An unusual supernova in the error box of the γ-ray burst of 25 April 1998

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The discovery of afterglows associated with γ-ray bursts at X-ray[1], optical[2] and radio[3] wavelengths and the measurement of the redshifts of some of these events[4,5] has established that γ-ray bursts lie at extreme distances, making them the most powerful photon-emitters known in the Universe. Here we report the discovery of transient optical emission in the error box of the γ-ray burst GRB980425, the light curve of which was very different from that of previous optical afterglows associated with γ-ray bursts. The optical transient is located in a spiral arm of the galaxy ESO184-G82, which has a redshift velocity of only 2,550 km s^{-1} (ref. 6). Its optical spectrum and location indicate that it is a very luminous supernova[7], which has been identified as SN1998bw. If this supernova and GRB980425 are indeed associated, the energy radiated in γ-rays is at least four orders of magnitude less than in other γ-ray bursts, although its appearance was otherwise unremarkable: this indicates that very different mechanisms can give rise to γ-ray bursts. But independent of this association, the supernova is itself unusual, exhibiting an unusual light curve at radio wavelengths that requires that the gas emitting the radio photons be expanding relativistically[8,9].

GRB980425 was detected[10] on 1998 April 25.91 UT with one of the Wide Field Cameras (WFCs) and the Gamma Ray Burst Monitor on board BeppoSAX, and with the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory. The BATSE burst profile consisted of a single wide peak. The burst flux rose in ~5 s to a maximum flux of $(3.0 \pm 0.3) \times 10^{-7}$ erg cm^{-2} s^{-1} (24–1,820 keV), at which it remained for ~5 s; it decayed steadily to the background in ~25 s. The burst fluence E_b is $(4.4 \pm 0.4) \times 10^{-6}$ erg cm^{-2}; its duration[11] T_{90} is 23.3 ± 1.4 s. The burst spectrum is well described by a smoothly broken power law, with a constant break energy (148 ± 33 keV) and high-energy power-law photon index (-3.8 ± 0.7); the low-energy power-law photon index varied from -1.0 ± 0.15 during the rise, to -2.6 ± 0.2 during the decay of the burst. Thus, with respect to its γ-ray properties, GRB980425 was not a remarkable event. In the Beppo SAX WFC no. 2 the burst lasted ~30 s, and reached a peak intensity of ~3 Crab (2–28 keV)[10]. The position derived from the WFC image is right ascension (RA) 19 h 34 min 54 s, declination (dec.) −52° 49.9′ (J2000.0), with an error radius of 8′ which comprises a 3′ statistical error (99% confidence level) and a 5′ systematic uncertainty due to incomplete satellite attitude information.

We observed the error box of GRB980425 in R_{MACHO} and B_{MACHO} wavebands[12] with the 50-inch telescope at the Australian National University's (ANU) Mt Stromlo Observatory (MSO) starting April 26.60 UT, and in standard U, B, V, R and I bands with the 30-inch telescope at MSO, the 40-inch telescope at the ANU Siding Spring Observatory, the Anglo-Australian Telescope at the Anglo-Australian Observatory, the 3.5-m New Technology Telescope (NTT), and the 1.5-m Danish and the 0.9-m Dutch telescopes at the European Southern Observatory.

Inspection of NTT images obtained on April 28.4 and May 1.3 UT revealed a point source in the WFC error box, which was not visible in the Digitized Sky Survey. Tying 40-inch V- and R-band images to the Hipparcos Tycho coordinate system, we determined its position at RA 19 h 35 min 03.34 s (±0.02 s), dec. = −52° 50′ 44.8″ (±0.2″) (J2000.0), 1.6′ away from the centre of the WFC error box. The source is within the BATSE/Ulysses Interplanetory Network annulus and coincides with the transient radio source in the WFC error box[8] to within 0.3″. It is located in an H II region in a spiral arm of the face-on barred spiral galaxy ESO184-G82 at a redshift[6] of 2,550 km s^{-1}, in the DN1931-529 group of galaxies[13].

The UBVRI light curves of the transient are shown in Fig. 1. These light curves are very different from those of γ-ray burst (GRB) afterglows—which decay as a power law, $F(t) \propto t^{-\alpha}$, with α in the range[14] 1–2—but are quite similar to those of supernovae. This, and the similarity of its spectrum to that of some supernovae (for example SN1994I, Fig. 2) leads us to conclude that the transient is a very luminous supernova of type Ic.

