The extraordinarily bright optical afterglow of GRB 991208 and its host galaxy


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The extraordinarily bright optical afterglow of GRB 991208 and its host galaxy

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Abstract. Broad-band optical observations of the extraordinarily bright optical afterglow of the intense gamma-ray burst GRB 991208 started ~2.1 days after the event and continued until 4 Apr. 2000. The flux decay constant of the optical afterglow in the R-band is ~2.30 ± 0.07 up to ~5 days, which is very likely due to the jet effect, and it is followed by a much steeper decay with constant ~3.2 ± 0.2, the fastest one ever seen in a GRB optical afterglow. A negative detection in several all-sky films taken simultaneously with the event, that otherwise would have reached naked eye brightness, implies either a previous additional break prior to ~2 days after the occurrence of the GRB (as expected from the jet effect) or a maximum, as observed in GRB 970508. The existence of a second break might indicate a steepening in the electron spectrum or the superposition of two events, resembling GRB 000301C. Once the afterglow emission vanished, contribution of a bright underlying supernova was found on the basis of the late-time R-band measurements, but the light curve is not sufficiently well sampled to rule out a dust echo explanation. Our redshift determination of z = 0.706 indicates that GRB 991208 is at 3.7 Gpc (for H0 = 60 km s−1 Mpc−1, Ω = 1 and Λ = 0), implying an isotropic energy release of 1.15 × 1053 erg which may be relaxed by beaming by a factor >102. Precise astrometry indicates that the GRB coincides within 0.2″ with the host galaxy, thus supporting a massive star origin. The absolute magnitude of the galaxy is M_B = −18.2, well below the knee of the galaxy luminosity function and we derive a star-forming rate of (11.5 ± 7.1) M_☉ yr−1, which is much larger than the present-day rate in our Galaxy. The quasi-simultaneous broad-band photometric spectral energy distribution of the afterglow was determined ~3.5 day after the burst (Dec. 12.0) implying a cooling frequency ν_c below the optical band, i.e. supporting a jet model with p = −2.30 as the index of the power-law electron distribution.

Key words. gamma rays: bursts { galaxies: general { cosmology: observations

1. Introduction

Gamma-ray bursts (GRBs) are flashes of cosmic high energy (~1 keV – 10 GeV) photons (Fishman & Meegan 1995). For many years since their discovery in 1967 they remained without any satisfactory explanation, but with the advent of the Italian-Dutch X-ray satellite BeppoSAX, it became possible to conduct deep counterpart searches only a few hours after a burst was detected. This led to the first detection of X-ray and optical afterglow for GRB 970228 (Costa et al. 1997; van Paradijs et al. 1997) and the determination of the cosmological distance scale for the bursts on the basis of the first spectroscopic measurements taken for GRB 970508, implying z ≥ 0.835 (Metzger et al. 1997).

Subsequent observations in 1997-2000 have shown that about a third of the well localized GRBs can be associated with optical emission that gradually fades away over weeks to months. Now it is widely accepted that long duration GRBs originate at cosmological distances with energy releases of 10^{51}–10^{53} ergs. The observed afterglow satisfies the predictions of the “standard” relativistic fireball model, and the central engines that power these extraordinary events are thought to be the collapse of massive stars (see Piran 1999; van Paradijs et al. 2000 for a review).

The detection of GRB host galaxies is essential in order to understand the nature of hosts (morphology, star forming rates) and to determine the energetics of the bursts (redshifts) and offsets with respect to the galaxy centres. About 25 host galaxies have been detected so far, with redshifts z in the range 0.43–4.50 and star-forming rates in the range 0.5–60 M_☉ year−1. See Klose (2000), Castro-Tirado (2001) and references therein.

Here we report the detection of the optical afterglow from GRB 991208 as well as its host galaxy. This GRB was detected at 04:36 universal time (UT) on 8 Dec. 1999, with the Ulysses GRB detector, the Russian GRB Experiment (KONUS) on the Wind spacecraft and the Near Earth Asteroid Rendezvous (NEAR) detectors (Hurley et al. 2000) as an extremely intense, 60 s long GRB with a fluence >25 keV of 10^{-4} erg cm^{-2} and considerable flux above 100 keV. Radio observations taken on 1999 December 10.92 UT with the Very Large Array (VLA) at 4.86 GHz and 8.46 GHz indicated the presence of a compact source which became a strong candidate for the radio afterglow from GRB 991208 (Frai et al. 1999).

