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OBSERVATIONS OF GRB 970228 AND GRB 970508 AND THE NEUTRON STAR MERGER MODEL

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ABSTRACT

We present the discovery observations for the optical counterpart of the γ-ray burster GRB 970508 and discuss its light curve in the context of the fireball model. We analyze the HST data for this object and conclude that any underlying galaxy must be fainter than $R = 25.5$. We also present a detailed analysis of the HST images of GRB 970228, from which a proper motion of the optical counterpart was claimed by Caraveo et al., and conclude that, within the uncertainties, there is no proper motion. We examine several aspects of the neutron star merger model for γ-ray bursts. In particular, we use this model to predict the redshift distribution of γ-ray bursters, and, adopting a recent determination of the cosmic star formation history, we show that the predicted log $N$–log $P$ distribution is consistent with that observed for GRBs.

Subject headings: cosmology: observations — gamma rays: bursts

1. INTRODUCTION

Recent observations of the two γ-ray bursts (GRBs) GRB 970228 and GRB 970508 have allowed unprecedented progress in our understanding of their sources, as a result of the fact that X-ray and optical counterparts have now been identified (Costa et al. 1997a, 1997b; Heise et al. 1997; Piro et al. 1997; van Paradijs et al. 1997; Sahu et al. 1997; Galama et al. 1997a; Bond 1997; Djorgovski et al. 1997a; and references therein). In particular, the discovery of an extended source, which may be the host galaxy of GRB 970228 (van Paradijs et al. 1997; Sahu et al. 1997), and the detection of an absorption- and emission-line system at $z = 0.835$ in the optical spectrum of GRB 970508 (Metzger et al. 1997a, 1997b), which may arise from a host (or intervening) galaxy, provide (if the identification of the sources is correct) the first direct evidence that GRBs are at cosmological distances.

However, the claim of an apparent proper motion for GRB 970228 (Caraveo et al. 1997a, 1997b) poses some difficulty with the cosmological hypothesis; we refute this claim in some detail.

In addition, although the X-ray, optical, and radio afterglows of the GRBs 970228 and 970508 are consistent with the cosmological fireball models (Wijers, Rees, & Mészáros 1997; Waxman 1997a, 1997b; Vietri 1997; see also § 2), little progress has been achieved toward the identification of the actual mechanism causing the bursts. We discuss some of the implications of the neutron star merger scenario and show that the predicted log $N$–log $P$ relation from this model is consistent with the observations.

2. GRB 970508

The optical counterpart of GRB 970508 was first identified by one of us (Bond 1997), observing at Kitt Peak National Observatory (KPNO) on the 0.9 m reflector with a 2048 × 2048 CCD camera, which provides a field of view of 23′ × 23′. Upon notification of the occurrence of the γ-ray burst by J. Halpern, Bond obtained CCD frames beginning at 1997 May 9 131, only 5.5 hr after the burst. However, since the GRB counterpart was well below the limits of the STScI Digitized Sky Survey, its actual identification was delayed until the following night, 1997 May 10, when it was then readily recognized as a variable source by blinking the frames from both nights.

Figure 1 (Plate L8) shows the discovery frames from May 9 and 10. The variable star–like object at the center of each panel is the proposed GRB counterpart, which brightened by about 1 mag over the 1 day interval. The frames, obtained in the standard Johnson V and Kron-Cousins $I$ bandpasses, were corrected for atmospheric extinction and calibrated using 14 standard stars from Landolt (1992). Table 1 presents the 0.9 m photometry, with 1σ errors calculated from the photon statistics using IRAF’s QPHOT routine.

