K coincides with the OT. To this end, we determined the location of the OT relative to 15 "tertiary" stars in the vicinity of the OT in the December 16.52 I-band image, and likewise for K in the January 10 R-band image. The error in the measured angular difference between the OT and K is determined by two factors. (1) The error in determining the centroid of K primarily arising from the small number of signal photons and the sky background. We estimate this to be 0.20 pixel (rms); each LRIS pixel is a square of size 0.211 arcsecond . The similar error for the OT is negligible since in the December 16 image that we used the OT is much brighter than K. (2) Errors due to coordinate transformation between the two images which are of different orientations. We determined a coordinate transformation between the frames using the measurements of the tertiary stars and then transformed the centroid of the OT into the frame of January 10 image. This error turns out to be negligible compared to the error discussed in (1). The difference between the position of the OT in the transformed image and that of K is $\Delta X = 0.24 \pm 0.20$ pixel $= 0.05 \pm 0.04$ arcsec and $\Delta Y = 0.14 \pm 0.20$ pixel $= 0.03 \pm 0.04$ arcsec, corresponding to a radial separation of 0.06 ± 0.06 arcsec.

One may argue that the density of galaxies as faint as K is sufficiently high that the coincidence of the OT with a background galaxy is not improbable. The cumulative surface density[36] of galaxies with $R \leq 25.5$ mag is 3.9×10^5 deg^{-2}. Considering angular offsets up to the apparent radius of the galaxy, 0.35 arcsecond (see Figure 1), the chance coincidence probability is reasonably small ($\sim 10^{-3}$). Thus we suggest that galaxy K is the host of the OT and thus that of GRB 971214.

Determining the redshift

Spectroscopic observations of the OT and its host galaxy were obtained using LRIS[24]. Our initial attempt to obtain the spectrum of the OT on UT 1997 December 17 was unsuccessful primarily due to the bright moonlight. Subsequent observations were obtained under much better sky conditions and after the OT had faded and object K dominated the light. Almost all spectra were obtained with the slit position angle close to the parallactic angle, and the wavelength-dependent slit losses are not important for the discussion below.

The log and the technical details of the spectroscopic observations can be found in Table 2.

The spectrum, shown in Figure 3, shows a prominent emission line at $\lambda_{obs,air} = 5382.1$ Å, with a clear continuum drop immediately blueward of the line. No other emission line is detected. The continuum rises slightly towards the red and is undetectable at about 4000 Å.

There are only two plausible interpretations of this prominent emission line. All other choices would require a presence of other, stronger emission lines which are not seen in our spectrum. First, the line could be [O II] 3727 at $z = 0.444$. We would then expect to see comparably strong [O III] 5007 and 4959 lines at 7230 Å and 7160 Å, Hβ 4861 Å at 7020 Å, and perhaps also other Balmer lines. Yet, none of these lines are seen in our data, even though they fall in a reasonably clean part of the spectrum. It would be also hard to understand the abrupt drop in the continuum blueward of the emission line.

The alternative interpretation, and the interpretation which we favor, is that the emission line is Lyα 1215.7 Å at $z_{em} = 3.428$. The overall appearance of the spectrum is typical of the known, star-forming galaxies at comparable redshifts[19,20,21]. In the absence of an active nucleus, no other strong emission lines would be expected within the wavelength range probed by our spectrum. Additional arguments in favor of the large redshift interpretation include:

(1) The drop across the Lyα line, due to the absorption by intervening hydrogen, is characteristic of objects at such high redshifts. The measured drop amplitude[37] $D_A = 0.35 \pm 0.05$ is exactly the mean value seen in the spectra of quasars at this redshift[38].