Any estimate of the probability that the supernova and the GRB coincided by chance (with respect to both time and direction) suffers from the problem of *a posteriori* statistics; that is, that the parameters of the problem tend to be set by the observed phenomenon itself. In this case the parameters are the size of the error box, the peak magnitude of the supernova, and the time window within which the events can be considered as possibly related. In our computation we have made generous estimates of these parameters.

The WFC error boxes have 99% confidence level radii varying between 3′ and 8′ (ref. 15). We conservatively estimate the angular distance, beyond which a connection can be rejected, at 10′. We included all supernovae with peak B-band magnitudes $m_B < 16$; that is ~2 mag below that of SN1998bw. The time of occurrence of the core collapse and the GRB coincide to within (+0.7, −2.0) days (ref. 16). As a GRB which occurred a few days earlier or later would have been considered at least remarkable, we have taken a time window of 10 days.

With peak absolute magnitudes $M_B - 5\log h = -18.28$, -16.68 and -15.69 (where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}) for supernovae of types Ia, Ib/c and II, respectively[17], for $m_B < 16$ such supernovae are detectable out to redshifts of 7,180, 3,440 and 2,180 km s^{-1}, respectively. (We note that these limiting values are independent of the assumed value of the Hubble constant.) The Shapley–Ames 'fiducial' sample of 342 galaxies within the Virgo circle[17] has a mean B-band luminosity of $6.7h^{-2} \times 10^9 L_{\odot}(B)$, and a supernova rate of $3.09h^2[100\ \mathrm{yr}\ 10^{10} L_{\odot}(B)]^{-1}$. Using galaxy numbers and heliocentric radial velocities from ref. 18, assuming a mean luminosity, galaxy composition, and supernova rate as in the 'fiducial' sample, and taking relative supernova rates[19] for types II:Ib/c:Ia of 4.0:0.8:1.8, we

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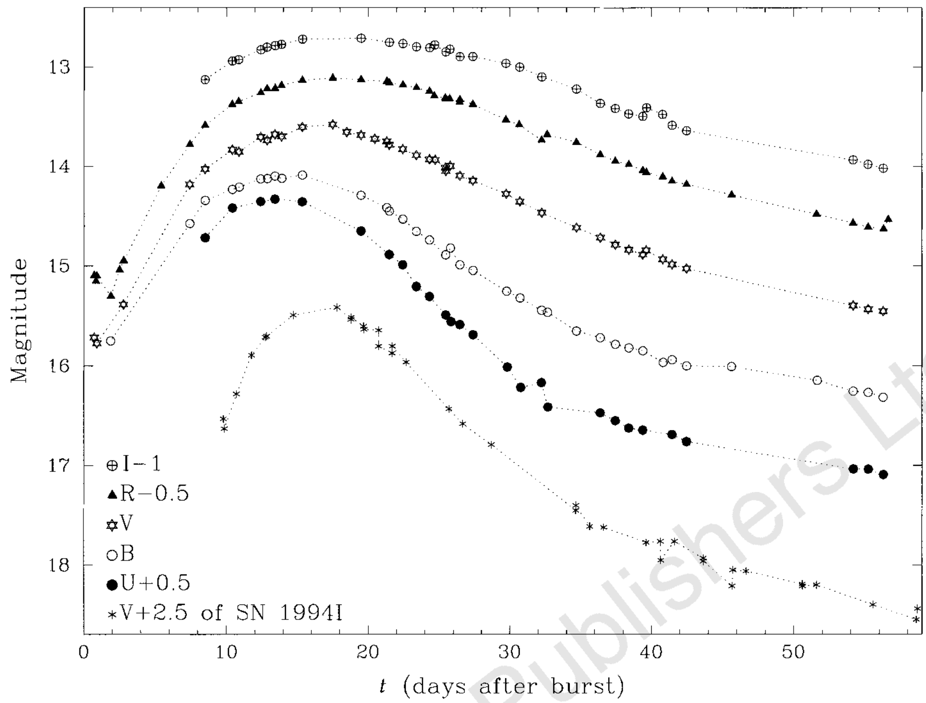

