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UNDER EMBARGO AT NATURE (submitted June 10, 1998)

Discovery of the peculiar supernova 1998bw in the error box of GRB980425

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The discovery of X-ray¹, optical² and radio³ afterglows of γ -ray bursts (GRBs) and the measurements of the distances to some of them^{4,5} have established that these events come from Gpc distances and are the most powerful photon emitters known in the Universe, with peak luminosities up to 10^{52} erg s⁻¹. We here report the discovery of an optical transient, in the BeppoSAX Wide Field Camera error box of GRB 980425, which occurred within about a day of the γ -ray burst. Its optical light curve, spectrum and location in a spiral arm of the galaxy ESO 184-G82, at a redshift $z = 0.0085$ ⁶, show that the transient is a very luminous type Ic supernova, SN 1998bw. The peculiar nature of SN 1998bw is emphasized by its extraordinary radio properties which require that the radio emitter expand at relativistical speed^{7,8}. Since SN 1998bw is very different from all previously observed afterglows of GRBs, our discovery raises the possibility that very different mechanisms may give rise to GRBs, which differ little in their γ -ray properties.

GRB 980425 was detected^{9,10} on April 25.90915 UT with one of the Wide Field Cameras (WFCs) and the Gamma Ray Burst Monitor (GRBM) on board BeppoSAX, and with the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory (CGRO).

The BATSE burst profile consists 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 (24–1820 keV), at which it remained for ~ 5 s; it decayed steadily to the background in ~ 25 s. The burst fluence $E_b = (4.4 \pm 0.4) \times 10^{-6}$ erg cm⁻²; its duration¹¹ $T_{90} = 23.3 \pm 1.4$ s. No burst emission is detected above 300 keV; GRB 980425 is therefore a so-called NHE burst¹², a group comprising about a quarter of the GRBs detected with BATSE. 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 (i.e., the burst spectrum became softer). These results show that with respect to duration, γ -ray spectrum, peak flux and fluence, GRB 980425 was not a remarkable event.

In the BeppoSAX WFC no. 2 the burst lasted ~ 30 a, and reached a peak intensity of about 3 Crab (2-28 keV)⁹. The position derived from the WFC image is RA= $19^{\text{h}}34^{\text{m}}54^{\text{s}}$, Decl = $-52^{\circ}49'9$ (equinox 2000.0), 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^{13,14}.

We observed the error box of GRB 980425 in¹⁵ R_{Macho} and B_{Macho} with the 30 and 50 inch telescopes 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) with the 40 inch telescope at the ANU Siding Spring Observatory (SSO), the 3.5m New Technology Telescope (NTT), and the 1.5m Danish and the 0.9m Dutch telescopes at the European Southern Observatory (ESO).

Inspection of NTT images obtained on Apr. 28.4 and May 1.3 UT revealed a point source in the WFC error box, which was not visible in the Digitized Sky Survey¹⁶ (see Fig. 1). Using the US Naval Observatory catalog and the NTT May 1.3 UT R band image we determine its position at R.A. = $19^{\text{h}}35^{\text{m}}03.14^{\text{s}} \pm 0.12^{\text{s}}$, Decl. = $-52^{\circ}50'45.3'' \pm 1.0''$ (equinox 2000.0), $1'.6$ away from the center of the WFC error box. The source coincides with the transient radio source in the WFC error box⁷ to within $1''.8$ (i.e., 1.2σ), and it is located in a spiral arm of the face-on barred spiral galaxy ESO 184-G82 at a redshift of $z = 0.0085^6$, in the DN 1931–529 group of galaxies¹⁷.

The UBVRI light curves of SN 1998bw are shown in Fig. 2. The R band light curve shows an initial 'plateau', then it rises at a rate of ~ 0.25 mag day⁻¹ to maximum light, after which it declines by ~ 0.05 mag day⁻¹. The plateau may be the late signature of a sharp initial peak in the

light curve, signalling the shock break out at the surface of the progenitor star¹⁸. Lack of early data prevents us from establishing its existence in the U, B, V and I light curves.

Times of maximum, and peak magnitudes in the five bands are listed in Table 1, together with the peak absolute magnitudes (we used $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, a redshift $z = 0.0085$, and corrected for galactic foreground extinction, $A_V = 0.20$, as inferred from a combination of COBE/DIRBE and IRAS/ISSA maps¹⁹). The longer the wavelength is, the later maximum light occurs.

