The Late Afterflow and Host Galaxy of GRB 990712

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ABSTRACT
and detected as having the strongest X-ray afterglow to date (Heise et al. 1999). Bakos et al. (1999b) discovered a bright, decaying optical afterglow (OA) \( R = 19.4 \pm 0.1 \) four hours after the burst. Galama et al. (1999b) measured a preliminary redshift of \( z = 0.430 \pm 0.006 \) from a set of absorption and emission lines, which makes it the nearest GRB with a secure redshift that has been observed to date (apart from SN 1998bw). ESO New Technology Telescope images obtained 3.7 days after the burst led Hjorth et al. (1999a) to hypothesize the existence of a bright host galaxy with \( R = 22 \) on the grounds of an apparent leveling off of the light curve relative to the suspected power-law decline \( (a = -1.05) \) (Kemp & Halpern 1999) of the OA. Subsequent ESO Very Large Telescope imaging (Hjorth et al. 1999b) confirmed the leveling off of the light curve, and yielded evidence for the existence of an extended object contributing to the flux at the position of the GRB. Hjorth et al. (1999b) predicted that the existence of a SN would lead to a bump in the light curve around 1 August 1999, and that a SN model could be distinguished from a no-SN model in late HST and ground-based imaging, as the OA would be brighter and the host fainter in the SN scenario than in the no-SN scenario. These predictions are presented in Sahu et al. (2000), which reports the discovery and early light curve of the OA of GRB 990712.

In this Letter we present late HST imaging, as well as ground-based imaging and spectroscopy, aimed at testing these predictions. At the time of the HST observations the \( R \)-band magnitudes of the host galaxy and the OA are predicted to be 22.25 \( \pm 0.05 \) and \( 23.91 \pm 0.05 \) in the SN scenario, and 21.75 \( \pm 0.05 \) and 25.39 \( \pm 0.1 \) in the no-SN scenario. We assume a standard Friedman cosmology with \( H_0 = 65 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.2 \), and \( \Lambda = 0 \). At \( z = 0.4337 \) this corresponds to a scale of 5.6 proper kpc per arcsecond, a luminosity distance of 2.57 Gpc, a distance modulus of 41.88, and a look-back time of 4.9 Gyr. Including a cosmological constant of \( \Lambda = 0.8 \) increases these values by \( \approx 10\% \).

2. Late Ground-Based Imaging

Direct images were obtained with the DFOSSC on the Danish 1.54-m telescope at La Silla on 7 \( (R \text{ band}) \) and 9 \( (V \text{ band}) \) October 1999 UT, i.e., 87 and 89 days after the burst. Exposure times were 3 \( \times \) 15 minutes in each band and the seeing full-width at half-maximum (FWHM) was \( 1.78 \) arcsec. The photometry was carried out using SEXTRACTOR v2.0.13 (Bertin & Arnouts 1996). The calibration was tied to the internal reference stars of Sahu et al. (2000) and gave \( R = 21.92 \pm 0.08 \) and \( V = 22.40 \pm 0.08 \) for the galaxy at the location of the GRB. Two more \( R \) images (120 sec and 180 sec) were obtained with the ESO 3.6-m telescope on 12 November 1999 UT (123 days after the burst) in \( 0.7 \) arcsec seeing (see §4). These images yielded \( R = 21.91 \pm 0.05 \) for the host galaxy. The ground-based images thus showed no signs of a transient source. The photometry is consistent with host magnitudes of \( R = 21.91 \pm 0.04 \) and \( V = 22.40 \pm 0.08 \).