2. Observations and data reduction

We have obtained optical images centered on the GRB location starting 2.1 days after the burst (Table 1). Photometric observations were conducted with the 1.04-m Sampurnananda telescope at Uttar Pradesh State Observatory, Nainital, India (1.0 UPSO); the 1.34-m Schmidt telescope at Tautenburg, Germany (1.3 TBG); the 1.5-m telescope at Observatorio de Sierra Nevada (1.5 OSN), Granada, Spain; the 2.5-m Isaac Newton Telescope (2.5 INT), the 2.56-m Nordic Optical Telescope (NOT), the 3.5-m Telescopio Nazionale Galileo (3.5 TNG) and the 4.2-m William Herschel Telescope (4.2 WHT) at Observatorio del Roque de los Muchachos, La Palma, Spain; the 1.23-m, 2.2-m and 3.5-m telescopes at the German-Spanish Calar Alto Observatory (1.2, 2.2 and 3.5 CAHA respectively), Spain; the 3.5-m telescope operated by the Universities of Wisconsin, Indiana, Yale and the National Optical Astronomical Observatories (3.5-m WIYN) at Kitt Peak, USA; and the 6.0-m telescope at the Special Astrophysical Observatory of the Russian Academy of Sciences in Nizhnij Arbyz, Russia.

For the optical images, photometry was performed by means of SExtractor (Bertin & Arnouts 1996), making use of the corrected isophotal magnitude, which is appropriate for star-like objects. The DAOPHOT (Stetson 1987) profile-fitting technique was used for the magnitude determination on the later epoch images, when the source is much fainter. Zero-points, atmospheric extinction and color terms were computed using observations of standard
fields taken throughout the run. Magnitudes of the secondary standards in the GRB fields agree, within the uncertainties, with those given in Henden (2000). Zero-point uncertainties are also included in the given errors.

Prompt follow-up spectroscopy of the OA was attempted at several telescopes (Table 2), but we only achieved a reasonable signal-to-noise ratio (S/N) at the 6-m telescope SAO RAS using an integral field spectrograph MPFS (Dodonov et al. 1999a). One 2700-s spectrum and one 4500-s spectrum were obtained on 13 and 14 Dec. 1999 UT. On the latter, the observing conditions were good; the seeing was ≈1.5′′ (at a zenithal distance of 60°), and there was good transparency. We used 300 lines/mm grating blazing at 6000 Å giving a spectral resolution of about 5 Å/pixel and effective wavelength coverage of 4100–9200 Å. The spectrophotometric standards HZ44 and BD+75 325 (Oke et al. 1995) were used for the flux calibration.

3. Results and discussion

3.1. The optical afterglow

At the same location of the variable radio source, a bright optical afterglow (OA) was identified on images taken at Calar Alto, La Palma and Tautenburg (Castro-Tirado et al. 1999a,b). The astrometric solution was obtained using 16 USNO-A stars, and coordinates were α$_{2000}$ = 16h33m53.50s; δ$_{2000}$ = +46°27′21.0″ (+0.2′′). A comparison among optical images acquired on 10 and 11 Dec. allowed us to confirm the variability in intensity of the proposed OA. About 2.1 d after the burst, we measured R = 18.7 ± 0.1 for the OA, and 19 h later we found R = 19.60 ± 0.03. In these images the object is point-like (resolution ≈1″) and there is no evidence of any underlying extended object, as seen at later epochs (Fig. 1). Coincident (within errors) with the location of optical and radio afterglows, Shepherd et al. (1999) detected at millimeter wavelengths the brightest afterglow of a GRB reported so far. At 15 GHz and 240 GHz, the GRB 991208 afterglow was observed at Ryle (Pooley et al. 1999) and Pico Veleta (Bremer et al. 1999a,b), respectively.

