

THE REDSHIFT OF THE OPTICAL TRANSIENT ASSOCIATED WITH GRB 010222

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ABSTRACT

The gamma-ray burst (GRB) 010222 is the brightest GRB detected to date by the *BeppoSAX* satellite. Prompt identification of the associated optical transient (OT) allowed for spectroscopy with the Tillinghast 1.5 m telescope at F. L. Whipple Observatory while the source was still relatively bright ($R \approx 18.6$ mag), within 5 hr of the burst. The OT shows a blue continuum with many superposed absorption features corresponding to metal lines at $z = 1.477$, 1.157, and possibly also 0.928. The redshift of GRB 010222 is therefore unambiguously placed at $z \geq 1.477$. The high number of Mg II absorbers and especially the large equivalent widths of the Mg II, Mg I, and Fe II absorption lines in the $z = 1.477$ system further argue either for a very small impact parameter or that the $z = 1.477$ system is the GRB host galaxy itself. The spectral index of the OT is relatively steep, $F_\nu \propto \nu^{-0.89 \pm 0.03}$, and this cannot be caused by dust with a standard Galactic extinction law in the $z = 1.477$ absorption system. This spectroscopic identification of the redshift of GRB 010222 shows that prompt and well-coordinated follow-up of bright GRBs can be successful even with telescopes of modest aperture.

Subject headings: galaxies: distances and redshifts — galaxies: ISM — gamma rays: bursts — ultraviolet: galaxies

1. INTRODUCTION

Since the discovery of gamma-ray bursts (GRBs; Klebesadel, Strong, & Olson 1973), their nature has proved enigmatic. The *Compton Gamma Ray Observatory* and BATSE observations demonstrated they were isotropically distributed on the sky (Meegan et al. 1992), which could have been explained by either Galactic (Lamb 1995) or cosmological (Paczynski 1995) spatial distributions. The *BeppoSAX* satellite (Boella et al. 1997) contributed the breakthrough in this field by providing rapid localizations of the X-ray afterglow of a GRB to a precision of several arcminutes. Such precision allowed for rapid optical (van Paradijs et al. 1997) and radio (Frail et al. 1997) identifications of transients associated with individual GRBs. The identification of the optical transient (OT) associated with GRB 970508 (Bond 1997; Djorgovski et al. 1997) led to the first optical spectroscopic redshift determination for a GRB, placing it at $z \geq 0.835$ (Metzger et al. 1997) and thus firmly at a cosmological distance.

Despite such rapid progress and intensive follow-up campaigns at many wavelengths, only some GRBs have had associated X-ray, optical, or radio afterglows, and all of these events have been among the “long-duration” GRB population (Kulkarni et al. 2000). Of these, only ~ 15 have had unambiguous spectroscopic redshift identification (see those to date tabulated by Bloom, Kulkarni, & Djorgovski 2001b). The primary difficulty is the combined delays imposed by the time necessary to improve the X-ray localizations, interruption of a telescope observing program to obtain optical imaging data, reduction and analysis of those data relative to POSS images to identify the OT, and interruption of another telescope observing program to obtain a spectrum (usually on a different telescope, since there are very few combined imaging and spectrograph instruments). By the

time a spectrum is taken, the OT has usually faded significantly, generally limiting such follow-up observations to only the largest available ground-based optical telescopes or the *Hubble Space Telescope*. Furthermore, observational conditions may not be optimal immediately after a GRB event, such that only approximately half of the known GRB redshifts were obtained with spectroscopy of the OT itself—the others were obtained at later times from the presumptive host galaxy, after the OT had faded.

Here we report the rapid identification of an OT associated with GRB 010222 and the spectroscopy of the source within 5 hr after the GRB occurred. The quick localization of the X-ray and OTs allowed for spectroscopic observations on a modest 1.5 m telescope, the smallest aperture telescope to measure the redshift of a GRB to date.