The principal features of the GRB afterglow at X-ray and optical wavelengths are well represented by a forward-radiating, blast-wave model of Mészáros & Rees (1997) with only four adjustable parameters, as shown in Figure 2a. In their model A1 those parameters are the peak flux, $F_p$ (which is independent of photon energy), the continuum power-law photon indices $\alpha$ and $\beta$ for photon energies less than and greater than, respectively, the peak flux density, and the duration of the γ-ray burst, $t_r$. Values of the parameters that represent the afterglow of GRB 970508 are $F_p = 6 \times 10^{-8}$ Jy, $\alpha = 0$, $\beta = -0.9$, and $t_r = 12$ s (Fig. 2a). For this value of $\beta$ the remnant fades as $t^{-1.4}$. The values of $\alpha$ and $\beta$ accord well with those expected for synchrotron emission by relativistic electrons in a blast wave (Mészáros & Rees 1997), and the fitted value of $t_r$ matches well the observed duration of the γ-ray burst: 15 s (Costa et al. 1997c), or FWHM = 3.6 s and total duration = 35 s (Kouveliotou et al. 1997). The γ-ray and X-ray brightness of the burst exceeds the peak flux density of the afterglow by a factor ~10 (Fig. 2a). This is probably a consequence of the fact that the γ-rays and the afterglow are produced at different stages of the fireball evolution (the GRB is produced before the self-similar stage; Waxman 1997a, 1997b). However, this model represents two general characteristics of the optical afterglow: the wavelength dependence of the fading...
TABLE 1
PHOTOMETRY OF GRB 970508 DURING THE FIRST 2 DAYS AFTER OUTBURST*  

<table>
<thead>
<tr>
<th>UT Date (1997 May)</th>
<th>V (mag)</th>
<th>Error</th>
<th>UT Date (1997 May)</th>
<th>I (mag)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.140 ........</td>
<td>21.49</td>
<td>0.21</td>
<td>9.131</td>
<td>21.2</td>
<td>0.8</td>
</tr>
<tr>
<td>9.189 ........</td>
<td>21.25</td>
<td>0.20</td>
<td>9.200</td>
<td>20.54</td>
<td>0.28</td>
</tr>
<tr>
<td>9.217 ........</td>
<td>21.28</td>
<td>0.14</td>
<td>9.226</td>
<td>21.21</td>
<td>0.40</td>
</tr>
<tr>
<td>10.135 ..........</td>
<td>20.66</td>
<td>0.22</td>
<td>10.138</td>
<td>19.76</td>
<td>0.16</td>
</tr>
<tr>
<td>10.147 ..........</td>
<td>20.42</td>
<td>0.05</td>
<td>10.156</td>
<td>19.65</td>
<td>0.06</td>
</tr>
<tr>
<td>10.165 ..........</td>
<td>20.37</td>
<td>0.05</td>
<td>10.173</td>
<td>19.42</td>
<td>0.06</td>
</tr>
<tr>
<td>10.182 ..........</td>
<td>20.32</td>
<td>0.05</td>
<td>10.191</td>
<td>19.60</td>
<td>0.08</td>
</tr>
<tr>
<td>10.200 ..........</td>
<td>20.36</td>
<td>0.05</td>
<td>10.209</td>
<td>19.63</td>
<td>0.09</td>
</tr>
<tr>
<td>10.218 ..........</td>
<td>20.29</td>
<td>0.06</td>
<td>10.227</td>
<td>19.43</td>
<td>0.07</td>
</tr>
</tbody>
</table>

* Notice that on May 10, the observations reveal brightening of the source from one frame to the next.

optical afterglow ($\Delta t > 2$ day), and the absence of wavelength dependence at earlier times. But the model does not match (in detail) the temporal evolution before peak brightness. The optical brightness before peak can be approximated with $\alpha = 0.5$, although the optical brightness before peak would then be predicted to be wavelength dependent, which is contradicted by observations. We therefore prefer the $\alpha = 0$ fit.

A more detailed comparison between the model presented in Figure 2a and the optical observations is shown in Figure 2b. The ratio of observed and modeled flux densities are wavelength independent both before and after peak brightness ($\Delta t \sim 2$ day). Before peak the observed flux density rises rapidly from approximately 5 times fainter than predicted (see, however, Waxman 1997b) to agreement with the model. Resolution of this discrepancy during the early phase of the afterglow may require intensive, rapid observations of new GRB counterparts. Generally speaking, given the simplicity of the model and the small number of adjustable parameters, the agreement with X-ray, optical, and (to some extent) radio observations should be considered remarkable (see also Wijers et al. 1997; Vietri 1997; Waxman 1997a, 1997b). This strengthens considerably the identification of the optical counterparts of both GRB 970228 and GRB 970508. It is beyond the scope of the present Letter to discuss the complex behavior of GRB 970508 in the radio wavelengths (Frail et al. 1997).