(2) We expect no flux blueward of 4030 Å, the redshifted Lyman continuum break. Additionally, we expect a relatively flat, star-formation-powered continuum redwards of Lyα line. Our spectrum is consistent with these expectations. The expected suppression of blue light is also supported by our imaging observations in the B band (Table 1); this band covers the range 3900 Å to 4800 Å. Our 3σ upper limit on the B magnitude of galaxy K is 26.8 mag corresponding to a B-flux of < 84 nJy. We find that the red portion of the spectrum can be approximated by $F_\nu = 174(\nu/\nu_R)^\alpha$ nJy with $\alpha = -0.7 \pm 0.2$; here F_ν is the spectral density at frequency ν and $\nu_R = 4.7 \times 10^{14}$ Hz, the center frequency of the R-band. The extrapolation of this spectrum to the B band ($\nu_B = 6.8 \times 10^{14}$ Hz) is 134 nJy, above our upper limit.

(3) Finally, we plot in Figure 3 the expected locations of some of the commonly observed interstellar gas absorption lines seen in the spectra of star-forming galaxies at high redshifts[19,20,21]. We note several suggestive coincidences with dips in the observed spectrum.

If this interpretation is correct, a better estimate of the galaxy's redshift can be obtained as follows. The Lyα emission line tends to be shifted systematically to the red in such galaxies, due to resonant scattering and absorption in the ambient gas. In any given case, the bias thus introduced in the centering of the peak of the Lyα emission depends on the exact geometry and kinematics of the gas and dust, which are not known; but on average the effect is to shift the peak of the Lyα emission to the red, relative to the systemic redshift of the galaxy[19,20,21]. We measure the wavelength of the apparent absorption dip immediately shortward of the emission line: $\lambda_{obs,air} = 5356.1$ Å. Taking the mean of this wavelength and that of the emission line, and applying the standard air-to-vacuum correction, we obtain for the systemic redshift of this galaxy, $z_K = 3.418 \pm 0.010$.

As discussed above the continuum slope of the observed spectrum redward of the emission line as $F_\nu \propto \nu^\alpha$ with $\alpha = -0.7 \pm 0.2$. Unobscured star-forming galaxies have $\alpha \sim$ 0.0 to -0.5, depending on the initial mass function and the history of star formation. The slightly steeper slope of our spectrum suggests a modest amount of restframe extinction for the galaxy as a whole. This of course does not constrain the extinction along any particular line of sight, such as the direction to the OT itself. We note that similar extinctions are inferred for star-forming galaxies at comparable redshift[19].

Two corrections must be taken into account before a quantitative interpretation of the spectrum can be done. First, the Galactic reddening in this direction is estimated[39] to be $E_{B-V} \approx 0.016$ mag, implying a Galactic extinction correction to the observed fluxes of about 6% at the wavelength of the emission line, and about 4% in the R band. Second, by comparing the spectrum to our measured R photometry of the galaxy, we estimate the slit loss to be a factor of 1.48.

The nature of the host galaxy

We now discuss the physical properties and nature of this galaxy. Assuming a standard Friedman model cosmology with $H_0 = 65\ \mathrm{km\,s^{-1}\ Mpc^{-1}}$ and $\Omega_0 = 0.3$ we derive a luminosity distance (d_L) of 9.7×10^{28} cm (changing the cosmological parameters to $H_0 = 50\ \mathrm{km\,s^{-1}\ Mpc^{-1}}$ and $\Omega_0 = 1$ yields $d_L = 8.6 \times 10^{28}$ cm). Assuming that the intrinsic spectrum F_ν is $\propto \nu^{-0.7}$ and scaling from the observed R-band magnitude corrected for the Galactic extinction, we find the rest-frame B-band flux to be ~ 0.45 μJy. The corresponding absolute B magnitude $M_B \approx -20.9$, and is about equal to the absolute magnitude of a typical, L_* galaxy today. Given its high redshift, this galaxy probably has yet to produce most of its stars, and even with some evolutionary fading its present-day luminosity it may evolve to be $\gtrsim L_*$.