Figure 1 UBVRI light curves of SN1998bw, corrected for galactic foreground extinction, $A_V = 0.20$, as inferred from a combination of COBE/DIRBE and IRAS/ISSA maps[25]. Time is in days since April 25.91 UT (a full log of the observations and the photometry can be found at http://www.astro.uva.nl/titus). We determined a photometric (U, B, V, R and I) calibration for a number of reference stars using NTT (May 4.4 UT) and 1.5-m Danish telescope (May 8.3 UT) observations of the Landolt[26] fields Mark A and SA110 (stars 496–507) (magnitudes of the reference stars can be found at http://www.astro.uva.nl/titus). We corrected for atmospheric extinction and, for U and B, also for a first-order colour term. By comparison of these two calibration nights we estimate an error of the absolute calibration of 0.10 mag in U and 0.05 mag in B, V, R and I. The R_{MACHO} and B_{MACHO} observations have been transformed using ref. 12. We consider a conservative minimum error of 0.03 mag realistic for the differential U, B, V, R and I light curves to account for the effect of seeing on the contribution of the underlying galaxy (<0.01 mag for each band) and the different instruments used. The longer the wavelength is, the later the maximum light occurs (see Table 1). The R-band light curve shows an initial 'plateau', then it rises at a rate of 0.25 mag d^{-1} to maximum light on May 12. Lack of early data prevents us from establishing the existence of the plateau in the U, B, V and I light curves. Starting early June 1998 the light curves decay exponentially with ~0.025 mag d^{-1}. For comparison the V-band light curve of the type Ic SN1994I is shown[27]. As discussed in Ref. 16, the width of the light-curve peak depends on the total ejected mass and the explosion energy.

find a total rate of supernovae (with $m_B < 16$ at the peak) of 80 per year. This value includes a correction for absorption[17] within the host galaxy disk. This number should perhaps be increased by a modest factor to account for incompleteness of the radial-velocity distribution[18]; we have adopted a final supernova rate ($m_B < 16$) of 120 per year.

With the above parameters, we estimate the probability of catching a supernova in one of the 13 WFC GRB error boxes to be 9×10^{-5}. In our probability estimate we have included all supernovae with peak magnitudes two magnitudes below that of SN1998bw, and we have ignored the fact that SN1998bw is of a rare type. We therefore believe our estimate is conservative. As a result, the notion that GRB980425 and SN1998bw are physically related becomes difficult to reject purely on the basis of the fact that afterglows observed so far from GRBs are very different from supernovae.

The WFC error box contains two X-ray sources[20,21], neither of which coincides with SN1998bw. One, 1SAX J1935.0 − 5248 has a constant (2–10 keV) flux of $\sim 2 \times 10^{-13}$ erg cm^{-2} s^{-1}. The other, 1SAX J1935.3 − 5252, was detected at $(1.6 \pm 0.3) \times 10^{-13}$ erg cm^{-2} s^{-1} about 1 day after the burst, and decayed to $< 1.2 \times 10^{-13}$ erg cm^{-2} s^{-1} (3σ) in 22 hours; it was not detected 6 days after the burst ($< 1.0 \times 10^{-13}$ erg cm^{-2} s^{-1}). This variability is consistent with that of previously observed X-ray afterglows of GRBs, and this object might be a possible counterpart for GRB980425. Comparison of the 50-inch April 26.63 UT and April 28.68 UT images at the locations of the two X-ray sources shows no sources variable by more than 0.2 mag down to $R = 21$. However, several GRBs have not shown optical afterglows either, most notably GRB970111[22] and GRB970828[23].

The (2–10) keV detection limit (3σ) for the GRB980425 Narrow-Field Instrument observations was 1.2×10^{-13} erg s^{-1} cm^{-2}. Using the ASCA (2–10 keV) source count distributions[24] one expects to find an average of 0.6 X-ray sources above this limit in the WFC error box; the probability of finding two or more sources there by chance coincidence is 12%. The case for a relation between this X-ray source and GRB980425 must therefore be considered tentative at best, in particular because variability is not rare among weak ROSAT sources.

Modelling[16] of the optical light curve of SN1998bw shows that it can be produced with the core collapse of a massive progenitor star composed mainly of carbon and oxygen (a C + O star); the time of collapse coincides with that of the GRB to within (+0.7, −2.0) days. In the case of the C + O star core collapse, the kinetic energy was $\sim 10^{52.5}$ erg. To achieve the observed high luminosity, substantial

Table 1 Times of maximum, and apparent and absolute peak magnitudes of SN1998bw

	U	B	V	R	I
Date 1998 (UT)	May 9.4 ± 0.2	May 10.3 ± 0.2	May 12.2 ± 0.2	May 13.2 ± 0.2	May 13.8 ± 0.3
Apparent mag	13.81 ± 0.10	14.09 ± 0.05	13.62 ± 0.05	13.61 ± 0.05	13.70 ± 0.05
Absolute mag	− 19.16 ± 0.10	− 18.88 ± 0.05	− 19.35 ± 0.05	− 19.36 ± 0.05	− 19.27 ± 0.05

We used $H_0 = 65$ km s^{-1} Mpc^{-1}, a redshift $z = 2{,}550$ km s^{-1} and corrected for galactic foreground extinction, $A_V = 0.20$, as inferred from a combination of COBE/DIRBE and IRAS/ISSA maps[25].

