XMM-NEWTON OBSERVATIONS OF THE FIELD OF GAMMA-RAY BURST 980425

E. Pian¹, P. Giommi², L. Amati³, E. Costa⁴, J. Danziger¹, M. Feroci⁴, M.T. Fiocchi², F. Frontera⁵, C. Kouveliotou⁶, N. Masetti³, L. Nicasio⁷, E. Palazzi³, L. Piro⁴, M. Tavani⁴, and J.J.M. in ’t Zand⁸

¹INAF, Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, I-34131 Trieste, Italy
²ASI Science Data Center, c/o ESRCIN, Via G. Galilei, I-00044 Frascati, Italy
³IASF-CNR, Sezione di Bologna, Via P. Gobetti 101, I-40129 Bologna, Italy
⁴IASF-CNR, Sezione di Roma, via Fosso Del Cavaliere 100, I-00133 Roma, Italy
⁵Physics Department, University of Ferrara, Via Paradiso 11, I-44100 Ferrara, Italy
⁶NASA MSFC, SD-50, Huntsville, AL 35812, USA
⁷IASF-CNR, Sezione di Palermo, via U. La Malfa 153, I-90146 Palermo, Italy
⁸Space Research Organization Netherlands, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

ABSTRACT

The error box of GRB980425 has been observed by XMM-Newton in March 2002, with the aim of measuring the late epoch X-ray emission of the supernova 1998bw and of clarifying its supposed association with the GRB itself. We present here the preliminary results obtained with the EPIC PN camera. Our observations confirm the association between SN 1998bw and GRB980425. The EPIC PN measurement of the SN 1998bw flux is significantly below the extrapolation of the power-law temporal trend fitted to the BeppoSAX points and implies a faster temporal decay. We propose different physical interpretations of the SN X-ray light curve, according to whether it is produced by one or more radiation components.

INTRODUCTION

The hypothesis that supernovae are the progenitors of Gamma-Ray Bursts (GRB) dates back to the epoch of first GRB discovery (Colgate 1974) and has received support in recent years from the detection of supernova features in the optical afterglows of GRBs. These are re-brightenings at rest-frame intervals of 10-15 days after the GRB (e.g., Galama et al. 2000; Bloom et al. 2002; Price et al. 2003; Masetti et al. 2003); circumburst media with wind characteristics (Berger et al. 2001; Jannsen et al. 2001; Price et al. 2002); iron emission lines (Piro et al. 1999; Reeves et al. 2002; Butler et al. 2003); association of GRBs with star-forming regions (Fruchter et al. 1999; Frail et al. 2002). The most tempting hint of association between GRBs and SNe is obviously the similarity of the intrinsic energy of these phenomena, when collimation and beaming are taken into account in GRBs (e.g., Frail et al. 2001).

While these circumstances represent only possible evidences of a GRB-SN connection, on two occasions a clear association has been found. GRB980425 and SN 1998bw have been detected within very tight temporal and angular limits: they exploded simultaneously (with an uncertainty of ±1 day) and with a maximum separation in the sky of 8′ (Galama et al. 1998). More recently, prominent spectral features similar to those detected for SN 1998bw have been detected in the afterglow of GRB030329 (Stanek et al. 2003; Hjorth et al. 2003). To date, no other such compelling case of GRB-SN association has been detected, and SN 1998bw, whose brightness and kinematic conditions were exceptional, is considered a typical “hypernova”, the powerful SN explosion speculated to be at the origin of GRBs (Woosley 1993; Paczyński 1998; Zhang et al. 2003, and references therein).
Fig. 1. XMM-Newton image of the field of SN 1998bw taken with the EPIC PN chip on 28 March 2002. The size of the image is $30' \times 30'$; North is at the top and East to the left. Overlaid are isophotes of the BeppoSAX MECS image taken in 26-27 April 1998. The brightest source near the center of the image corresponds to SN 1998bw. About 4 arcmin SE of it, one can distinguish a number of very faint sources, the sum of which may have been detected by BeppoSAX as a single source S2 at the limit of MECS detectability.