The observed Lyα emission line flux is $F_{Ly\alpha} = (3.8 \pm 0.4) \times 10^{-18}$ erg cm^{-2} s^{-1}. Correcting for the flux calibration zero-point and the Galactic extinction, this becomes $F_{Ly\alpha} = (6.2 \pm 0.7) \times 10^{-18}$ erg cm^{-2} s^{-1} . For our assumed cosmology, the implied Lyα line luminosity is $L_{Ly\alpha} = (7.3 \pm 0.8) \times 10^{41}$ ergs s^{-1}. Estimates of conversion of the Lyα line luminosity to the implied unobscured star-formation rate (SFR) are in the range $L_{Ly\alpha} = (7 \pm 4) \times 10^{41}$ erg s^{-1} for $SFR = 1 M_\odot$ yr^{-1}, depending on the stellar initial mass function (IMF)[40,41]. We thus estimate the unobscured SFR in this galaxy to be $SFR \approx (1.0 \pm 0.5)$.

However, the Lyα emission line is likely attenuated by resonant scattering in neutral hydrogen and absorption by dust. An independent, and perhaps more robust estimate of the SFR can be obtained from the restframe continuum luminosity at 1500Å (ref. 42). We note that the observed flux at a wavelength of $1500(1 + z_K)$ Å is 0.22 μJy. This translates to a star-formation rate under the usual assumption of a Salpeter IMF of 5.2 $M_\odot$ yr^{-1}. These numbers should be regarded as lower limits given the unknown extinction in the restframe of galaxy K.

On the whole, the properties of this galaxy are typical of the known systems at comparable redshifts[19,20,21], thus giving us some confidence that our redshift interpretation is indeed correct.

The fluence of this gamma-ray burst[17] above the observed photon energy of 20 keV is $F = 1.1 \times 10^{-5}$ erg cm^{-2}. 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 burst was also observed by the All Sky Monitor aboard the X-ray satellite XTE (ref. ref. 43). D. A. Smith (pers. comm.) estimates the fluence in the 2-12 keV band to be $1.8(\pm 0.03) \times 10^{-7}$ erg cm^{-2}. Thus the isotropic energy loss in γ-rays alone at the distance to the host is $4\pi d_L^2 F/(1+z) \sim 3 \times 10^{53}$ erg.

The currently favored model[44] for GRBs is coalescence of neutron stars. The coalescence is expected to release most of the energy in neutrinos (as in Type II supernovae) and $\sim 10^{51}$ erg is supposed to be in the form of electromagnetic energy. The measured fluence of GRB 971214 when combined with our proposed redshift for the GRB may be inconsistent with the expectations of the neutron star merger model in its simplest form, although it is possible that more elaborate versions of this model can be made to fit these observations. Non-spherical emission could reduce the strain on the energy budget but will not alter the fact that this fairly bright burst originated from such a large redshift.

The most significant of our hypothesis that K is the host galaxy of GRB 971214 is the implied extreme energetics. The energy budget for GRBs goes up from the traditional 10^{51} ergs to perhaps the entire energy available in the coalescence of neutron-star mergers[44]. Other energetic models such as the death of an extremely massive star[23] to coalescence of black-hole neutron star binaries[22] may then become more attractive. In the latter models, GRBs are directly related to the formation rate of massive stars. If that is the case then the typical redshift of GRBs is ~ 2 (ref. 45), consistent with the suggested high redshift for GRB 971214. Moreover, this burst evidently did not originate in a highly obscured star forming region in its host galaxy.

Regardless of the details of their genesis, GRBs appear to be the brightest known objects in the Universe, albeit over the limited duration of the burst. The term "hypernova[23]" can be justifiably used to describe these most extreme events, especially their afterglow. GRB 971214 was not a particularly faint event and thus statistically we expect many fainter events to arise from larger redshifts. The high brightness of GRBs and their OTs offer us exciting and new opportunity to probe the Universe at high redshifts.

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. 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).

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

5. 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).

6. 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 γ-ray burst of 8 May 1997. *Nature* **387**, 878-880 (1997).