3. HST Imaging

3.1. The STIS Data

HST observations of the OA were made on 29 August 1999 UT, 47.7 days after the burst, as part of the Cycle 8 program GO-8189. Six 620 second exposures were taken with the STIS in each of its 50 CCD (clear, hereafter referred to as CL) and F28X50LP (long pass, hereafter referred to as LP) modes. The CCD gain was set to 1 e\(^{-}/\)ADU, giving a read-out noise of 4 e\(^{-}/\)pixel, and the data was processed through the standard STIS pipeline. We retrieved this data from the HST Data Archive and combined the images using the DITHER (v1.2) software (Fruchter & Hook 2000) as implemented in IRAF\(^{8} \) (v2.11.1)/STSDAS (v2.0.2). We used “pixfrac” = 0.5, and a final output scale of 0.0254 arcsec/pixel. Figure 1 shows the drizzled CL image of the probable host galaxy.

Conversion from counts to \( AB \) magnitudes was achieved using the zero points given in the STIS Instrument Handbook. We assumed that the galaxy had a power-law spectrum of the form \( F_\nu (\nu) = k\nu^\beta \), where \( k \) is constant, and converted the \( AB \) magnitudes to standard Johnson V- and Kron-Cousins R-band magnitudes using

\[
M = m_{\text{CL}} + K_M + 48.6 + 2.5 \log_{10} \left( \frac{\nu_{\text{CL}}}{\nu_M} \right) \tag{1}
\]

\(^{8}\)Image Reduction and Analysis Facility (IRAF), a software system distributed by the National Optical Astronomy Observatories (NOAO).
where $M$ represents the $V$- or $R$-band magnitude, as appropriate, $m_{CL}$ and $m_{LP}$ are the instrumental $AB$ magnitudes measured in the CL and LP filters, $K_M$ is the appropriate zero point, $v_{CL}$ and $v_{LP}$ are the central frequencies of the CL and LP filters, and

$$\beta = -0.4(m_{CL} - m_{LP})/\log_{10}(v_{CL}/v_{LP}).$$

3.2. Photometry of the Optical Afterglow

We estimated the total $AB$ magnitude of the OA on both the CL and the LP images by using the DAOPHOT/ALLSTAR (Stetson 1987) photometry package. A point-spread function (PSF) was constructed in the manner described in §4 of Holland & Hjorth (1999). The OA was identified by matching the coordinates of the OA given by Sahu et al. (2000) to the CL and LP STIS images, and looking for point sources inside the Sahu et al. (2000) error circle (see Fig. 1). The ALLSTAR "sharp" statistic is related to the angular size of an object relative to a PSF. Isolated point sources will have "sharp" values of ~ 0 while extended sources will have "sharp" values > 0.1. The only point source ("sharp" = 0.000 in the CL filter and 0.053 in the LP filter) on the STIS images that lies within the error circle is located $0''033 (= 1.3$ drizzled STIS pixels) from the Sahu et al. (2000) position for the OA. Therefore, we conclude that this point source is the OA for GRB 990712. The brighter, point-like feature $0''24$ to the southeast of the OA has "sharp" = 0.990 in the CL filter which suggests that it is the nucleus of the galaxy and not a point source (see § 5).

Aperture corrections were performed by using the DAOPHOT II ADDSTAR routine to generate an artificial star with the same instrumental magnitude as the OA and measuring the total flux in apertures with radii of $r''108$ (CL) and $r''963$ (LP). Tables 14.3 and 14.5 of the STIS Instrument Handbook suggest that these radii correspond to 100% of the encircled energy in the PSF. The OA magnitudes are $V = 25.69 \pm 0.02$ and $R = 25.23 \pm 0.09$, which yields a color of $V - R = 0.46 \pm 0.09$. The Galactic reddening towards the OA ($E_{B-V} = 0.033$) is $A_V = 0.11$ and $A_R = 0.08$ to obtain extinction-corrected magnitudes of $V_0 = 25.58 \pm 0.02$ and $R_0 = 25.15 \pm 0.09$.

A visual examination of each STIS image, after the PSF for the OA has been subtracted, shows that we have slightly oversubtracted the OA. We estimate that this oversubtraction has resulting in our magnitudes being overestimated by at most 0.23 mag in the $V$ band and 0.40 mag in the $R$ band. Therefore, the true magnitudes of the OA are $V_0 = 25.58-25.81$ and $R_0 = 25.15-25.55$. The corresponding range in color is $(V-R)_0 = 0.26-0.43$, and in spectral index is $-1.24 \leq \beta_{OA} \leq -0.37$.