2. DATA

GRB 010222 was detected by the Gamma-Ray Burst Monitor and Wide Field Camera 1 instruments on board *BeppoSAX* at 07:23:30 UT on 2001 February 22 (Piro 2001). An OT associated with GRB 010222 was reported within several hours by Henden (2001a, 2001b). McDowell et al. (2001) provided independent confirmation of the OT from images taken with the F. L. Whipple Observatory (FLWO) 1.2 m telescope and 4Shooter CCD mosaic camera (A. H. Szentgyorgyi et al. 2001, in preparation). The identification of the OT ($\alpha = 14^{\text{h}}52^{\text{m}}12^{\text{s}}.54$, $\delta = +43^{\circ}01'06''.2$, J2000.0) on these latter discovery images is shown in Figure 1.

A spectrum of the OT was obtained with the FLWO 1.5 m Tillinghast telescope beginning at UT 2001 February 22 12:18, 4.92 hr after the burst. The OT apparent magnitude was $R \approx 18.6$ mag around the time of the spectroscopy (McDowell et al. 2001; Henden 2001c). Despite the faintness of the OT, it was visible on the telescope acquisition camera, such that it could be unambiguously identified and placed on the spectrograph slit. The observations were made with the FAST spectrograph (Fabricant et al. 1998) using a 3" wide slit and 300 line mm^{-1} grating, yielding 6 Å FWHM resolution over the range $3720 \text{ \AA} < \lambda < 7540 \text{ \AA}$. Two 1200 s exposures were taken with the slit rotated to the parallactic angle (and moreover the air mass

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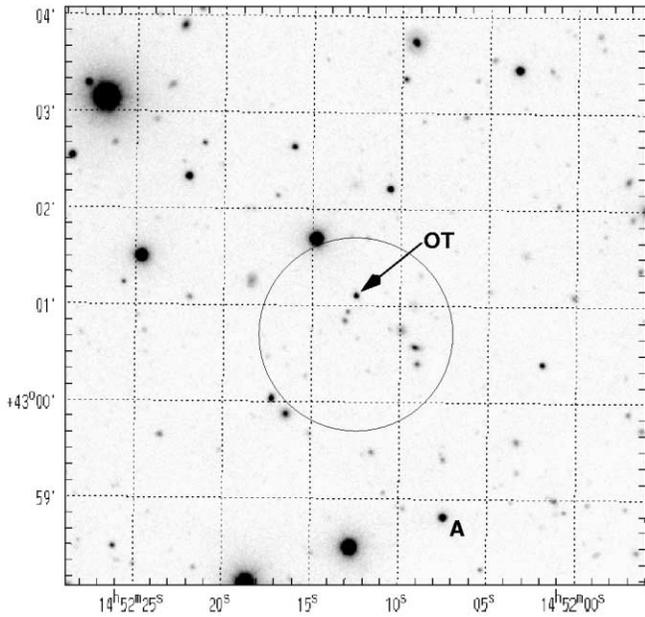


FIG. 1.—Identification of the OT associated with GRB 010222. This 600 s R_C -band image, taken with the FLWO 1.2 m telescope (+4Shooter) beginning at UT 2001 February 22 12:12, shows the OT and comparison star A of McDowell et al. (2001). The image covers 6' on a side, with north up and east to the left. The position error circle from the *BeppoSAX* follow-up of the X-ray afterglow (Gandolfi 2001) is also shown.

was ≤ 1.04), reduced in the standard manner with an optimal extraction (Horne 1986), and combined. Wavelength calibration was provided via HeNeAr lamp spectra taken immediately after the OT exposures, with minor adjustment based on night-sky lines in the OT frames. We corrected for telluric lines (Wade & Horne 1988) and flux-calibrated the spectra with exposures of the spectrophotometric standard star Hiltner 600 (Stone 1977), also taken at the parallactic angle, yielding relative fluxes in our OT spectrum accurate to $\sim 5\%$ over the observed wavelength range. The discovery spectrum is shown in Figure 2, and preliminary results from it have been reported previously (Garnavich et al. 2001; Jha et al. 2001). Four additional spectra of 1800 s each were obtained the following night (UT 2001 February 23) when the OT had faded by ~ 1.5 – 2 mag (Stanek et al. 2001). The dispersed spectrum was at the detection threshold of the spectrograph; hence, no reliable results could be obtained from these data.