The field of SN 1998bw and GRB980425 was observed with the BeppoSAX Narrow Field Instruments one day, one week and 6 months after the event (Pian et al. 2000). The most sensitive of these instruments, the BeppoSAX MECS, had detected two X-ray sources within the BeppoSAX Wide Field Cameras $8'$-radius error box of GRB980425. The brighter one (hereafter S1) was variable and positionally consistent with the SN 1998bw and had been identified with X-ray emission from the SN. The fainter source (hereafter S2) is $\sim 4'$ away from SN 1998bw, and therefore inconsistent with it, within the $1.5'$ positional uncertainty of the MECS detectors (see Fig. 1 in Galama et al. 1999). No firm statement could be made about the variability of S2, given its low flux level, at the limit of the MECS sensitivity.

Since the X-ray light curve of S2 may have been marginally compatible with an afterglow behavior, given the big uncertainties (see Pian et al. 2000), some reservations had remained as to whether GRB980425 and SN 1998bw were physically associated. However, the above mentioned case of GRB030329 and SN 2003dh argues strongly in favor of the GRB980425/SN 1998bw association and considerably weakens the case for association between S2 and GRB980425.

The peculiarity of SN 1998bw made it imperative to further investigate its X-ray emission at late epochs. Therefore, we have re-observed its field with Chandra and XMM-Newton in late 2001 and March 2002, respectively, and report here the preliminary results of the latter campaign. A detailed presentation of both campaigns will be given in future papers.
Fig. 2. X-ray light curve of SN 1998bw constructed from BeppoSAX MECS (first 4 filled circles, from Pian et al. 2000) and XMM-Newton EPIC PN (last filled circle) observations. The temporal origin coincides with the trigger time of GRB980425, 1998 April 25.9091 UT. For comparison, the X-ray light curve of SN 1980K is also shown (open circles, from Canizares et al. 1982; Schlegel 1994. The original data points have been converted to the 2-10 keV range, using a power-law spectrum $\propto \nu^{-\alpha}$ with index $\alpha \approx 1$).

OBSERVATIONS AND DATA ANALYSIS

The field of SN 1998bw was observed by XMM-Newton on 28 March 2002, between 13:53:34 and 20:10:38 UT, with the European Photon Imaging Cameras (EPIC, 0.15-15 keV) PN (Strüder et al. 2001) and MOS (Turner et al. 2001), operating in full-frame mode and with the medium filter applied. The data have been cleaned and processed using the Science Analysis Software (SAS 5.3) and analyzed using standard software packages (FTOOLS 5.2). The latest calibration files released by the EPIC team have been used (update: 29 Jan 2003). Event files produced from the pipeline have been filtered from high-background time intervals and only events corresponding to pattern 0-12 for MOS and pattern 0-4 for PN have been used (see the XMM-Newton Users' Handbook, Ehle et al. 2001; see also http://xmm.vilspa.esa.es/external). The net exposure times, after data cleaning, are $\sim 13.0$ ks, $\sim 16.8$ ks, and $\sim 16.7$ ks for PN, MOS1, and MOS2, respectively. Count rates (see next Section) have been estimated by integrating the signal within circles of 30" radius, which enclose $\sim 80\%$ of the encircled energy function, and by subtracting the background signal estimated from blank sky exposures, in circles of equal area.

RESULTS AND DISCUSSION

In Fig. 1 we show the EPIC PN image. At a position consistent with that of source S1 in the BeppoSAX MECS image, we detect in the EPIC PN image a source with a count rate of $(9.6 \pm 1.4) \times 10^{-3}$ counts s$^{-1}$
in the 0.5-5 keV range within a circular area of 30" radius. Assuming a spectrum similar to that measured by BeppoSAX for S1 (see Pian et al. 2000) and accounting for Galactic absorption by neutral hydrogen (\(N_{HI} = 3.95 \times 10^{20} \text{ cm}^{-2}\), Dickey & Lockman 1990), we derive a flux of \((3.18 \pm 0.46) \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}\) between 2 and 10 keV. The signal-to-noise ratio of our XMM-\textit{Newton} observations is not sufficient to perform a detailed spectral analysis.

