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Letter to the Editor

HST Data suggest proper motion for the optical counterpart of GRB 970228*

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Abstract. After a quarter of a century of γ-ray burst (GRB) astronomy, the Italian-Dutch satellite BeppoSAX on Feb 28^{th}, 1997 detected a soft X-ray afterglow from GRB 970228 and positioned it accurately. This made possible the successful detection of an optical transient.
Two public Hubble Space Telescope (HST) images of the GRB/optical transient region were taken on March 26^{th} and April 7^{th}, 1997. They are analyzed here, with the purpose of understanding the nature of GRB 970228. We find that the position of the faint point-like object ($m_v \sim 26$) seen at the transient location changed by 0.40 ± 0.10 pixels in 12 days, corresponding to a proper motion of $\sim$ 550 mas/year. By comparison, four adjacent sources in the same field do not show any significant displacement, with astrometric residuals close to zero and average absolute displacements less than 0.09 pixels. If confirmed, this result would strongly support the galactic nature of GRB 970228.

Key words: Gamma Ray Burst, optical, GRB970228

1. Introduction

GRB 970228 stands out in the history of γ ray bursts (GRBs). For the first time, an X-ray afterglow from a GRB was detected and positioned accurately thanks to the Italian-Dutch satellite BeppoSAX (Costa et al, 1997a,b,c).

This triggered a number of optical searches in the error box. In particular, an m_V = 21.3 object found inside the error box $\sim$ 20 hours after the event (van Paradijs et al, 1997; Guarnieri et al, 1997) could not be detected ($m_V \geq$ 23.6) $\sim$ 8 days later. van Paradijs et al. (1997) proposed the optical transient to be the counterpart of GRB 970228. Subsequent deeper images showed a faint extended object ($m_R \sim$ 24) at the transient's location (Groot et al, 1997; Metzger et al, 1997a). If this is interpreted as a galaxy (van Paradijs et al, 1997), the "cosmological distance scale" for GRBs would be strongly favored. However, deep HST images of the field (Sahu et al, 1997a,c), taken on March 26^{th} with the WFPC2, fail to clearly show the existence of a galaxy. At best, an extended emission surrounding an off-centered point-like source is visible in the V-band image, while the I-band image is inconclusive, also owing to significantly lower signal-to-noise. Indeed, it would now appear that, according to ground-based measurements taken on April 2^{nd}, the nebulosity has faded away (Metzger et al, 1997b). This might be taken for evidence of time variability of the extended emission, which would then not be cosmological at all. Rather, it would be galactic, and the extended optical emission might be tracing the remnant of the burst event. The WFPC2 point-like source would also be nearby. It could, for example, be a local neutron star, moving at typical pulsar speeds (Lyne & Lorimer, 1994), or a stellar object of different nature. A proper motion search is then justified since, as shown by Caraveo et al (1996) in the case of the parallactic displacement of the Geminga neutron star (d $\sim$ 160 pc and m_V = 25.5), the HST Planetary Camera can measure relative displacements to better than one tenth of a pixel even for faint objects.

2. Data reduction

A second set of HST images was taken on April 7^{th}, 1997 between 3:42-7:45 UT, and made public after few hours (Sahu et al, 1997b). To achieve the highest angular resolution, the Planetary Camera (Field of View 35" x 35", pixel size 0.0455 arcsec) was centered on the coordinates of the optical transient.

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* Based on observations with the NASA/ESA Hubble Space Telescope

Fig. 1. HST/WFPC2 4700 sec exposure of the field of GRB 970228 using filter F606W taken on March 26^{th}, 1997. Numbers 1 to 4 identify the field stars used for relative astrometry. The faint point source at the center of the field, labelled as GRB, is the proposed counterpart of GRB 970228.