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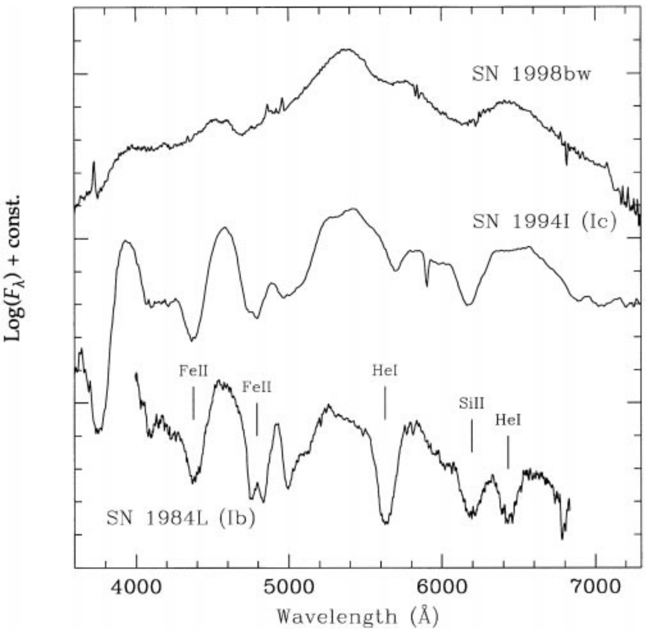

Figure 2 Representative spectra near maximum light of SN1998bw, SN1994I (type Ic; ESO supernova archive, courtesy of M. Turatto), and SN1984L (type Ib)[28]. Hydrogen lines, characteristic of type II supernovae, and Si II, characteristic of type Ia supernovae, are absent in the spectrum of SN1998bw. The strong He I 5876 line which characterizes type Ib supernovae is very weak in SN1994I and absent in SN 1998bw. The overall shape of the spectrum of SN1998bw is similar to that of a type Ic supernova, although the spectral features are less pronounced. The difference is strongest in the 3,500–5,000 Å region, where the Ca II and Fe II lines are much weaker than in SN1994I. In this respect, SN1998bw appears to represent an extreme case in the odd class of type Ic supernovae.

amounts of ^{56}Ni (~0.7 solar masses) have to be synthesized in the explosion[16]; the large energy and ^{56}Ni mass would be unprecedented for a core-collapse supernova.

If one accepts the possibility that GRB980425 and SN1998bw are associated, one must conclude that GRB980425 is a rare type of GRB, and SN1998bw is a rare type of supernova. The radio properties[8,9] of SN1998bw show the peculiar nature of this event independent of whether or not it is associated with GRB980425.

The consequence of an association is that the γ-ray peak luminosity of GRB980425 is $L_\gamma = (5.5 \pm 0.7) \times 10^{46}\,\mathrm{erg\,s^{-1}}$ (in the 24–1,820 keV band) and its total γ-ray energy budget is $(8.1 \times 1.0) \times 10^{47}$ erg. These values are much smaller than those of 'normal' GRBs which have peak luminosities of up to $10^{52}\,\mathrm{erg\,s^{-1}}$ and total energies[5] up to several times 10^{53} erg. This implies that very different mechanisms can produce GRBs which cannot be distinguished on the basis of their γ-ray properties, and that models explaining GRB980425/SN1998bw are unlikely to apply to 'normal' GRBs and vice versa. □

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A hypernova model for the supernova associated with the γ-ray burst of 25 April 1998

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The discovery of the unusual supernova SN1998bw, and its possible association with the γ-ray burst GRB 980425[1–3], provide new insights into the explosion mechanism of very massive stars and the origin of some classes of γ-ray bursts. Optical spectra indicate that SN1998bw is a type Ic supernova[3,4], but its peak luminosity is unusually high compared with typical type Ic supernovae[3]. Here we report our findings that the optical spectra

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