3. RESULTS

The optical spectrum of GRB 010222 in Figure 2 shows a blue continuum that is typical for GRBs. Superposed on this continuum are a number of strong and weak absorption line systems at $z = 1.157$ and 1.477 , which are identified by the metallic lines of Mg I, Mg II, Fe II, Mn II, Si II, Al II, Zn II, Cr II, and C IV. Two additional lines are tentatively identified with Mg II at $z = 0.928$ because these lines are weaker and no other lines are found at a similar redshift (although the signal-to-noise ratio [S/N] is worse at these shorter wavelengths). All three systems were independently detected by Bloom et al. (2001a) and confirmed by Castro et al. (2001) from spectroscopy at the Keck Observatory. Our line identifications are summarized in Table 1; as is typical for metal-line absorption systems, the Mg II lines are the strongest in the

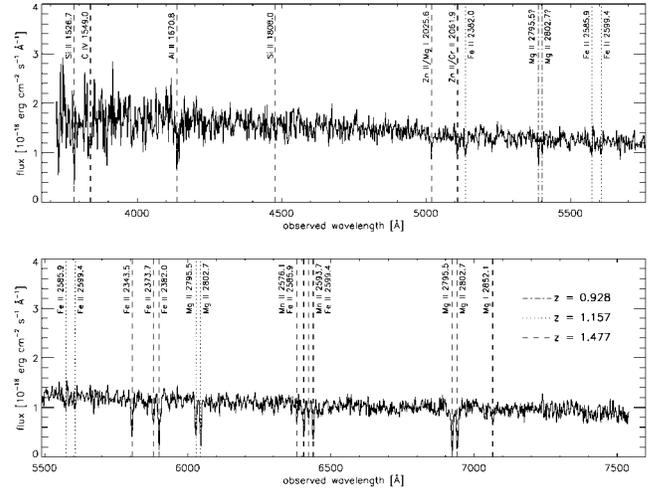


FIG. 2.—Discovery spectrum of the OT associated with GRB 010222 taken with the FLWO 1.5 m telescope (+FAST spectrograph) on UT 2001 February 22, approximately 5 hr after the GRB. The OT has a blue continuum spectrum with two absorption systems at $z = 1.157$ (dotted vertical lines) and 1.477 (dash-dotted vertical lines). Various redshifted metal absorption features are labeled. Two absorption lines at $\lambda = 5389.1$ and 5402.2 Å (dash-dotted vertical lines) may be due to an additional Mg II system at $z = 0.928$. The redshift of GRB 010222 is therefore constrained to lie at $z \geq 1.477$. If the highest redshift absorption lines correspond to the host galaxy of the OT, then the redshift of GRB 010222 is $z = 1.477$.

spectrum, nearly reaching zero flux for the highest redshift system even at this relatively low spectral resolution.

The redshift of GRB 010222 is therefore unambiguously $z \geq 1.477$, corresponding to the most distant absorber. Furthermore, the nondetection of Ly α forest absorption or continuum decrement at $\lambda > 4000$ Å would suggest the GRB host is at $z < 2.3$, although this is not a firm constraint given the S/N of the data. If the highest redshift lines are from the GRB host itself, then the GRB is at $z = 1.477$. Several other GRB OTs have shown absorption-line systems that have been argued to arise from the interstellar medium of the GRB host galaxy: GRB 090508 (Metzger et al. 1997), GRB 980703 (Djorgovski et al. 1998), GRB 990123 (Kulkarni et al. 1999), GRB 990510 and GRB 990712 (Vreeswijk et al. 2001), and GRB 991216 (Vreeswijk et al. 1999).