The observing strategy was identical to that used for the March observation, i.e. four F606W (an extended V filter centered at λ = 5843Å with $\Delta\lambda$ = 1578Å) images for a total exposure time of $\sim$ 4700 s, and two F814W (roughly equivalent to I, centered at λ = 8269Å with $\Delta\lambda$ = 1758Å) images for a total time of $\sim$ 2400 s. First, the March and April data sets have been cleaned for cosmic ray hits, using the IRAF/STSDAS task *combine*. Next, to overcome the limitation on star centering accuracy induced by the PC undersampling of the Point Spread Funtion, a 3x3 box smoothing is applied. Although based on a simple algorithm, this procedure is very effective in restoring the astrometric potential of the PC data (see Caraveo et al, 1996). Figure 1 shows the March 26 V-band field image. The point-like source seen on March 26^{th} is well detected on April 7^{th}. Our measured V-band magnitude is 26.1 ± 0.2 (26.0 ± 0.3, according to Sahu et al, 1997b), as opposed to the value of 25.7 ± 0.3 measured on March 26^{th} (Sahu et al, 1997a). The conservative errors leave room for significant fading. However, more data are required to define a clear trend. The shape of the diffuse emission is difficult to assess, due to higher background in the new observations as compared to the previous ones. In the following, we concentrate on the V-band images (which show the best signal to noise) to obtain a very accurate relative astrometry of all point-like objects present in both observations. The centroid of each star was computed in the MIDAS environment. A Gaussian function was used to fit the source data, yielding the best positions and associated errors. Particular care was used in the computation of the centroid of the presumed counterpart of GRB970228. Although it is not the purpose of this paper to study in detail the diffuse emission discussed by Sahu et al.(1997c), close attention has been given to its possible influence on the GRB counterpart centering. A blow-up of the region in the March frame, where such a nebulosity is more apparent, is shown in figure 2a where green identifies backgroung pixels, averaging 8 counts, while yellow covers the range 8.1-8.4 counts (read noise $\sim$ 0.75 and gain $\sim$ 7.12). For comparison the peak source intensity is 14 counts/pixel. The contribution of the diffuse emission to the source counts is indeed negligible. The faintness of the diffuse emission stems clearly from the two orthogonal tracings of Figures 2b(row) and 2c (column). The shape of the point-source is clearly unaffected by the very faint nebulosity. Therefore, we are confident that the GRB centering is not polluted by it.

Table 1. The table lists the magnitudes of the stars labelled in Fig.1. For the GRB counterpart the two values correspond to the March and April observations, respectively. In columns 3 and 4 the FWHM components of the gaussian functions best fitting the stars' profiles are given (in pixels, 1pix=0.0455 arcsec). Numbers in brackets refer to the April observation.

Obj.	*mag*	$FWHM_x$	$FWHM_y$
1	24.3 ± 0.1	6.6 [6.2]	5.0 [5.2]
2	22.9 ± 0.05	3.2 [4.7]	3.2 [4.1]
3	25.8 ± 0.2	3.0 [4.4]	2.8 [4.6]
4	23.8 ± 0.1	3.1 [4.3]	3.1 [4.3]
GRB	$25.7 - 26.1 \pm 0.2$	3.5 [4.6]	3.1 [4.2]

Table 1 lists magnitudes and Gaussian widths measured in the March and April observations for all our stars. While objects 2,3,4 and the GRB 970228 counterpart are point-like with very similar width of the Gaussian profiles, object 1 is slightly extended. However, we are confident that its centering can be accurately performed. We note that the width values, measured for the point-like sources, in April are larger than the March ones. This must be due to some systematic effect. However, since all the sources are affected in the same way, such a broadening does not hamper our astrometric comparison. In the presence of such a systematic difference between the star profiles in the two observations, the use of a variable Gaussian profile for accurate star positioning is certainly superior to the standand PSF fitting. The centering errors of the reference stars are between 0.02 and 0.07 pixels, while for the candidate counterpart of GRB 970228 the uncertainties are $\sim$ 0.07 pixels. The values of all the centroids were corrected for the instrument geometrical distorsion, following the detailed procedure outlined by the WFPC2 team (Holtzmann et al, 1995).

The two observations cannot be immediately superimposed because they have been obtained with slightly different roll angles and pointing directions. Thus, precise alignment of the two images is needed. This has been performed following the procedure used by Caraveo et al (1996) to measure the parallactic displacements of Geminga. To account for image rotation, we have rotated the source coordinates according to the known telescope roll angles, ending up with the X-axis aligned with increasing right ascension and the Y-axis aligned with increasing declination. Thus, the statistical weight of the reference sources