H and He lines are absent in the early spectra of SN 1998bw, which exclude SN types II and Ib, respectively. Type Ia supernovae are normally identified by a Si II line, which is not detected in the spectrum of SN 1998bw. This has led to the classification of this event as a type Ic supernova^{16,20}. The light curve of SN 1998bw is inconsistent with a type Ia, although the luminosity of SN 1998bw rivals that of typical type Ia supernovae. To achieve such luminosities substantial amounts of ^{56}Ni ($\sim 0.7 M_\odot$) have to be synthesized in the explosion²¹, which would be unprecedented for a core-collapse supernova. (Typical values for the amount of ^{56}Ni are $< 0.1 M_\odot$; the most luminous SN II event so far has been SN 1992am with a ^{56}Ni mass of $0.3 M_\odot$ ²²).

Modelling²¹ of the optical light curve of SN 1998bw shows that it can be reproduced with the core collapse of a massive CO progenitor star; the time of collapse coincides with that of the GRB to within about a day. In the case of the CO star core collapse the kinetic energy was $\sim 10^{52.5}$ ergs; the total energy (including neutrinos) likely exceeded 10^{54} ergs.

Any estimate of the probability that the supernova and the GRB coincided by chance (both with respect to time and direction) suffers from the problem of *a posteriori* statistics, i.e., 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 estimate we have made generous estimates of these parameters.

The WFC error boxes have 99% confidence level radii varying between 3' and 8' (Ref. 13). We conservatively estimate the angular distance beyond which a connection can be rejected, at 10'. We included all supernovae with peak magnitudes $m_B < 16$, i.e., ~ 2 mag below that of SN1998bw. The time of occurrence of the GRB and the onset of the supernova coincide to within about a day (see above). Since a GRB which would have 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 $M_B = -18.28, -16.68, \text{ and } -15.69$ for supernovae of types Ia, Ib/c and II, respectively²³, for $m_B < 16$ they are detectable out to redshifts of 7180, 3440 and 2180 km/s, respectively (note that the limiting values of z are independent of the assumed value of the Hubble constant). The Shapley-Ames ‘fiducial’ sample of 342 galaxies within the Virgo circle²³ has a mean B-band luminosity of $6.7 \times 10^9 L_\odot(B)$, and a supernova rate of $3.09 [100 \text{ yr } 10^{10} L_\odot(B)]^{-1}$. Using galaxy numbers and heliocentric radial velocities from Ref. 24, assuming a mean luminosity, galaxy composition, and SN rate as in the ‘fiducial’ sample, and taking relative supernova rates²⁵ for types II: Ib/c : Ia = 4: 2: 1, we find a total rate of supernovae (with $m_B < 16$ at the peak) of 120 per year. This value includes a correction for absorption within the host galaxy disk. This number should perhaps be increased by a modest factor to account for incompleteness of the radial velocity distribution²⁴; we have adopted a final SN rate ($m_B < 16$) of 150 per year.

With the above parameters we estimate the probability of catching a SN in one of the 13 WFC GRB error boxes to be 1.1×10^{-4} . In our probability estimate we have included all supernovae with peak magnitudes two magnitudes below that of SN 1998bw, and we have ignored the fact that

SN 1998bw is of a rare type. We therefore believe our estimate is conservative. As a result, the notion that GRB 980425 and SN 1998bw are physically related becomes difficult to reject purely on the basis of the fact that afterglows observed so far from GRB are very different from supernovae.

Follow-up X-ray observations with the BeppoSAX narrow-field instruments, showed that the WFC error box contains two X-ray sources^{26,27}, neither of which coincides with SN 1998bw. 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 similar to that of previously observed X-ray afterglows of GRBs, and this object might be a possible counterpart for GRB 980425. Comparison of the Mt. Stromlo April 26.63 UT and Apr 28.68 UT R_{Macho} band images at the locations of the two X-ray sources shows no variation > 0.2 mag down to 21 mag^{28,29}. However, in several cases optical afterglows were not detected, most notably GRB 970111³⁰ and GRB 970828³¹.

The (2–10) keV detection limit (3σ) for the GRB 980425 NFI observations was 1.2×10^{-13} erg s⁻¹ cm⁻². Using the ASCA (2–10 keV) source count distributions³³ 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 GRB 980425 must therefore be considered tentative at best, in particular since among weak ROSAT sources variability is not rare³².