A number of very faint sources are visible at the location of source S2 detected by the BeppoSAX MECS in the WFC error box of GRB980425 (Fig. 1). The integral of the EPIC PN signal within the 1.5 radius MECS error circle of S2 is consistent with the average flux measured by the MECS for S2, suggesting that it may be not a single source, but rather the sum of several faint sources and that its marginal variability in the BeppoSAX observations is determined by background fluctuations, or possibly by the random variations of those sources. This definitely rules out the afterglow nature of S2.

From the EPIC imaging we do not detect significant contamination of the X-ray emission of SN 1998bw by its host galaxy, therefore the SN decay measured by BeppoSAX must be authentic. That was satisfactorily fitted both by a power-law \(t^{-0.2}\) and by an exponential with \(e\)-folding time of \(\sim 500\) days (Pian et al. 2000). The addition of the EPIC point to the X-ray light curve of SN 1998bw (Fig. 2) shows that neither a power-law nor an exponential law are particularly satisfactory, although the exponential may be somewhat better. For this reason we favor an interpretation of the X-ray light curve as a result of the superposition of different radiation components. In fact, while the overall temporal behavior of SN 1998bw is unlike that of the very few X-ray SNe monitored at both early and late times (e.g., SN 1987A, Park et al. 2002; SN 1993J, Kohmura et al. 1994; Swartz et al. 2003; Zimmermann & Aschenbach 2003; SN 1994I, Immler et al. 1998; Immler et al. 2002), at late epochs (i.e., after day \(\sim 100\)) it is reminiscent of that of previous X-ray SNe (e.g., SN 1980K, Canizares et al. 1982; Schlegel 1994; Schlegel 1995; SN 1994I, Immler et al. 2002). Thus, one may interpret the early X-rays of SN 1998bw as afterglow radiation, while the late epoch X-ray emission is dominated by the interaction of the SN shock with the circumstellar material, as proposed for other X-ray SNe (Kohmura et al. 1994; Schlegel 1995; Suzuki and Nomoto 1995; Fransson et al. 1996; Chevalier and Fransson 2002; Immler and Lewin 2002). In fact, if the main sequence progenitor of SN 1998bw was a star of \(\sim 40M_\odot\) as postulated by Iwamoto et al. (1998) one would expect circumstellar material in the neighbourhood of the SN as a result of an earlier mass loss wind.

On the other hand, assuming that a single mechanism is responsible for X-ray emission of SN 1998bw, we may not exclude that the observed X-rays are cooling radiation from the compact remnant, provided the GRB has swept up all the surrounding material by creating an evacuated cone. Tavani (1997) has shown, in the context of X-ray afterglows of GRBs, that cooling neutron stars with “external” disturbances (e.g., a fallback) may radiate in X-rays with a temporal rate faster than a power-law. A longer diffusion time than considered by Tavani (1997) should be adopted in our case. The predicted decay rates for neutron stars with simple cooling (i.e., no fallback) are much longer than the fading time scale measured by BeppoSAX and XMM-\textit{Newton} for SN 1998bw (Page 1998). However, exotic cooling mechanisms can significantly increase the cooling rate (Slane et al. 2002). Our observations may thus allow us to place constraints on non-standard neutron star cooling scenarios and may have important implications for determining the nature of GRB remnants.

ACKNOWLEDGEMENTS

We are grateful to Matteo Guainazzi and Matthias Ehle for their assistance with observations scheduling, and to Paolo Mazzali for his valuable comments.