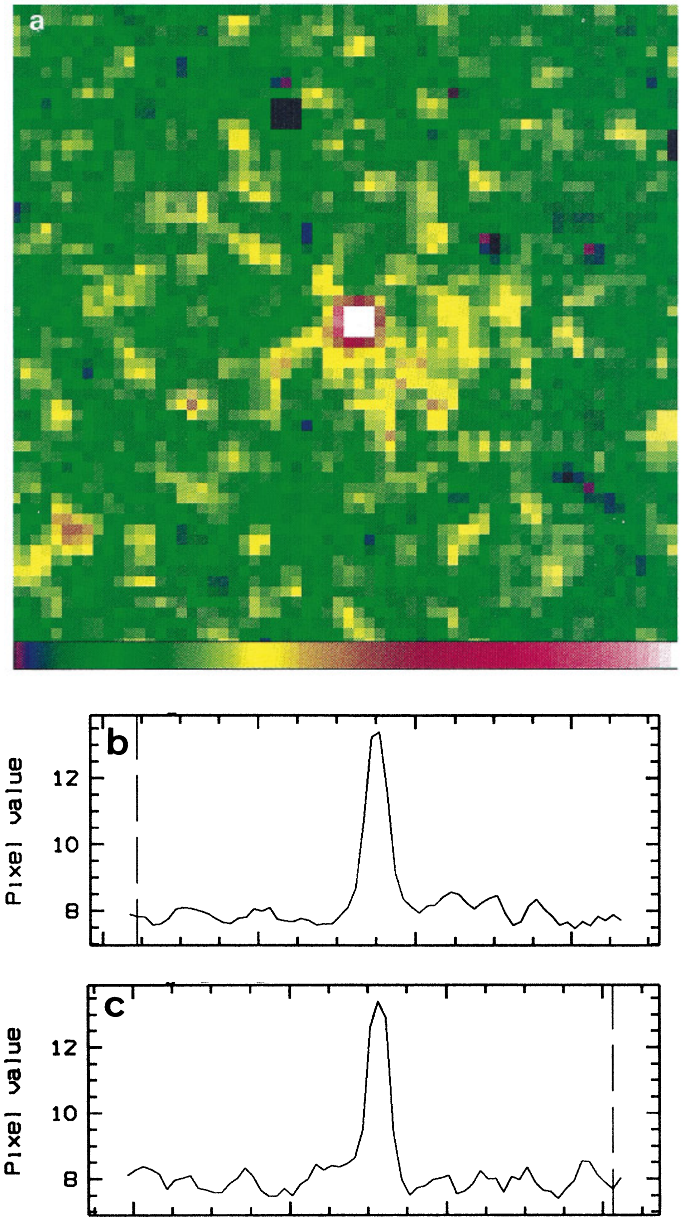

Fig. 2. (a) Blow-up of the F606W March 26^{th} image centered on the GRB 970228 counterpart (pixel size is 0.0455 arcsecs). The square shape of the point source is an artifact due to the color scale used to display the very faint nebulosity (b) Tracing of the above image along the row passing through the GRB maximum. X-axis: each tic corresponds to 5 PC pixels, Y-axis: count/pixel (c) idem for column of maximum

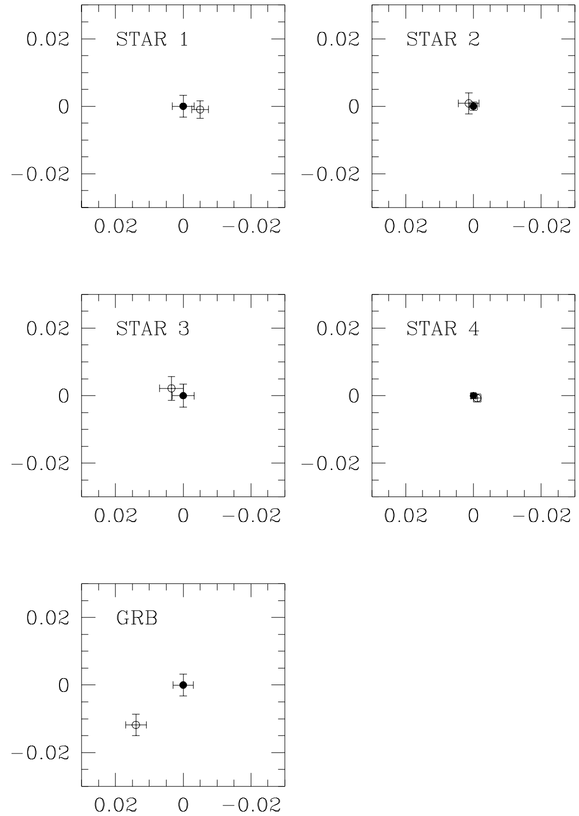

Fig. 3. April 7^{th} vs March 26^{th}, 1997 displacements of reference star centroids and of the GRB 970228 proposed counterpart. The March 26^{th} positions (identified with filled circles) have been used as zero point. Open circles identify the positions measured on April 7^{th}. While the reference stars show no angular displacements, the proposed counterpart of GRB does. North to the top, East to the left. Axis units are in arcsec.

was used in establishing the translation factors. Since neither the net shifts nor their errors change when object #1 is excluded, all reference objects were used. To evaluate globally the errors introduced by the procedure described above, we compare the coordinates of our stars in the two images. In the absence of significant proper motions, they should be the same, within errors, i.e., their residuals should cluster around zero.