Our B, V, R, I light curve (Fig. 2) shows that the source was declining in brightness. The optical decay slowed down in early 2000, indicating the presence of an underlying source of constant brightness: the host galaxy. The decay of previous GRB afterglows appears to be well characterized by a power law (PL) decay F(t) ∝ (t − t$_0$)$^{-\alpha}$, where F(t) is the flux of the afterglow at time t since the onset of the event at t$_0$ and α is the decay constant. Assuming this parametric form and by fitting least square linear regressions to the observed magnitudes as function of time, we derive below the value of flux decay constant for GRB 991208. The fits to the B, V, R, and I light curves are given in Table 3, but the poor quality of the PL fit is reflected in the relatively large reduced chi-squared values. This is specially noticeable in the R-band light curve,

<table>
<thead>
<tr>
<th>Date of</th>
<th>Telescope</th>
<th>Filter</th>
<th>Integration time (s)</th>
<th>Magnitude</th>
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<td>B</td>
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<td>02.1431 Jan</td>
<td>3.5 TNG</td>
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Table 1. Journal of the GRB 991208 optical/NIR observations

3.2. The narrow-band observations

Table 2. Journal of the GRB 991208 spectroscopic observations

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<th>Date of</th>
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<th>Wavelength range (Å)</th>
<th>Exposure time (s)</th>
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<td>2000 Jan</td>
<td>3.5 TNG</td>
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Table 3. Journal of the GRB 991208 narrow-band observations

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3.1.1. The existence of two breaks

The $R$ and $I$-band data up to $t_0 + 10$ days are better fitted by a broken PL with a break time $t_{\text{break}} \sim 5$ days. For the $B$ and $V$-band, such a fit is not possible due to the scarcity of the data in these bands. See Table 4. Hence, we adopt a value of $\alpha_1 = -2.30 \pm 0.07$ for 2 days < $(t - t_0)$ < 5 days and $\alpha_2 = -3.2 \pm 0.2$ for 5 days < $(t - t_0)$ < 10 days as flux decay constants in further discussions.

Further support for the existence of an additional break at $(t - t_0) < 2$ days in GRB 991208 comes from the extrapolation of the $R$-band data towards earlier epochs (Fig. 3), that predicts an optical flux that should have been seen with the naked eye by observers in Central Europe.

The optical event exceeding magnitude 11 could be detected by the Czech stations of the European Fireball

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<th>Table 3. PL fits to the $BVRI$ observations of GRB 991208</th>
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<th>Table 4. Broken PL fits to the $RI$ observations of GRB 991208</th>
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Network. Unfortunately, it was completely cloudy during the night of Dec. 8/9 in the Czech Republic, so none of the 12 stations of the network was able to take all-sky photographs. The first photographs after the GRB trigger were taken on Dec. 8, 16:25 UT, i.e. nearly 12 h after the event, and shows no object at its position brighter than mag $V \sim 10$. However, sky patrol films taken for meteor research were exposed in Germany during Dec. 8/9, 1999 but no OA exceeding $R \sim 4$ with a duration of 10 s or more is detected simultaneous to the GRB event. This upper limit derived from the films implies that this additional break in the power-law decay of GRB 991208 has to be present at 0.01 days $<(t-t_0) < 2$ days although a maximum in the light curve similar to GRB 970508 (Castro-Tirado et al. 1998) cannot be excluded.

The flux decay of GRB 991208 is one of the steepest of all GRBs observed so far (Sagar et al. 2000). Before deriving any conclusion from the flux decays of these GRBs, we compare them with other well studied GRBs. Most OAs exhibit a single power-law decay index, generally $\sim -1.2$, a value reasonable for spherical expansion of a relativistic blast wave in a constant density interstellar medium (Mészáros & Rees 1997; Wijers et al. 1997; Waxman 1997; Reichart 1997). For other bursts, like GRB 990123, the value of $\alpha = -1.13 \pm 0.02$ for the early time (3 hr to 2 day) light curve becomes $-1.75 \pm 0.11$ at late times (2-20 day) (Kulkarni et al. 1999; Castro-Tirado et al. 1999c; Fruchter et al. 1999) while the corresponding slopes for GRB 990510 are $-0.76 \pm 0.01$ and $-2.40 \pm 0.02$ respectively with the $t_{\text{break}} \sim 1.57$ day (Stanek et al. 1999; Harrison et al. 1999). If the steepening observed in both cases is due to beaming, then one may conclude that it occurs within $<2$ days of the burst.