4. Spectroscopy of the Host

We used the ESO Faint Object Spectrograph and Camera 2 (EFOSC2), mounted at the cassegrain focus of the ESO 3.6-m telescope, to obtain a 30-minute optical spectrum of the host galaxy of GRB 990712 on 12 November 1999 UT. The weather conditions were good, with 0.7" seeing and photometric sky. We observed in binned mode, with an effective pixel size of $0''32$ and a resolution of 4.28 Å/pixel (or $R \sim 550$) between 4000 Å and 8000 Å. The slit was $1''02$ wide and oriented along the parallactic angle. The data were reduced with IRAF and the CTIO long-slit package. A spectrum of the standard star ETT9491 (Landolt 1992) was used to perform the relative flux calibration. As the standard was observed with a relatively narrow slit ($1''02$), we tied the absolute flux calibration to our measurement of the $V$-band flux for the galaxy.

The spectrum (Fig. 2) exhibits four prominent narrow (unresolved) emission lines which we identify as $[O II]\lambda 3727$, H$\beta$ $\lambda 4861$, and $[O III]\lambda 4959,5007$. Table 1 lists the observed- and rest-frame wavelengths, $\lambda$ and $\lambda_0$, the redshifts, $z$, the observed- and rest-frame line widths, $W$ and $W_0$, and the line fluxes, $f$, for each line. The mean redshift derived from these lines is $z = 0.4337 \pm 0.0004$ where the uncertainty is the $1\sigma$ uncertainty in the mean. We detect no trace of stellar absorption features such as the Ca H and K ($\lambda\lambda 3968,3933$) lines or the 4000 Å break, and we do not detect any obvious intervening absorption systems along the line of sight.

We note that the $[O III]\lambda 5007$ line lies near at the red edge of the bandpass of the $R$ filter. This may complicate the interpretation of late-time $R$-band light curves of the OA when the data is collected using different instruments, and when the total flux is dominated by the light of the host galaxy.
TABLE 1
Emission line identifications and fluxes

<table>
<thead>
<tr>
<th>Line</th>
<th>$\lambda$ (Å)</th>
<th>$\lambda_0$ (Å)</th>
<th>$z$</th>
<th>$W$ (Å)</th>
<th>$W_0$ (Å)</th>
<th>$f$ (10^{-17} erg s^{-1} cm^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>[O II]</td>
<td>5345.48</td>
<td>3727.4</td>
<td>0.4341</td>
<td>66 ± 10</td>
<td>46 ± 7</td>
<td>6.5</td>
</tr>
<tr>
<td>H/β</td>
<td>6562.80</td>
<td>4861.3</td>
<td>0.4336</td>
<td>30 ± 5</td>
<td>21 ± 3.5</td>
<td>2.5</td>
</tr>
<tr>
<td>[O III]</td>
<td>7318.68</td>
<td>4958.9</td>
<td>0.4335</td>
<td>75 ± 10</td>
<td>52 ± 7</td>
<td>4.6</td>
</tr>
<tr>
<td>[O III]</td>
<td>7177.00</td>
<td>5006.9</td>
<td>0.4336</td>
<td>195 ± 30</td>
<td>136 ± 21</td>
<td>10.9</td>
</tr>
</tbody>
</table>

Fig. 1.— This figure shows the central 3.25′ × 3.25′ section of the drizzled 50CCD (clear) HST/STIS image. The scale is 0″0254 per pixel. The arrow indicates north and the line indicates east. Both lines are 0.5 long. The circle shows the error circle from matching the coordinates of the OA given in Sahu et al. (2000) to the CL image. The OA is the only point source in this error circle.