7. Bond, H. E. *et al. IAU Circ.* **6665**, (1997).

8. Djorgovski, S. G. *et al.* The Optical Counterpart to the Gamma-Ray Burst 970508. *Nature* **387**, 876-878 (1997).

9. Costa, E. et al. *Intl. Astron. Union Circ.* **6649** (1997).

10. Piro, L. et al. *Intl. Astron. Union Circ.* **6656** (1997).

11. Bloom, J.S., Kulkarni, S.R., Djorgovski, S.G., and Frail, D.A., *GCN Note #30*, (1998).

12. Zharikov, S. V., Sokolov, V. V. & Baryshev, Y. V. *GCN Note # 31*, (1998).

13. Galama, T. J. et al. Optical Followup of GRB 970508. Astrophs. J. (submitted), (1998).

14. Sahu, K. C. et al. Observations of GRB 970228 and GRB 970508 and the Neutron Star Merger Mode. *Astrophys. J.* **489**, L127-L131 (1997).

15. Halpern, J. P., Thorstensen, J. R., Helfand, D. J., & Costa, E., Optical afterglow of the gamma-ray burst GRB971214. *Nature*, in press (1998).

16. Heise, J., in't Zand, et al. *Intl. Astr. Union Circ.* **6787** (1997).

17. Kippen, R. M. et al. Intl. Astr. Union Circ. **6789**, (1997).

18. Antonelli, L. A., Bulter, R. C., Piro, L., Celidonio, A., Tesseri, A. & de Libero, C. *Intl. Astr. Union Circ.* **6792**, (1997).

19. Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K., Spectroscopic confirmation of a population of normal star-forming galaxies at redshifts $z > 3$, *Astrophys. J.* **462**, L17-L21 (1996).

20. Steidel, C. C., Giavalisco, M., Dickinson, M., & Adelberger, K. L., Spectroscopy of Lyman break galaxies in the Hubble Deep Field, *Astron. J.* **112**, 352-358 (1996).

21. Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., Pettini, M., & Kellogg, M. A large structure of galaxies at redshift $z \sim 3$ and its cosmological implications, *Astrophys. J.* **492**, 428-438 (1998).

22. Meszáros, P. & Rees, M.J. Poynting Jets from Black Holes and Cosmological Gamma-Ray Bursts. *Astrophys. J.* **482**, L29-L31 (1997).

23. Paczyński, B. Are Gamma-Ray Bursts in Star-Forming Regions? *Astrophys. J.* **494**, L45-L48 (1998).

24. 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).

25. Halpern, J., Thorstensen, J., Helfand, D. & Costa, E. *Intl. Astr. Union Circ.* **6788**, (1997).

26. Rhoads, J., *Intl. Astr. Union Circ.* **6793** (1997).

27. Diercks, A., Deutsch, W. W., Wyse, R., Gilmore, G., Corson, C., Castander, F. J. & Turner, E., *Intl. Astr. Union Circ.* **6791** (1997).

28. Castander, F. J., Wyse, R., Gilmore, G., Corson, C., Diercks, A., Deutch, E. W., Lamb, D. Q. & Turner, E. *GCN Note #11*, (1997).

29. Henden, A.A., Luginbuhl, C. B. & Vrba, F. J., *GCN Note #16*, (1997).

30. Bessell, M. S. UBVRI Passbands. *Publ. Astr. Soc. Pacific* **102**, 1181-1199 (1990).

31. Landolt, A. U., UBVRI photometric standard stars in the magnitude range $11.5 < V < 16.0$ around the celestial equator. *Astr. J.* **104**, 340-371 (1992).

32. Wijers, R. A. M. J., Rees, M. J. & Meszáros, P. Shocked by GRB 970228: the afterglow of a cosmological fireball. *Mon. Not. Roy. Soc.* **288**, L51-L56 (1997).

33. Sokolov, V. V. et al. BVR_cI_C photometry of GRB 970508 optical remnant: May-August, 1997. *Astron. Astrophys.*, in press; preprint http://xxx.lanl.gov, astro-ph/9802341 (1998).

34. Galama, T. J. et al. Optical follow-up of GRB 970508. *Astrophys. J.*, in press; preprint http://xxx.lanl.gov, astro-ph/9802160 (1998).

35. Waxman, E. Gamma-Ray–Burst Afterglow: Supporting the Cosmological Fireball Model, Constraining Parameters, and Making Predictions. *Astrophys. J.* **485**, L5-L8 (1997).