Rapid decays in OAs have been seen in GRB 980326 with $\alpha = -2.0 \pm 0.1$ (Bloom et al. 1999a), GRB 980519 with $\alpha = -2.05 \pm 0.04$ (Halpern et al. 1999), GRB 990510 with $\alpha = -2.40 \pm 0.02$ (Stanek et al. 1999; Harrison et al. 1999) and GRB 000301C with $\alpha = -2.2 \pm 0.1$ (Masetti et al. 2000; Jensen et al. 2001; Rhoads & Fruchter 2001), and have been interpreted as the sideways expansion of a jet (Rhoads 1997, 1999; Mészáros & Rees 1999). For GRB 991208, $\alpha_1 = -2.30 \pm 0.07$ and we therefore argue that the observed steep decay in the optical light curve up to $\sim 5$ days may be due to a break which occurred before our first optical observations starting $\sim 2.1$ day after the burst. The break is expected in several physical models, but beaming is the most likely cause in GRB 991208 taking into account that the rapid fading of optical afterglows is considered as evidence for beaming in GRBs (Huang et al. 2000).

According to the current view, the forward external shock wave would have led to the afterglow as observed in all wavelengths. The population of electrons is assumed to be a power-law distribution of Lorentz factors $\Gamma_e$, following $dN/d\Gamma_e \propto \Gamma_e^{-p}$ above a minimum Lorentz factor $\Gamma_m$, corresponding to the synchrotron frequency $\nu_m$. The value of $p$ can be determined taking into account the occurrence of the jet effect: the break due to a lateral expansion in the decelerating jet occurs when the initial Lorentz factor $\Gamma$ drops below $\Gamma_0^{-1}$ (with $\theta_0$ the initial opening angle), i.e. the observer “sees” the edge of the jet. A change in the initial power-law decay exponent $\alpha_0$ (unknown to us) from $\alpha_0 = 3(1-p)/4$ to $\alpha_1 = -p$ (for $\nu_m < \nu < \nu_c$), or from $\alpha_0 = (2-3p)/4$ to $\alpha_1 = -p$ (for $\nu \geq \nu_c$) is expected (Rhoads 1997, 1999). If this is the case, then $p = -\alpha_1 = 2.30 \pm 0.07$, in the observed range for other GRBs.

Whether the jet was expanding into a constant density medium or in an inhomogeneous medium (Chevalier & Li 1999; Wei & Lu 2000) cannot be determined with our data alone, as we do not have information on $\alpha_0$. For a density gradient of $s = 2$, as expected from a previously ejected stellar wind ($\rho \propto r^{-s}$), the light curve should steepen by $\Delta \alpha = (\alpha_1 - \alpha_0) = (3-s)/(4-s) = 0.5$ whereas $\Delta \alpha = 0.75$ for a constant density medium.

What is the reason for the second break observed in GRB 991208 after $\sim 5$ days? The passage of the cooling frequency $\nu_c$ through the optical band (that would steepen the light curve by $\Delta \alpha \sim 0.25$, Sari et al. 1998) can be discarded: following Sari et al. (1999), if $\nu < \nu_c$ then we should expect a spectral index $\beta (F_\nu \propto \nu^{-\beta})$ such as
with a SN1998bw-like component at $z = 0.706$ (long dashed line) superposed on the broken power-law OA light curve displaying the second break at $t_{\text{break}} \sim 5$ d (with $\alpha_1 = -2.3$ and $\alpha_2 = -3.2$, short dotted lines) and the constant contribution of the host galaxy ($R = 24.27 \pm 0.15$, dotted line)

\[
\beta = \frac{(p - 1)}{2} = 0.65 \pm 0.04 \quad \text{and if } \nu > \nu_c \text{ then } \beta = p/2 = 1.15 \pm 0.04 \quad \text{which is compatible with } F_{\nu} \propto \nu^{-1.05 \pm 0.08} \text{ on 12 Dec. (see Sect. 3.3). Hence we conclude that } \nu_c \text{ has already passed the optical band 4 days after the burst onset.}
\]