We have undertaken an extensive analysis of the HST optical images of GRB 970508 (see also Pian et al. 1997), in an attempt to detect an unambiguous signature of an underlying host galaxy (as suggested by the line strengths and the line-strength ratios of the Mg ii/Mg ii absorption system and the [O ii] emission line; Metzger et al. 1997a, 1997b). To this end, we have used the most updated dark frames and an average point spread function (PSF) constructed from the stars in the observed field of the GRB (rather than from the archive), which, within the uncertainties, is indistinguishable from the PSF derived for the GRB. Our analysis suggests that the limit quoted by Fruchter et al. (1997) is rather conservative, and we find that if a host galaxy is underlying the GRB (with an angular extent of about 0.5), it must be fainter than $R \sim 25.5$ (or else it is extremely compact with an angular extent of less than about 0.2', which at $z = 0.835$ corresponds to $\sim 1.7$ kpc). To confirm this result, we did the following exercise: we took the galaxy (size $\times 0.7$ $\times 0.9$ with $R \sim 24.8$ at about 56 NE of the GRB (Djorgovski et al. 1997d), artificially made it fainter by different factors, superposed the result on the GRB, and checked whether the galaxy is still detectable. The galaxy is clearly detected when its magnitude is $R \sim 25.5$, but barely so at $R \sim 26$, after the proper PSF subtraction. We note that this process not only adds the galaxy but also adds the sky noise, so even this method gives a conservative limit to the detectable magnitude. Since the redshift is $\geq 0.8$, this implies that an underlying galaxy, if present, is at least 10 times fainter than an $L^*$ galaxy.

3. ON THE PROPER MOTION OF GRB 970228

GRB 970228 was observed with the HST Wide Field and Planetary Camera 2 (WFC2) in “wide V” and “I" filters on 1997 March 26 and April 7. The telescope roll angles during the two epochs of observation differed by about 23982 (for full details of the observations see Sahu et al. 1997). On the basis of these observations Caraveo et al. (1997a, 1997b) reported that the point source moved 0.016 toward the south east over this 12 day interval. If correct, such a proper motion would imply a Galactic origin for this GRB. Here we present a detailed independent analysis of any possible proper motion.

For the proper-motion analysis, it is important to correct for cosmic-ray (CR) and hot-pixel effects in the images. The standard STScI pipeline calibration typically uses dark frames taken
a few days prior to the observations and therefore may not remove all the hot pixels efficiently. Consequently, we have recalibrated the images ourselves, starting with the raw, uncalibrated images, and using the dark frames taken closest (within 1 day) to the actual observations. The bias subtraction, flat-field correction, and CR rejection were carried out in the usual way. Since there are refractive elements in the optics, color terms could play a role in the image positions. Therefore the analysis was done for the V and I images separately, giving independent proper-motion information in the two bands. Two of the V images had CRs close to the GRB image, and they were therefore treated with special care. Specifically, we carried out two analyses, one with the CR-affected (and CR-corrected) images included, and one where we simply discarded the CR-affected images. (CRs and their rejection cause loss of information in the affected pixels; thus discarding such images may be the preferred procedure.) There are four reference stars (marked in Fig. 3 [PL L9]) in the PC chip whose colors and brightness imply that their expected parallaxes and proper motions are orders of magnitude smaller than the measurement uncertainties.

The centroids of the stars were determined using two-dimensional Gaussian fits. The positional accuracy for the stars is typically 2 to 3 milliarcsec (mas) in each coordinate at each epoch, while for the relatively faint GRB it is ~4 mas (corresponding to a “proper-motion” uncertainty of ~6 mas in each coordinate). The measured coordinates were then corrected for the camera’s geometric distortion using the Gilmozzi, Ewald, & Kinney (1995) and Holtzman et al. (1995) solutions (these give identical results to within 0.5 mas and differ slightly only at the edge of the field). A linear transformation from the first epoch to the second was then performed, using the four reference stars and assuming zero mean motion. This was done with two different methods: one where the rotation and the translation were done separately, and the other where they were done in a single step. The first method involves using the program “metric” in the STSDAS package, which first takes the rotation into account (from the roll-angle information in the header) in converting the pixel coordinates to R.A. and decl. The centroids of the stars are determined in R.A. and decl., and a linear translation from the first to the second epoch is then performed as a separate step. In the second method, the centroids are determined in pixel coordinates taking only the geometric distortion of the detector into account, and a transformation from the first to the second epoch is then made taking the rotation and translation as a single step. Both methods, however, gave almost identical results (to within 1 mas), which shows that the telescope roll angle information in the header has sufficient precision for this analysis. The resulting “proper motions” for the four stars and the GRB are shown in Figure 4 for the V and I filters separately. As can be seen, the positions of the reference stars are within the expected uncertainties, which shows that the transformations have been done correctly. The GRB displays a “proper motion” relative to the reference stars of about 0.007 in the NW direction in the CR-free V-band images, and about 0.0065 in the same direction in the I band, the uncertainties being of comparable magnitude to the motion. The fact that the observed shift is not significantly larger than the measurement errors, coupled with the fact that the GRB is faint and embedded in a nebula, lead us to conclude that no proper motion has been detected (within the uncertainties). Our result disagrees with the findings of Caraveo et al. (1997a, 1997b), both in magnitude and in the direction of motion, for the V-band images (they claim a motion of 0.016