While Mg II absorption systems are commonly found along the line of sight to distant quasi-stellar objects, the three detected at 3800 Å $< \lambda < 7500$ Å—corresponding to a redshift interval of $0.36 < z < 1.68$, or $\Delta z = 1.32$ —is significantly larger than the mean of $\langle N/z \rangle = 0.97$ (Steidel & Sargent 1992). Moreover, that value was derived based on systems with an Mg II $\lambda 2796$ rest-frame equivalent width $W_0(\lambda 2796) \geq 0.3$ Å, measured with generally similar spectral resolution as the observations presented here. Although our detection threshold for this line is difficult to determine a priori, it is likely at least 0.6 Å, and Steidel & Sargent (1992) find an average of $\langle N/z \rangle = 0.52$ for systems with such strong absorption [$W_0(\lambda 2796) \geq 0.6$ Å]. Thus, there is quite a discrepancy between the expectation of ~ 0.7 systems over the observed wavelength region compared to the three systems actually detected. This discrepancy would be mitigated if the $z = 1.477$ system were the host galaxy of the GRB.

In addition, the $z = 1.477$ system has an unusually large rest-frame equivalent width of the Mg II $\lambda 2796$ line of $W_0(\lambda 2796) = 3.0 \pm 0.2$ Å, which is larger than all 111 systems found by Steidel & Sargent (1992). The $z = 1.157$ system equivalent width places it in the top 10%, while the $z =$

TABLE 1

ABSORPTION-LINE IDENTIFICATIONS IN THE SPECTRUM OF GRB 010222

Observed Wavelength (Å)	Line Identification	Rest Wavelength (Å)	Rest-Frame Equivalent Width (Å)	Redshift
7065.4	Mg I	2852.1	0.9 ± 0.2	1.477
6941.7	Mg II	2802.7	2.7 ± 0.2	1.477
6924.0	Mg II	2795.5	3.0 ± 0.2	1.477
6438.5	Fe II	2599.4	1.9 ± 0.2	1.477
6422.4	Mn II	2593.7	0.7 ± 0.2	1.476
6405.4	Fe II	2585.9	1.5 ± 0.2	1.477
6381.2	Mn II	2576.1	0.7 ± 0.2	1.477
5900.1	Fe II	2382.0	2.4 ± 0.2	1.477
5879.6	Fe II	2373.7	1.2 ± 0.2	1.477
5805.4	Fe II	2343.5	1.8 ± 0.2	1.477
5108.5	Zn II/Cr II blend	2061.9	0.7 ± 0.3	1.478
5018.5	Zn II/Mg I blend	2025.6	1.0 ± 0.3	1.478
4478.9	Si II	1808.0	0.5 ± 0.3	1.477
4137.8	Al II	1670.8	1.1 ± 0.3	1.477
3838.0	C IV blend	1549.0	1.9 ± 0.4	1.478
3781.8	Si II	1526.7	1.4 ± 0.4	1.477
6045.0	Mg II	2802.7	2.1 ± 0.2	1.157
6028.2	Mg II	2795.5	1.9 ± 0.2	1.156
5606.7	Fe II	2599.4	0.5 ± 0.3	1.157
5574.1	Fe II	2585.9	0.6 ± 0.3	1.156
5137.2	Fe II	2382.0	1.2 ± 0.3	1.157
5402.2	Mg II?	2802.7	0.6 ± 0.3	0.927
5389.1	Mg II?	2795.5	0.9 ± 0.3	0.928

0.928 system is more typical. The Mg II doublet ratios $W_0(\lambda 2796)/W_0(\lambda 2803)$ are 1.1 ± 0.3 , 0.9 ± 0.3 , and 1.5 ± 0.4 for systems with redshifts of 1.477, 1.157, and 0.928, respectively; these values are typical of the anticorrelation between $W(\lambda 2796)$ and the doublet ratio, indicating the lines are strongly saturated (Steidel & Sargent 1992). The Fe II and Mg I equivalent widths for the $z = 1.477$ system are likewise unusually strong (Churchill et al. 2000). Since these absorption-line strengths for the $z = 1.477$ system are so large, either the impact parameter is extremely small or this system represents the OT host galaxy. Nearly all of the absorption-line systems in GRB OTs show substantially weaker lines than the $z = 1.477$ system [the host of GRB 990712 is the lone exception, with an equivalent width of $W_0(\lambda 2796) + W_0(\lambda 2803) = 9 \text{ \AA}$; Vreeswijk et al. 2001], further strengthening the case that the high-redshift system is the OT host.