The difference between the mid and late time decay slopes is $\Delta \alpha = (\alpha_2 - \alpha_1) = 0.9 \pm 0.3$. A possible explanation could be two superposed events: a major burst followed by a minor burst, expected from some SN-shock models (Mészáros et al. 1998) similar to that proposed for GRB 000301C (Bhargavi & Cowsik 2000). SN-shock models (Meszaros et al. 1998) similar to that proposed for GRB 000301C (Bhargavi & Cowsik 2000).

3.2. The host galaxy

Evidence for a bright host galaxy came from the BTA/MPS 4500-s spectrum of the GRB 991208 optical transient taken on 14 Dec. (see Fig. 5). We found four emission lines at $\lambda = 6350 \, \text{Å}, 8300 \, \text{Å}, 8550 \, \text{Å},$ and $8470 \, \text{Å},$ with the most likely identifications of these emission lines being: [OII] 3727 Å, H$_\alpha$ 4861 Å, [OIII] 4959 Å, 5007 Å at a redshift of $z = 0.7063 \pm 0.0017$ (Dodonov et al. 1999b), a value confirmed by other measurements taken late (Djorgovski et al. 1999). Line parameters are measured with a Gaussian fit to the emission line and a flat fit to the continuum.

Considering the redshift of $z = 0.7063 \pm 0.0017$, $H_0 = 60 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_0 = 1$ and $\Lambda_0 = 0$, the luminosity distance to the host is $d_L = 1.15 \times 10^{28} \, \text{cm}$, implying an isotropic energy release of $1.15 \times 10^{53} \, \text{erg}$. Taking into account the time of the break, $t_{\text{break}} < 2$ d, this implies an upper limit on the jet half-opening angle $\theta_0 < 8^\circ n^{1/8}$ with $n$ the density of the ambient medium (in cm$^{-3}$) (see Wijers & Galama 1999), and thus the energy release should be lowered by $>100$, i.e. the energy released is $<1.15 \times 10^{52} \, \text{erg}$.

For the galaxy, which is present in the late images (March-April 2000), the astrometric solution also obtained using the same 16 USNO-A stars was $\alpha_{2000} = 16^h33^m53.53^s; \delta_{2000} = +46^\circ27'21.0'' (\pm 0.2'')$, which is consistent with the OA position. See also Fruchter et al. (2000).
Our broad-band measurements of $B = 25.19 \pm 0.17$, $V = 24.55 \pm 0.16$, $R = 24.27 \pm 0.15$ on 31.9 Mar. and $I = 23.3 \pm 0.2$ on 4.2 Apr., once dereddened by the Galactic extinction, imply a spectral distribution $F_\nu \propto \nu^{-\beta}$ with $\beta = +1.45 \pm 0.33$ ($\chi^2$/degree of freedom, $\chi^2$/dof = 1.20). See Sokolov et al. (2000) for further details. The unobscured flux density at 7510 Å, the redshifted effective wavelength of the B-band, is $0.65 \, \mu$Jy, corresponding to an absolute magnitude of $M_B = -18.2$, well below the knee of the galaxy luminosity function, $M_B \approx -20.6$ (Schechter 1976).

The star-forming rate (SFR) can be estimated in different ways. Again, we have assumed $H_0 = 60 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$ and $\Omega_0 = 1$, $\Lambda_0 = 0$. From the H$\beta$ flux which is $(3.84 \pm 0.33) \times 10^{-16} \, \text{erg cm}^{-2} \, \text{s}^{-1}$, this corresponds to $(18.2 \pm 0.6) \, M_\odot \, \text{yr}^{-1}$ (Pettini et al. 1998). From the [O II] 3727 Å flux (Kennicutt 1998), which is $(1.79 \pm 0.22) \times 10^{-16} \, \text{erg cm}^{-2} \, \text{s}^{-1}$ we get $(4.8 \pm 0.2) \, M_\odot \, \text{yr}^{-1}$. The mean value, $(11.5 \pm 7.1) \, M_\odot \, \text{yr}^{-1}$, is much larger than the present-day rate in our Galaxy. In any case, this estimate is only a lower limit on the SFR due to the unknown rest frame host galaxy extinction. See also Sokolov et al. (2001b).

