The decay of optical emission from the γ-ray burst GRB 970228

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Abstract. We present the Rc band light curve of the optical transient (OT) associated with GRB970228, based on re-evaluation of existing photometry. Data obtained until April 1997 suggested a slowing down of the decay of the optical brightness. However, the HST observations in September 1997 show that the light curve of the point source is well represented by a single power law, with a “dip”, about a week after the burst occurred. The exponent of the power law decay is \( \alpha = -1.10 \pm 0.04 \). As the point source weakened it also became redder.

INTRODUCTION

The γ-ray burst of February 28, 1997, detected [1] with the Gamma-Ray Burst Monitor on the BeppoSAX observatory, and located with an \( \sim 3' \) radius position with the Wide Field Camera on the same satellite, was the first for which a fading X-ray [1] and optical counterpart [2,3] were found.

The optical counterpart was discovered from a comparison of V and Ic band images taken with the William Herschel Telescope (WHT) on February 28.99 UT, and the Isaac Newton Telescope (INT; V band) and the WHT (Ic band) on March 8.86 UT. After the counterpart had weakened by several magnitudes, it was found to coincide with an extended object [3–5]. In subsequent observations with the Hubble Space Telescope (HST) on March 26 and April 7, 1997, it was found that the optical counterpart consists of a point source and an extended (\( \sim 1'' \)) object, offset from the point source by \( \sim 0.5'' \) [6].

We here reassess the photometric information presented by Galama et al. [7]
in the light of the recent HST findings [8,9], and present the $R_c$ band optical light curve of the GRB counterpart.

I OBSERVATIONS

In Table 1 we have collected the optical photometry reported on GRB970228, obtained in the $V$, $R_c$, and $I_c$ passbands (effective wavelengths $\sim 5500$, $\sim 6500$, and $\sim 8000$ Å, respectively, corresponding closely to the Cousins VRI system). In the interpolations to the $R_c$ band (see Table 2) we have assumed that the spectra of both the point source and the extended emission are smooth (i.e., not dominated by emission lines). We have used the relation between the color indices $V-R_c$ and $V-I_c$ given by Thé et al. [10] for late-type stars; for bluer stars we have inferred this relation from the tables given by Johnson [11] for main-sequence stars and the color transformations to the Cousins VRI system given by Bessel [12]. We have tested the validity of these color-color relations from numerical integrations of power law flux distributions and of Planck functions, and conclude that if the flux distribution of the optical counterpart is smooth, the uncertainty in the interpolated $R_c$ magnitude is unlikely to exceed 0.1 magnitude [7]. Here we discuss the differences with respect to Galama et al. [7].

![Figure 1](image_url)

**FIGURE 1.** The $R_c$ band lightcurve of GRB 970228. Indicated is a power-law fit, $F_{\nu} \propto \nu^\alpha$, to the data with slope $\alpha = -1.10 \pm 0.04$ ($\chi_r^2 = 2.3$ with 9 degrees of freedom).
The earliest image of the OT was obtained by Pedichini et al. [13]. This observation was obtained with a wide filter; we have transformed this wide filter magnitude, using the reported filter characteristics, to the $R_c$ band. In the images of Guarnieri et al. [14], the OT is blended with the nearby late type star, due to bad seeing. We corrected for the contribution of the late type star (for which $R_c = 22.1 \pm 0.1$ [7]) and find for the OT $R_c = 21.7^{+0.5}_{-0.3}$ (Note that in [7] the time of the observation of Guarnieri et al. [14] is given slightly incorrect). We have included a lower limit to the $R_c$ magnitude on Mar. 1.791 [14], which after correction for the contribution of the late type star, gives $R_c > 22.2$. We have not included the subsequent measurements and upper-limits as given by Guarnieri et al. [14] as they are consistent with detections of the late-type star only. We noticed that the Keck calibration [5,15] differs by +0.3 magnitudes; we have corrected for this in Table 2. HST STIS observations between Sept. 4.65 and 4.76 UT [8,9] show that both the nebula and the point-source optical transient found in earlier HST WFC2 observations [6], are also detected in the STIS images at a level of $V = 28.0 \pm 0.25$ for the point source and $V = 25.7 \pm 0.15$ for the nebula. Reanalysis of the earlier HST WFC2 F606W observations gives $V = 25.6 \pm 0.25$ for the nebula [8]. From the recent HST observations and the reanalysis we infer that the $R_c$ band magnitude of the nebula is $R_c = 25.0 \pm 0.3$, fainter than but consistent with $R_c = 24.7 \pm 0.3$ [7]. Assuming that the colors of the OT remained constant during the decay (i.e., taking the observed $V - I = 1.85$ from the HST March 26 and April 7 observations) we infer from the Sept. 4.71 HST observations that $R_c = 27.25 \pm 0.27$ for the OT. In all ground-based photometry we corrected for the contribution of the extended object ($R_c = 25.0 \pm 0.3$) and show the results in Table 2 and in Fig. 1. We have fitted a power-law, $F_R = F_0 t^\alpha$, to the detections and find a magnitude $m_0 = 21.14 \pm 0.13$ (corresponding to $F_0$) and a slope $\alpha = -1.10 \pm 0.04$ ($\chi^2_r = 2.3$; the three upper-limits are not included in this fit).