Fig. 2.— This figure shows the EFOSC2 spectrum of the host galaxy, obtained 123 days after the burst. The absolute flux calibration has been derived from our V-band photometry of the galaxy. The spectral resolution is $R \sim 550$ (4.28 Å per pixel). The line widths and ratios indicate that the host may be a Seyfert 2 galaxy.
5. The Host Galaxy

The host galaxy is an extended source with elliptical isophotes, a bright, concentrated nucleus, and a bright, extended feature to the northwest of the nucleus. The nucleus has a FWHM of 0′′11 (≈ 0.62 kpc) in the CI filter, which is only slightly wider than the PSF. There is some indication that the isophotes twist to the north at the northwest end of the galaxy and to the south at the southeast end.

The integrated $V$- and $R$-band magnitudes of the galaxy were obtained by subtracting the light from the OA and performing aperture photometry with an aperture of radius 2′′5 in each of the CI and LP images. The measured spectral index is $\beta_{\text{rad}} = -2.69$, and Eq. 1 yields $V = 22.51 \pm 0.04$ and $R = 21.89 \pm 0.06$. Correcting for Galactic extinction, and assuming no internal extinction in the host galaxy, gives $(V-R)_0 = 0.68 \pm 0.07$. For $z = 0.4337$ the observed $R$-band is approximately equivalent to the rest-frame $B$-band, so $\mu_B \approx -19.5$. Lilly et al. (1995) finds $M_B = -21.23$ in the rest frame for blue galaxies with redshifts of $0.2 \leq z \leq 0.5$. This corresponds to the host galaxy for GRB 990712 having $L_B \sim 0.24L_B$ where $L_B$ is the $B$-band luminosity of a typical blue galaxy at $z = 0.4337$.

We estimated the star-formation rate (SFR) in the host galaxy using Eq. 2 of Madan et al. (1998) as described in Holland & Hjorth (1999). The total SFR is $0.29-0.45M_\odot \text{yr}^{-1}$, depending on the assumed initial mass function (IMF). The SFR is corrected for extinction in our Galaxy, but it assumes that there is no dust, or obscured star formation, in the host galaxy. This is probably a poor assumption so our derived SFR should be considered to be a lower limit on the true SFR in the host. The implied [O II] luminosity (Table 1), corrected for Galactic extinction, is $L_{\text{O II}} = 6.3 \times 10^{44}$ erg s$^{-1}$. If we assume that the strength of the [O II] line is related to star formation, then this corresponds to a SFR of $0.88 \pm 0.25M_\odot \text{yr}^{-1}$ (Kennicutt 1998). This is 2–3 times less than the SFR derived from the continuum flux, possibly indicating internal extinction in the host or a contribution from non-thermal emission. The derived SFR (from the [O II] flux) is $\sim 20\%$ of the SFR found by Bloom et al. (1999b) for the host of GRB 990123 and comparable to that of the host of GRB 970508 (Bloom et al. 1998). The specific SFR per unit luminosity of the GRB 990712 host galaxy is $\sim 0.4$ times that of the host galaxies of GRB 990123 and GRB 970508.

The OA is located in the bright, extended source $\theta_C 242$ (≈ 1.4 kpc) to the northwest ($\sim 50^\circ$ north of east) of the nucleus (see Fig. 1). This region has a FWHM of $\theta_C 28$ (≈ 1.6 kpc), which is significantly more extended than the STIS PSF (FWHM $\approx 0.09$). The surface brightness, after subtracting the OA and correcting for Galactic extinction, is $\mu_{\text{V,0}} = 15.83 \pm 0.01$ and $\mu_{\text{R,0}} = 15.04 \pm 0.01$ for an integrated color of $(V-R)_0 = 0.79 \pm 0.01$. The OA is located $\sim 0.025$ (≈ 140 pc) south of the center of this extended structure.

The total $V$-band flux in the feature, after subtracting the flux from the [O II] emission line, is $0.323 \pm 0.063\mu$Jy. Assuming a power-law spectrum with $\beta = -2.93$ the SFR is $0.03-0.05M_\odot \text{yr}^{-1}$ depending on the IMF. Again, we wish to stress that this is a lower limit on the true SFR in the feature. The estimated SFR is approximately one third of the SFR that Holland & Hjorth (1999) found for the star-forming region that coincides with the position of GRB 990123 where as the diameters and luminosities are comparable.