### 3.3. The multiwavelength spectrum on Dec. 12.0

We have determined the flux distribution of the GRB 991208 OA on Dec. 12.0, 1999 UT by means of our broad-band photometric measurements (Dec. 12.2) and other data points at mm and cm wavelengths (Dec. 11.6-11.8) (Fig. 6). We fitted the observed flux distribution with a power law $F_\nu \propto \nu^{-\beta}$, where $F_\nu$ is the flux at frequency $\nu$, and $\beta$ is the spectral index. Optical flux at the wavelengths of $B$, $V$, $R$ and $I$ passbands has been derived subtracting the contribution of the host galaxy and assuming a reddening $E(B-V) = 0.016$ from (Schlegel et al. 1998). The long dashed lines are the fits to the multiwavelength spectrum. Rough estimates of the self-absorption ($\nu_a$) and synchrotron frequencies ($\nu_m$) are also indicated.
From the maximum observed flux (Shepherd et al. 1999), we derive a rough value of $v_m \sim 100$ GHz. The low-frequency spectrum below $v_m$ ($F_\nu \propto \nu^{p/3}$) is in agreement with the expected tail of the synchrotron radiation plus a self absorption that becomes important below a critical frequency $v_c \sim 13$ GHz, taking into account that $F_\nu \propto \nu^{1.4}$ in the range $4.86-8.46$ GHz (Frail et al. 1999), deviating from $F_\nu \propto \nu^{1/3}$ as seen for 15 GHz $< \nu < 100$ GHz (Pooley et al. 1999). Much more accurate estimates for $v_c$ and $v_m$ are given by Galama et al. (2000a). Above $v_m$, the IRAM observations (Bremer et al. 1999a,b) indicate a $F_\nu \propto \nu^{-0.6}$, with a cooling frequency $3 \times 10^{11}$ GHz $< \nu_c < 3 \times 10^{14}$ GHz. Then we expect a slope between $v_m$ and $v_c$ of $\beta = (p-1)/2 = 0.68 \pm 0.06$, consistent with the observed value. As we have already mentioned, if the $p=2.3$ jet model is correct, by this time (Dec. 12.0 UT), the cooling break should be already below the optical band, with an optical synchrotron spectrum $F_\nu \propto \nu^{-p/2} = \nu^{-1.15}$ that is in agreement with our optical data ($\beta = -1.05 \pm 0.09$). Therefore our Dec. 12.0 observations support a jet model with $p = 2.30 \pm 0.07$, marginally consistent with $p = 2.52 \pm 0.13$ as proposed by Galama et al. (2000a) on the basis of a fit to the multiwavelength spectra from the radio to the $R$-band data.

4. Conclusion

Most currently popular theories imply a direct correlation between star formation and GRB activity. How does GRB 991208 fit into this picture? The angular coincidence of the OA and the faint host argues against a compact binary merger origin of this event (Fryer et al. 1999) and in favor of the involvement of a massive star (Bodenhaimer & Woosley 1983; Woosley 1993; Dur & De Rújula 2001). The very rapid photometric decline of the afterglow of GRB 991208 provided hope for the detection of the much fainter light contamination from the underlying supernova, what we have confirmed on the basis of the late-time $R$-band measurements, thus giving further support to the massive star origin. There are still many unsolved riddles about GRBs, like the second break in the light curve of this event, i.e. responsible for the steep decay seen after 5 days. The community continues to chase GRB afterglows, and with every new event we make progress by finding more clues and creating even more new puzzles.

References

Bessell, M. S. 1979, PASP, 91, 589
Bremer, M., et al. 1999a, GCN Circ., No. 459
Bremer, M., et al. 1999b, IAU Circ., No. 7333
Dodonov, S., et al. 1999a, GCN Circ., No. 461
Dodonov, S., et al. 1999b, GCN Circ., No. 475
Henden, A. A. 2000, GCN Circ., No. 631