## II DISCUSSION

The lightcurve can be well represented by a power-law. In the interval between $\log(t) = 0.7$ and 1.2 we have three detections and one upper-limit located below the power-law fit. The three detections deviate from the power-law by: 1.9 $\sigma$ for the Keck observation (Mar 6.32 UT), 1.7 $\sigma$ for the INT observation (Mar 9.90 UT) and 1.4 $\sigma$ for the NTT observation (Mar 13.00 UT). This might indicate that the lightcurve is not smooth, but superposed on the power law behaviour we have deviations of small amplitude. A similar result has been found for the OT of GRB 970508 [16,17]. As the point source weakened it also became redder ($V - I = 0.7 \pm 0.14$ on Feb. 28.99 to $V - I = 1.90 \pm 0.14$ on March 26 and $V - I = 1.80 \pm 0.14$ on April 7; see Tab. 1).
### Table 1. Summary of optical observations.

| Date (UT) | Telescope | Magnitude | Remarks |
|-----------|-----------|-----------|---------|
| Feb. 28.81 | RAO wide | $R = 20.5 \pm 0.5$ | OT |
| Feb. 28.83 | BUT | $R = 21.1 \pm 0.2$ | OT+LTS |
| Feb. 28.99 | WHT | $V = 21.3 \pm 0.1$ | OT |
| Feb. 28.99 | WHT | $I = 20.6 \pm 0.1$ | OT |
| Mar. 01.79 | BUT | $R > 21.4$ | OT+LTS |
| Mar. 03.10 | APO | $B = 23.3 \pm 0.5$ | OT |
| Mar. 04.86 | NOT | $V > 24.2$ | OT+EXT |
| Mar. 06.32 | Keck | $R = 24.0$ | OT+EXT |
| Mar. 08.86 | INT | $V > 23.6$ | OT+EXT |
| Mar. 08.88 | WHT | $I > 22.2$ | OT+EXT |
| Mar. 09.85 | INT | $B = 25.4 \pm 0.4$ | OT+EXT |
| Mar. 09.90 | INT | $R = 24.0 \pm 0.2$ | OT+EXT |
| Mar. 13.00 | NTT | $R = 24.3 \pm 0.2$ | OT+EXT |
| Mar. 26.38 | HST | $V = 26.1 \pm 0.1$ | OT |
| Mar. 26.47 | HST | $I = 24.2 \pm 0.1$ | OT |
| Mar. 26.38 & Apr. 07.22 | HST | $V = 25.6 \pm 0.25$ | EXT |
| Mar. 26.47 | HST | $I = 24.5 \pm 0.3$ | EXT |
| Apr. 05.76 | Keck | $R = 24.9 \pm 0.3$ | OT+EXT |
| Apr. 07.22 | HST | $V = 26.4 \pm 0.1$ | OT |
| Apr. 07.30 | HST | $I = 24.6 \pm 0.1$ | OT |
| Apr. 07.30 | HST | $I = 24.3 \pm 0.35$ | EXT |
| Sept 04 | P5m | $R = 25.5 \pm 0.5$ | OT+EXT |
| Sept 04.71 | HST | $V = 28.0 \pm 0.25$ | OT |
| Sept 04.71 | HST | $V = 25.7 \pm 0.15$ | EXT |

**Abbreviations:**
- RAO, Rome Astrophysical Observatory; BUT, Bologna University Telescope; WHT, William Herschel Telescope; APO, Apache Point Observatory; NOT, Nordic Optical Telescope; INT, Isaac Newton Telescope; HST, Hubble Space Telescope; P5m, Palomar 5-m Hale telescope.