If one accepts the possibility that GRB 980425 and SN 1998bw are associated, one must conclude that GRB 980425 is a rare type of GRB, and SN 1998bw is a rare type of supernova. The optical and radio properties of SN 1998bw show the rare nature of this event independent of whether

or not it is associated with GRB 980425.

The consequence of an association is that the γ -ray peak luminosity of GRB 980425 is $L_\gamma = 5.5 \pm 0.7 \times 10^{46}$ erg s⁻¹ (24–1820 keV) and its total γ -ray energy budget of $8.5 \pm 1.0 \times 10^{47}$ erg. These values are much smaller than those of ‘normal’ GRBs which have peak luminosities of up to 10^{52} erg s⁻¹ and a total energy budget of several times 10^{53} erg⁵. This implies that very different mechanisms can produce GRBs which cannot be distinguished on the basis of their γ -ray properties.

The radio and optical properties of SN 1998bw imply the simultaneous presence of a photosphere moving out at several 10^4 km/s, and a relativistic outflow (this accounts for the super-Compton brightness temperature of the radio source⁸, and is required for the γ -ray burst emission). The relativistic flow could perhaps develop in the medium around the supernova after shock breakout. Alternatively, it may require anisotropy of the SN explosion, possibly related to rapid rotation. The latter picture is reminiscent of the ‘hypernova’ model, i.e., a very massive core collapse to a black hole, temporarily encircled by a disk, proposed by Paczyński³⁴ as a mechanism for GRBs. If SN 1998bw is caused by such a ‘hypernova’, this model is unlikely to apply to the ‘normal’ GRBs, which are $\sim 10^5$ times more energetic in γ rays than GRB 980425.

This work is based partly upon images obtained by the MACHO Project with the 50in telescope and the RAPT Group with the 30in telescope at the Australian National University’s Mt. Stromlo Observatory, and by Dr. H. Jerjen with the 40in telescope at the Australian National University’s Siding Spring Observatory. RMK and KH acknowledge support from NASA grant NAG5-6747.

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Table 1: Times of maximum, and apparent and absolute peak magnitudes of SN 1998bw.

	U	B	V	R	I
Date 1998 (UT)	May 9.6	May 10.2	May 12.2	May 13.4	May 13.8
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

Fig. 1.— Left panel: NTT R band image May 1.3 UT. Right panel: DSS image

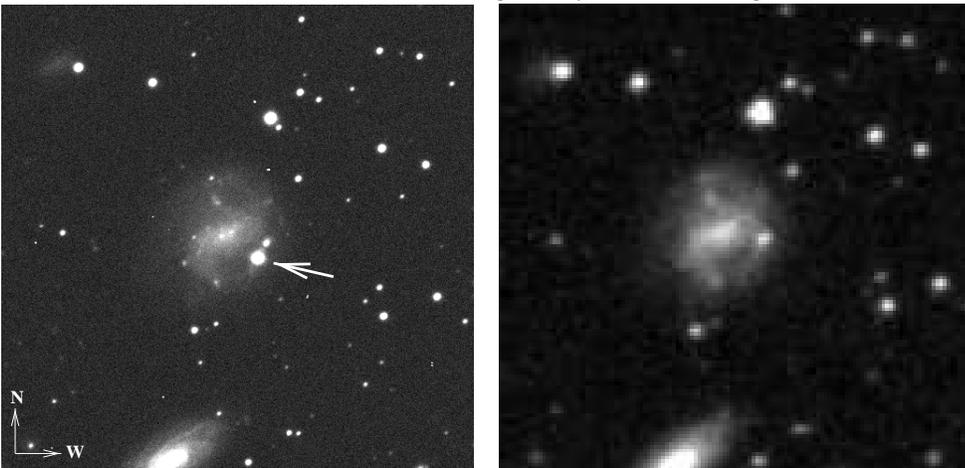


Fig. 2.— UBVRI light curves of SN 1998bw. Time is in days since April 25.90915 UT. We determined a photometric (U, B, V, R and I) calibration for a number of reference stars using NTT (May 4.4 UT) and 1.5D (May 8.3 UT) observations of the Landolt³⁵ fields Mark A and SA110 (stars 496-507). We corrected 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 for B, V, R and I. The R_M and B_M observations have been transformed using Ref. 15. 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.

SN 1998 bw light curves