![Image](image_url)

**Fig. 4.**—Measured “proper motion” of the optical counterpart of GRB 970228 and the four stars in the PC chip (see Fig. 3), assuming zero mean motion for the four stars. The left and the right panels show the results obtained from the analysis of the V and I images, respectively. The error bars refer to ±1σ. Note that considering only the CR-free images reduces the “proper motion” (see text).

in the southeast direction during the 12 day period). No comparison is possible for the I band since they do not quote a value for these images.

4. NEUTRON STAR MERGERS

While a generic fireball model (e.g., Paczyński & Rhoads 1993; Mészáros & Rees 1997) appears consistent with all the available data, the same cannot yet be said about any specific mechanism for the production of the fireball. In the following we examine several aspects of neutron star mergers (see also Sahu et al. 1997, and references therein) in light of the recent observations and theoretical developments.

4.1. The Redshift Distribution of Neutron Star Mergers

Neutron star mergers in close binary systems have been suggested as a promising mechanism for the production of fireballs (e.g., Eichler et al. 1989; Narayan, Paczyński, & Piran 1992). Population synthesis calculations which take into account the evolution of the entire binary population of a galaxy, (e.g., Tutukov & Yungelson 1994) predict that the frequency of mergers should peak at about $3 \times 10^7$ yr following a burst of star formation. Consequently, we can use recent findings on the cosmic history of star formation to predict the redshift distribution of neutron star mergers, and thereby of GRBs, if such mergers indeed represent the correct model for their origin.

Using the Hubble Deep Field (Williams et al. 1996) in conjunction with ground-based observations, Madau et al. (1996; see also Madau 1997) were able to show that the cosmic star formation rate SFR(z) peaked at $z \sim 1.25$. Given the short delay time of $\sim 3 \times 10^7$ yr, we therefore predict that the rate of neutron star mergers should roughly follow the SFR(z) of Madau (1997) (even delays of up to $\sim 10^7$ yr are hardly noticeable within the uncertainties). Furthermore, since much of the star formation may be occurring in small, low-mass galaxies that experience short starbursts (e.g., Babul & Rees 1992; Babul & Ferguson 1996), we predict that, if GRBs are produced by neutron star mergers, they may originate preferentially in such galaxies.

We have checked whether this strongly nonuniform redshift distribution (Madau 1997) is compatible with the observed log $N(> P)$–log $P$ relationship for GRBs, where $N(>P)$ is the number of bursts with peak flux greater than $P$ (in photons cm$^{-2}$ s$^{-1}$). We have used a standard candle luminosity distribution function for a range of luminosities $L_\gamma = 10^{49} - 10^{53}$
ers$^{-1}$ s$^{-1}$ (100–500 keV), a power-law photon spectrum with index $-1.5$, and Friedmann cosmology with $q_{0} = 0.2$ and $H_{0} = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The synthetic log $N$–log $P$ distribution functions thus obtained are presented in Figure 5. Also presented in Figure 5 is the distribution function observed with the Pioneer Venus Orbiter (PVO) and the Compton Gamma-Ray Observatory Burst and Transient Source Experiment (BATSE) (Fenimore et al. 1993, Fenimore & Bloom 1995). A reasonable representation of the observed distribution is found for $L_{\gamma} = 10^{53}$ ergs$^{-1}$. Thus the density evolution that follows the Madau et al. SFR function and a single-peak GRB luminosity are consistent with the observations. We would like to stress that if neutron star mergers are the correct model for GRBs, then their redshift distribution can provide an independent test for the cosmic history of the SFR.