**Notes:**
- OT, optical transient; EXT, extended source; LTS, late-type star.
### TABLE 2. The R-band lightcurve of GRB 970228.

| Date(UT) | Telescope | R(OT+LTS+EXT) | R(OT+EXT) | R(OT) | Reference |
|----------|-----------|---------------|-----------|-------|-----------|
| Feb. 28.81 | RAO | 20.3 ± 0.5 | 20.5 ± 0.5 | [13] |
| Feb. 28.83 | BUT | 21.1 ± 0.2 | 21.7±0.3 | 21.7±0.3 | [14] |
| Feb. 28.99 | WHT | 20.9 ± 0.14 | 20.9 ± 0.14 | [7] |
| Mar. 01.79 | BUT | > 21.4 | > 22.2 | > 22.3 | [14] |
| Mar. 03.10 | APO | 22.2 ± 0.7 | 22.3±0.8 | 22.3±0.8 | [7] |
| Mar. 04.86 | NOT | >23.3 | >23.4 | >23.4 | [7] |
| Mar. 06.32 | Keck | 23.7 ± 0.2 | 24.1±0.4 | [5] |
| Mar. 08.88 | INT+WHT | >22.6 | >22.7 | >22.7 | [7] |
| Mar. 09.90 | INT | 24.0 ± 0.2 | 24.6±0.3 | [7] |
| Mar. 13.00 | NTT | 24.3 ± 0.2 | 25.1±1.3 | 25.1±1.3 | [7] |
| Mar. 26.20 | HST | 24.3 ± 0.2 | 25.17 ± 0.13 | [7,6] |
| Apr. 05.76 | Keck | 24.6 ± 0.3 | 25.9±∞ | [15] |
| Apr. 07.23 | HST | 24.5 ± 0.15 | 25.50 ± 0.13 | [7,6] |
| Sep. 04 | P5m | 25.5 ± 0.5 | 25.5 ± 0.5 | [18] |
| Sep 04.71 | HST | 24.9 ± 0.3 | 27.25 ± 0.27 | [8,9] |

*a Abbreviations as in Table 1.

### REFERENCES

1. Costa, E. et al., *Nat* 387, 783 (1997)
2. Groot, P.J. et al., *IAU Circular* No. 6584 (1997).
3. Van Paradijs, J. et al., *Nat* 386, 686 (1997)
4. Groot, P.J. et al., *IAU Circular* No. 6588 (1997).
5. Metzger, M.R. et al., *IAU Circular* No. 6588 (1997).
6. Sahu, K. et al., *Nat* 387, 476 (1997)
7. Galama, T.J. et al., *Nat* 387, 479 (1997)
8. Fruchter et al., *IAU Circular* No. 6747 (1997).
9. Fruchter et al., *These proceedings* (1997).
10. Thé, P.S., Steenman, H., Alcaino, G., *A&A* 132, 385 (1984)
11. Johnson, H.L., *ARA&A* 4, 191 (1966)
12. Bessel, M.S., *UBVRI Photometry with a Ga-As Photomultiplier, PASP* 88, 557 (1976)
13. Pedichini et al., *A&A* 327, L32 (1997)
14. Guarnieri, A. et al., *submitted to A&A* Astro-ph 9707164 (1997)
15. Metzger, M.R. et al., *IAU Circular* No. 6631 (1997).
16. Galama, T.J. et al., *submitted to ApJL* (1997)
17. Groot, P.J. et al., *These proceedings* (1997)
18. Djorgovski, S.G., et al., *IAU Circular* No. 6732 (1997).