36. Hogg, D. W., Pahre, M. A., McCarthy, J. K., Cohen, J. G., Blandford, R., Smail, I., & Soifer, B. T., Counts and colors of faint galaxies in the U and R bands, *Mon. Not. R. Astron. Soc.* **288**, 404-410 (1997).

37. Oke, J. B., & Korycansky, D., Absolute spectrophotometry of very large redshift quasars, *Astrophys. J.* **255**, 11-19 (1996).

38. Kennefick, J. D., Djorgovski, S. G., & de Carvalho, R. R., The luminosity function of $z > 4$ quasars from the second Palomar sky survey, *Astron. J.* **110**, 2553-2565 (1995).

39. Schlegel, D. J., Finkbeiner, D. P. & Davis, M. Maps of dust IR emission for use in estimation of reddening and CMBR foregrounds. *Astrophys. J.*, in press; preprint http://xxx.lanl.gov, astro-ph/9710327.

40. Thompson, D., Djorgovski, S., & Trauger, J., A narrow-band imaging survey for primeval galaxies, *Astron. J.* **110**, 963-981 (1995).

41. Charlot, S., & Fall, S. M., Lyman-alpha emission from galaxies, *Astrophys. J.* **415**, 580-588 (1993).

42. Leitherer, C., Robert, C., & Heckman, T. M., Atlas of synthetic ultraviolet-spectra of massive star populations, *Astrophys. J. Suppl.* **99**, 173-187 (1995).

43. Doty, J.P., The All Sky Monitor for the X-ray Timing Explorer, *Proc. S.P.I.E.* **982**, 164-172 (1988).

44. Narayan, R., Paczyński, B., & Piran, T. Gamma-ray bursts as the death throes of massive binary stars. *Astrophys. J.* **395**, L83-L86 (1992).

45. Wijers, R. A. M. J., Bloom, J., Bagla, J. S. & Natarajan, P. Gamma-ray bursts from stellar remnants: probing the universe at high redshift. *Mon. Not. Royal Astron. Soc.* **294**, L13-L17, (1998).

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Table 1. Summary of R and I band measurements

UT Date	Band	Magnitude	Notes & References
1997, December 15.47	I	21.27 ± 0.30	Ref. 25
1997, December 16.52	I	22.85 ± 0.33	9×120 s, 0.9", R. Goodrich.
1997, December 17.45	I	23.34 ± 0.31	9×120 s, 1.1", R. Goodrich, (b).
1997, December 17.60	I	23.55 ± 0.26	11×120 s, 0.8", R. Goodrich.
1997, December 17.63	I	23.57 ± 0.40	11×120 s, 0.63", R. Goodrich, (c).
1997, December 20.53	I	> 24	10×360 s, A. Filippenko, 1.4", (d).
1997, December 22.63	I	> 24.5	2×400 s, 0.9", M. Davis (e).
1997, December 15.50	R	21.7 ± 0.10	Ref. 29
1997, December 15.51	R	22.1 ± 0.10	Ref. 27
1997, December 16.46	R	23.3 ± 0.17	6×180 s, 0.86", R. Goodrich.
1997, December 16.63	R	23.7 ± 0.10	3×180 s, 0.56", R. Goodrich, (c).
1997, December 16.52	R	23.7 ± 0.30	Ref. 27
1997, December 17.51	R	24.4 ± 0.50	Ref. 28
1998, January 10.62	R	25.6 ± 0.17	12×300 s, 0.86", J. Aycock, (f).
1998, February 24.54	R	25.6 ± 0.15	10×300 s, 0.87", S. Kulkarni.
1998, February 24.58	B	> 26.8	6×300, 3×600, 1.00", S. Kulkarni, (g).

(a) The entries in the last column are: (for Keck observations) the number of frames obtained, the integration time, the seeing specified as full width at half maximum, the observer or the reference (for observations reported in literature). Additional notes are indicated by a letter. The log of the December 15 "guide" camera observations is not included here since we did not use that data in any quantitative analysis. (The OT was detected in that data, though.) Successive frames are displaced by 5-15 arcsec and the final image is obtained by registering the frames and then adding. All the imaging analysis was carried out with IRAF, a software package supplied by the National Optical Astronomy Observatories.