4.2. “Kicks”

Another issue that should be addressed in relation to neutron star mergers is that of “kicks” that are required for the formation of the neutron star binaries as inferred, for example, from observations of radio pulsars (e.g., Lyne & Lorimer 1994) and low-mass X-ray binaries (White & van Paradijs 1996). In particular, Fryer & Kalogera (1997) find that the formation rate of double neutron star systems with separations that are smaller than $5 R_{\odot}$ (a fraction of which are the candidates for mergers within a Hubble time) peaks at kick velocities of $200 \text{ km s}^{-1}$. Furthermore, Fryer and Kalogera find minimum center-of-mass velocities of $200 \text{ km s}^{-1}$ and $225 \text{ km s}^{-1}$ for the two double neutron star systems PSR 1913+16 and 1534+12 (respectively). Since the escape velocity from small galaxies is of order $100 \text{ km s}^{-1}$ (e.g., Gallagher, Hunter, & Tutukov 1984), neutron star binaries with center-of-mass velocities $\geq 200 \text{ km s}^{-1}$ would easily escape from such host galaxies. The $HST$ observations of GRB 970228 (Sahu et al. 1997) are consistent with such an interpretation, since the observed point source lies about 0.7 south of the center of the extended source (which may be the host galaxy).

No host galaxy has been detected yet for GRB 970508 (see § 2). The $HST$ image, however, shows two nearby faint galaxies, at transverse distances of $\sim 30 \text{ kpc}$ and $35 \text{ kpc}$ (for $z = 0.835$, $H_{0} = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$) from the point source. A neutron star binary moving at $\sim 300 \text{ km s}^{-1}$ (away from a low-mass galaxy) for about $10^{5}$ yr could reach a distance of $\sim 32 \text{ kpc}$. However, the ratio of the Mg $\tau$/Mg $\alpha$ lines and the strength of these lines, and in particular the reported [O $\tau$] emission line (Metzger et al. 1997a, 1997b), argue for the presence of a host galaxy at the GRB location. We conclude that if a host is not found (even after the GRB fades away), an interpretation associating the GRB with one of the faint galaxies will have to be reexamined. In such a case, one would probably have to argue that the [O $\tau$] emission is produced by a nebula in the vicinity of the GRB itself, in a similar manner to the production of emission lines from the ring around SN 1987A (e.g., Sonneborn et al. 1997). One test for such an interpretation would be to spectroscopically monitor GRB 970508, since the strength of the line would then be expected to change, as in the case of SN 1987A.

We are grateful to P. Madau and E. Fenimore for useful discussions. We acknowledge the help of Colin Cox with the geometric distortion correction of the $HST$ images, and Ray Lucas and others in the scheduling division for efficiently scheduling the observations of GRB 970228. We thank F. Frontera and M. Garcia for communication of results in advance of publication. M. L. acknowledges support from NASA grant NAGW-2678. KPNO is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

REFERENCES

Bond, H. E. 1997, IAU Circ. No. 6654
Caraveo, P. A., Mignami, R., Tavani, M., & Bignami, G. F. 1997a, IAU Circ. No. 6629
Chevalier, C., & Ilovasky, S. A. 1997, IAU Circ. No. 6663
———, 1997b, IAU Circ. No. 6572
———, 1997b, IAU Circ. No. 6655
———, 1997c, IAU Circ. No. 6660
———, 1997d, in preparation
———, 1997b, IAU Circ. No. 6663

![Fig. 5.—Representation of GRB source counts with density evolution of standard candles in a Friedmann cosmology.](image-url)
———. 1997b, Nature, 387, 876
Fig. 1.—Discovery images for the optical counterpart of GRB 970508. These are coadded V-band frames, taken at mean times of 1997 May 9.19 (top, 600 s exposure) and May 10.18 (bottom, 1800 s exposure). Each frame is 138” high, with north at the top and east on the left. The GRB counterpart is the variable source marked in the bottom frame. It brightened by 1 mag between May 9 and 10.

Sahu et al. (see 489, L127)
FIG. 3.—The reference stars used for the proper-motion analysis of the GRB.

Sahu et al. (see 489, L129)