3. Results

The results of the centroid cross-comparisons are shown in Figure 3 where, for each star, we plotted the April position relative to the March one, taken as zero point. While the positioning errors originate from the original star centering uncertainties (plus translation accuracy), the actual values of the displacements provide a measure of the precision achieved in the image superposition.

Pixel displacements of stars 1,2,3,4 are:
$\Delta\alpha = -0.08 \pm .09, 0.03 \pm .08, 0.07 \pm .10, -0.02 \pm .04$,
$\Delta\delta = -0.05 \pm .09, 0.02 \pm .08, 0.05 \pm .10, -0.01 \pm .04$,
yielding *total* April vs. March residuals < 0.1 pixels. This gives confidence in the overall correctness and accuracy of our procedure and provides a global estimate of the final uncertainty. The behaviour of the candidate counterpart of GRB 970228 is different: it shows an angular displacement of $\Delta\ \alpha = 0.30 \pm 0.1$ pixels and $\Delta\ \delta = -0.26 \pm 0.1$ pixels, for a total displacement of 0.40 ± 0.10 pixels equivalent to 18 ± 4.5 mas to the South-East. We note that star #3, of $m_{606} = 25.8$, does not show any displacement to within a global error budget of 0.1 pixel.

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4. Discussion

In summary, although in need of confirmation, our comparison of the two available HST images shows evidence that the point-like counterpart of GRB 970228 is moving.

Taking the result of our method at face value, the angular displacement found for the optical counterpart of GRB 970228 is $\sim$ 550 ($\pm$ 140) mas/yr for a constant speed, and implies a transverse velocity-distance relation of the type : $v(km/sec)$ = 2.7 $\times$ $d(pc)$. For $v = c$, a value of d $\sim$ 100 kpc is obtained. In this case, the optical emission seen by Hubble 36 days after the burst would be due to a relativistic plasmoid ejected from a compact source in a jet-like geometry. A transverse velocity of few hundreds km/sec, typical of radio pulsars (Lyne & Lorimer, 1994), would correspond to a distance of $\sim$ 100 pc.

The WFPC2 has already measured comparable V-band fluxes from nearby neutron stars such as Geminga (Bignami et al, 1996) and PSR0656+14 (Mignani et al, 1997), two middle-aged isolated neutron stars (INSs) with faint optical emission. However, we note that the colors of the GRB candidate may not follow a simple Rayleigh-Jeans extrapolation of the spectrum, also owing to possible circumstellar nebulosity. Moreover, different emission mechanisms (see Tavani, 1997) should also be considered, possibly in the context of older and cooler isolated neutron stars, emitting optical radiation because of a burst-driven heat release or residual accretion.

Constraints on a galactic population of compact objects producing GRBs can be deduced from the isotropic and apparently non-homogeneous distribution of GRBs obtained by BATSE (e.g. Fishman & Meegan, 1991). Arguments against a local disk population of GRBs (Paczynski, 1991; Mao & Paczynski, 1992) are mostly based on the difficulty of reconciling the observed GRB isotropic and non-homogeneous distribution (Meegan et al, 1992; Briggs et al, 1996) with compact objects distributed as Population I stars. However, a recent analysis of BATSE data indicates that non-homogeneity may not apply to the whole sample of GRBs (e.g. Kouveliotou et al, 1996). Several classes of GRB sources with different spatial distributions may exist. A fast moving counterpart of GRB 970228 can be ascribed to a local population of compact objects with an isotropic and homogeneous spatial distribution. The relatively long duration of GRB 970228 ($\sim$ 80 s) and its likely low value of the average spectral hardness (Costa et al, 1997) are consistent with being a burst belonging to the homogeneous population detected by BATSE (e.g. Kouveliotou et al, 1996). Alternatively, a relativistic plasmoid at d $\sim$ 100 kpc may be consistent with observations. Relatively rapid fading within a time scale of 1-2 months after the burst is expected for a relativistic plasmoid. A slower decay of emission from the point-like object may result from residual surface or disc emission of a compact object. More interpretative work is needed to clarify these issues.

In any case, any proper motion of the GRB 970228 counterpart would prove its galactic nature. The reported fading of the surrounding optical nebulosity seems to support a galactic origin of the source. However, this fading has now been put in question (Fox et al, 1997). GRB 970228 may be representative of a large fraction, if not all, of GRB sources. In view of the importance of the topic and of the preliminary nature of our result, which stretches HST capabilities to their limit, further observations are needed. They will both extend the time span for the proper motion measurement and gauge the source luminosity evolution. More X-ray afterglows from other GRBs may be detected in the near future by BeppoSAX, and rapid optical follow-up observations will further constrain the nature of GRB sources.

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