(b) Rhoads[26] reports I=22.9 ± 0.4 on 1997 Dec 17.37 UT. This is consistent, within errors, with our measurement of the same night. However, due to the large error bars, this is not included in our compilation (above).

(c) This observation was affected by light diffracted by the telescope structure contaminating the region in the vicinity of the OT (see Figure 1). The diffracted pattern was about 15 pixels wide and long. An image was formed by assigning each pixel a value equal to the median of a box 75×5 pixels, aligned along the diffraction spikes. All features smaller than this box disappear in the resultant image leaving only the diffracted rays. This median image was then subtracted from the original image leaving an image free from the diffracted pattern. Photometry of the OT, reported in this Table, was then performed on this subtracted image.

(d) The data was taken in the polarimetric mode of LRIS and hence the light is split into two orthogonal polarization components – we call this the top and bottom channels. The images from each of the channels were reduced separately, averaged together and the two resultant images were coadded to give the final image. The seeing as estimated by observations of the standard star SA 104 440 (ref. 31) was exceptionally bad, about 1.4 arcsecond. No object was found in the final image at the position of the OT. We do not have a good estimate of the true point spread function in the final image since the useful field is only 25 arcseconds across and there are no bright stars within this. Based on noise statistics within an aperture of radius 1.5 arcsecond we set a 3-σ detection limit of I=24 for this data. Analysis of artificial stars with FWHM of 1.4 arcsecond using the IRAF task DAOFIND led to a detection limit of 23 mag. However, visual inspection of the artificial stars knowing the position of the position of the object results in a more stringent limit, closer to the I=24 obtained above.

(e) 3σ upper limit estimated from the detection statistics of artificial stars which have the same point spread function as that of nearby stars and embedded in the general vicinity of the OT. This observation suffered from high sky brightness (19.1 mag/sq. arcsec) and also lack of numerous exposures.

(f) The first four exposures suffered from brighter sky since the moon was still up in the sky. The image shown in Figure 1 is the sum of the next eight exposures.

(g) 3σ upper limit. See note (e) for details of the procedure of deriving the upper limit.

Table 2. **Summary of Spectroscopic Observations (a)**

UT Date	Grating	Slit Width	Int. Time	Notes
1997 December 28	300 line/mm	1.5”	2×1800 s	T. Kundic
1998 February 3	300 line/mm	1.0”	5×1800 s	S. Kulkarni
1998 February 22	600 line/mm	1.0”	2×1800 s	S. Kulkarni
1998 February 23	600 line/mm	1.0”	6×1800 s	S. Kulkarni

(a) The entries (from left to right), the UT date of the observation, the grating used, the slit width in arcsecond, the number of exposures and the integration time per exposure, and the name of the principal observer. The 300 line/mm grating is blazed to 5000 Å and the blaze wavelength of the 600 line/mm is 7500 Å. The center wavelength of the 300 line/mm spectra (hereafter “lower” resolution data) is about 6400 Å and the dispersion is about 2.45 Å/pixel. The center wavelength of the 600 line/mm spectra, the “higher resolution” data, is 6100 Å and the dispersion is 1.25 Å/pixel. In both cases, the spectral resolution as parametrized by the full width at half maximum is ~ 5 pixels. The spectrum of the standard star HZ 44 (ref. 46) obtained on February 3 was used to flux calibrate the lower resolution spectra, and the spectrum of GD 153 (ref. 47), observed on February 22, was used to calibrate the higher resolution spectra. The zero-point uncertainty of the flux calibration is estimated to be about 10%, judging by the internal agreement, but the slit losses are likely to be higher. Wavelength calibration was derived from arc lamps spectra taken immediately after the observations of the target. The random errors in the wavelength calibration is 0.3 Å and the estimated systematic errors due to instrument flexure is of the same order. Both these uncertainties are unimportant for our redshift determination discussed in the text.