The spectroscopic data demonstrate that all emission lines, both forbidden and permitted, have narrow widths that are consistent with a Seyfert 2 galaxy (the instrumental resolution only gives an upper limit on the rest-frame velocity widths of a few hundred km s$^{-1}$). The ratio [O III]/H$\beta$ is greater than three, which is indicative of an active galaxy (Shuder & Osterbrock 1981). The object lies on the borderline between H II regions and narrow-line AGNs in the log([O III]/H$\beta$) vs. log([O II]/[O III]) diagram—uncorrected for extinction, see Baldwin et al. (1981). This suggests that the host galaxy of GRB 990712 may be a Seyfert 2 galaxy, but further spectroscopic observations will be needed to confirm this. For example, a measurement of log([O II]/H$\alpha$) from near-IR spectroscopy would discriminate between a star-forming galaxy or a Seyfert 2 (Veilleux & Osterbrock 1987).
6. The Late Afterglow and the Possible GRB 990712–Supernova Association

Table 2 summarizes the predicted and observed V- and R-band magnitudes for the OA and its host galaxy in both the pure power-law (PL), and power law + supernova (PL+SN) scenarios. The magnitudes for the host galaxy are the weighted means of the magnitudes that we obtained from the Danish 1.54-m and ESO 3.6-m telescopes, and the HST. Allowing for small systematic uncertainties, the observed magnitudes and colors for the host and OA are consistent with the predictions of the pure power-law model, which indicates that the OA followed a slow power-law decay with a constant index of $\alpha \sim -1.0$, with no significant late-time break towards steeper decay. Our results are inconsistent with the presence of a SN like SN1998bw. The discrepancy between the observations and the predictions of the PL+SN scenario suggests that a SN in the late-time light curve of GRB 990712 would have had to be $> 1.5$ mag fainter than SN1998bw to be consistent with the data presented in this Letter. Therefore, we conclude that either GRB 990712 did not produce a SN, or that the flux received from the SN was much smaller than expected from scaling SN1998bw to $z = 0.4337$.

If there was no SN then this supports the view that long-duration GRBs have more than one type of progenitor (Livio & Waxman 1999). GRB 970508 is the only other GRB for which there is some evidence that a SN was not present. However, the paucity of observations around the time of the predicted peak luminosity of the SN makes it difficult to unambiguously rule out a SN contribution in GRB 970508’s light curve. Therefore, GRB 990712 provides the first solid evidence that not all long-duration GRBs are associated with standard-candle SNe. There are some similarities between GRB 990712 and GRB 970508 that suggest that they may be members of the same class of bursts. Both had shallow late-time decay slopes ($\alpha \sim -1.0$), both appear to lack a 1998bw-type SN, both bursts were strong X-ray sources, and both bursts have host galaxies that are significantly fainter than $L^*$.

If there was a SN associated with GRB 990712, then its peak intensity was $> 1.5$ mag fainter than that of SN1998bw. Type Ib/c SNe are poor standard candles since their predicted peak intensities can vary by 1–2 mag, with a mean peak $B$-band magnitude that is 1.16 mag fainter than that of SN1998bw (van den Bergh & Tammann 1991). Moreover, the predicted peak magnitude for a SN associated with GRB 990712 depends on the cosmological model, the exact spectral shape of SN1998bw at very short wavelengths, the width of the lightcurve peak, the possible extinction in the host galaxy, and the possible evolution of SNe with redshift. A large sample of GRB afterglows with measured redshifts and detectable SN signatures is needed to establish the intrinsic luminosity distribution of SNe accompanying GRBs.

FC is supported by Chilean grant Fondecyt/3990024. Additional funding from the European Southern Observatory is gratefully acknowledged. This work was supported by the Danish Natural Science Research Council (SNF).
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