REFERENCES

Berger, E., A. Diercks, D. A. Frail, et al., \textit{ApJ}, \textbf{556}, 556, 2001.
Bloom, J. S., S. R. Kulkarni, S. R.; Price, P. A., et al., \textit{ApJ}, \textbf{572}, L45, 2002.
Butler, N. R., H. L. Marshall, G. R. Ricker, et al., \textit{ApJ}, submitted (astro-ph/0303539), 2003.
Canizares, C. R., G. A. Kriss, and E. D. Feigelson, \textit{ApJ}, \textbf{253}, L17, 1982.
Chevalier, R. A., and C. Fransson, in \textit{Supernovae and Gamma-Ray Bursts}, ed. K. W. Weiler, in press, Springer (astro-ph/0110060), 2002.
Colgate, S. A., \textit{ApJ}, \textbf{187}, 333, 1974.
Dickey, J. M., and F. J. Lockman, \textit{ARA&A}, \textbf{28}, 215, 1990.
Frail, D. A., S. R. Kulkarni, R. Sari, et al., ApJ, 562, L55, 2001.
Frail, D. A., F. Bertoldi, G. H. Moriarty-Schieven, et al., ApJ, 565, 829, 2002.
Fransson, C., P. Lundqvist, and R. A. Chevalier, ApJ, 461, 993, 1996.
Fruchter, A. S., S. E. Thorsett, M. R. Metzger, et al., ApJ, 519, L13, 1999.
Galama, T. J., P. M. Vreeswijk, J. van Paradijs, et al., Nature, 395, 670, 1998.
Galama, T. J., P. M. Vreeswijk, J. van Paradijs, et al., A&AS, 138, 465, 1999.
Galama, T. J., N. Tanvir, P. M. Vreeswijk, et al., ApJ, 536, 185, 2000.
Hjorth, J., J. Sollermann, P. M/oller, et al., Nature, submitted, 2003.
Immler, S., W. Pietsch, and B. Aschenbach, A&A, 336, L1, 1998.
Immler, S., A. S. Wilson, and Y. Terashima, ApJ, 573, L27, 2002.
Immler, S., and Lewin, W. H. G., in Supernovae and Gamma-Ray Bursts, ed. K. W. Weiler, in press, Springer (astro-ph/0202231), 2002.
Iwamoto, K., P. A. Mazzali, K. Nomoto, et al., Nature, 395, 672, 1998.
Jaunsen, A. O., J. Hjorth, G., Björnsson, et al., ApJ, 546, 127, 2001.
Kohmura, Y., H. Inoue, T. Aoki, et al., PASJ, 46, L157, 1994.
Masetti, N., E. Palazzi, E. Pian, et al. A&A, in press (astro-ph/0302350), 2003.
Paczynski, B., ApJ, 494, L45, 1997.
Page, D., in The Many Faces of Neutron Stars, ed. R. Buccheri, J. van Paradijs, M. A. Alpar, pp. 539-551, Kluwer Academic Publishers, Dordrecht, 1998.
Park, S., D. N. Burrows, G. P. Garmire, et al., ApJ, 567, 314, 2002.
Piro, L., E. Costa, M. Feroci, et al., ApJ, 514, L73, 1999.
Price, P. A., E. Berger, D. Reichart, et al., ApJ, 572, L51, 2002.
Price, P. A., S. R. Kulkarni, E. Berger, et al., ApJ, in press (astro-ph/0208005), 2003.
Reeves, J. N., D. Watson, J. P. Osborne, et al., Nature, 416, 512, 2002.
Schlegel, E. M., AJ, 108, 1893, 1994.
Schlegel, E. M., Rep. Prog. Phys., 58, 1375, 1995.
Slane, P. O., D. J. Helfand, and S. S. Murray, ApJ, 571, L45, 2002.
Stanek, K. Z., T. Matheson, P. M. Garnavich, et al., ApJL, in press (astro-ph/0304173), 2003.
Strüder, L., U. Briel, K. Dennerl, et al., A&A, 365, L18, 2001.
Suzuki, T., and K. Nomoto, ApJ, 455, 658, 1995.
Swartz, D. A., K. K. Ghosh, M. L. McCollough, et al., ApJS, 144, 213, 2003.
Tavani, M., ApJ, 483, L87, 1997.
Turner, M. J. L., A. Abbey, M. Arnaud, et al., A&A, 365, L27, 2001.
Woosley, S. E., ApJ, 405, 273, 1993.
Zhang, W., S. E. Woosley, and A. MacFadyen, ApJ, 586, 356, 2003.
Zimmermann, H.-U., and B. Aschenbach, A&A, in press (astro-ph/0304322), 2003.