Figure 1a. I band image of the field of the optical transient (OT) of GRB 971214. The image is 3.5 arcmin by 3.0 arcmin and has been smoothed by a Gaussian of full-width at half maximum of 0.53 arcseconds. The numbered stars are "secondary" stars used for achieving consistency within our various data sets. Stars H1 and H2 allow us to link our photometry with that of Halpern et al.[25] and Henden et al.[29]. The "rays" are light from the bright star (6.7 mag.) SAO 15663 diffracted by the telescope structure; this bright star (6.7 mag.) is about one arcminute NE of the optical transient. The rays rotate as the telescope tracks the source.

Figure 1b. (*Left*) Image of the OT in I-band obtained from data taken on December 16, 1997 UT. The image is a square of size 1 arcminute. The image has been smoothed by a Gaussian with FWHM of 0.53 arcseconds. The OT is marked. (*Right*) Image of the field of OT in R-band obtained from data taken on January 10, 1998 UT. The image is a square of size 1 arcminute. The image has been smoothed by a Gaussian with FWHM of 0.53 arcseconds. An extended object is seen at the position of the OT. We suggest that this is the host galaxy of GRB 971214. For all three images North is to the top and East to the left. We have also obtained the spectrum of of the galaxy about 4.5 arcsecond to the NE of the OT. m the OT. The spectrum shows a prominent [O II] 3727 emission line and the usual absorption features at a redshift of 0.5023.

Figure 2. The R- and I-band light curve of the optical transient (OT) of GRB 971214. The OT is identified in Figure 1. The x-axis is $\log(t - t_0)$ where t is the UT date of the observation and t_0 is the UT date of the gamma-ray burst. All times are measured in units of days. The GRB took place on UT 1997 December 14.9727 (ref. 16). At I-band the OT is well detected for the first three nights. Upper limits exist for the night of UT 1997 December 20 and December 22. The dotted line is a linear least squares fit to the I-band data but restricted to these first three nights. The assumed model is $\mathrm{I}(t - t_0) = \mathrm{I}_1 + s\log(t - t_0)$; here I is the magnitude at time t and s is the slope and I_1 the offset. The fits yield $\mathrm{I}_1 = 22.22 \pm 0.18$ and $s = 3.09 \pm 0.52$. For reasons discussed in the text it is reasonable to assume that the R-band light curve has the same slope, s. The solid line is parallel to the dotted line but goes through our R magnitude of UT 1997 Dec. 16.63. This line does an adequate job of describing the R light curve for the first three nights. clearly, the Dec. 15.50 point of Henden et al.[29] is not well accounted by this model. The R-band measurements of 1998 January 10 and February 24 10 January lie well above the extrapolation of the dotted line. We attribute this excess over the decaying optical transient as arising from galaxy K shown in Figure 1. In both the January 10 and February 24 images, the full width at half maximum (FWHM) of K is 1.07 arcseconds which is larger than the same estimated from stars in the vicinity of K (Table 1). The rough size of K is thus about 0.65 arcseconds.

Figure 3. The composite Keck spectrum of the host galaxy of the GRB 971214. The top panel shows the original data, with the locations of the prominent night sky (n.s.) emission lines as indicated. The bottom panel shows the same spectrum smoothed with a Gaussian with $\sigma = 5$ Å, which is approximately equal to the effective instrumental resolution. Locations of several absorption features commonly seen in the spectra of $z \sim 3$ galaxies are indicated. The redshift, $z = 3.418$, has been derived from the mean point of the Lyα emission and absorption features, as described in the text. The log of the observations and the details of the spectrograph settings can be found in Table 2. The "lower" resolution data were reduced completely independently by two of the authors (SGD and KLA), using independent reduction packages. The results are in an excellent mutual agreement. The "higher" resolution data are also fully consistent with them, showing essentially the same spectroscopic features. The useful wavelength range spanned by the lower resolution data is approximately 4000 to 7600 Å, and of the higher resolution data approximately 4900 to 7300 Å. All of the spectra have been averaged with the proper signal-to-noise weighting, after the suitable resampling.