To make these arguments more quantitative, we calculate the Bayesian odds ratio for the following two hypotheses (assumed to be equally likely a priori): H_1 , that the OT is at redshift $z > 1.477$ with three foreground absorption systems; and H_2 , that the OT is at redshift $z = 1.477$ with two foreground absorption systems. For H_1 , the redshift path length for detection of absorption systems is our full spectral window,³ $\Delta z = 1.32$, implying, as above, an expectation of $\bar{N} = 0.52 \times 1.32 = 0.69$ absorption systems, assuming a detection threshold of $W_0 \geq 0.6 \text{ \AA}$ (Steidel & Sargent 1992). For H_2 , the redshift path has an upper bound at $z = 1.477$, yielding $\Delta z = 1.12$ and $\bar{N} = 0.52 \times 1.12 = 0.58$. The observed number of systems follows a simple Poisson distribution, and so the Bayesian odds $p(H_2)/p(H_1)$ are given by $[P(N = 2; \bar{N} = 0.58)/P(N = 3; \bar{N} = 0.69)] = 3.4$, indicating that H_2 is more than 3 times as likely as H_1 under the given assumptions. In addition to the *number* of observed absorption systems, we can also

³ Actually, this leads to a very slight overestimate of the likelihood of H_1 , because the spectral window for detecting foreground Mg II is less than our observed wavelength range if the OT redshift is $z \leq 1.7$. This only strengthens the argument presented.

take into account their *strength*, by adopting the Mg II $\lambda 2796$ equivalent width distribution function of Steidel & Sargent (1992): $n(W_0)dW_0 \propto \exp(-W_0/W_0^*)dW_0$ with $W_0^* = 0.66 \text{ \AA}$ (a good fit to the data for $W_0 \geq 0.6 \text{ \AA}$, our detection threshold⁴). Because of the rarity of absorption systems as strong as the one detected at $z = 1.477$, incorporating the line strengths into the calculation increases the Bayesian odds favoring H_2 over H_1 to 28 : 1. Thus, there is strong support for the identification of the $z = 1.477$ system as the host of GRB 010222.

Beyond the absorption systems along the line of sight, we also use the observed spectrum to measure the spectral power-law index of the OT. The continuum flux is overwhelmingly dominated by the OT, so contamination from an underlying host or other objects on the slit is negligible. After correcting for Galactic extinction, $E(B-V) = 0.023 \text{ mag}$ (Schlegel, Finkbeiner, & Davis 1998), adopting a standard $R_V = 3.1$ extinction law (Cardelli, Clayton, & Mathis 1989), we bin the spectrum into 10 segments (excluding the absorption lines), using the rms deviation in each bin as an estimate of the uncertainty, as shown in Figure 3. We have adjusted the normalization to match the concurrent photometry (Stanek et al. 2001). A least-squares minimization yields a power-law index $\beta = 0.89 \pm 0.03$ (where $F_\nu \propto \nu^{-\beta}$). As mentioned above, additional uncertainty due to the relative flux calibration is likely to be small. The

⁴ Steidel & Sargent (1992) note that for the strongest absorbers, $n(W_0)$ seems to change with redshift, whereas we have assumed it to be fixed over the redshift range $0.35 \leq z \leq 1.7$. However, we do not expect significant changes in the results taking this evolution into account, because the mean redshift of the absorber population that Steidel & Sargent (1992) used to derive $n(W_0)$, ($z_{\text{abs}} = 1.17$, well matches our observable redshift range.

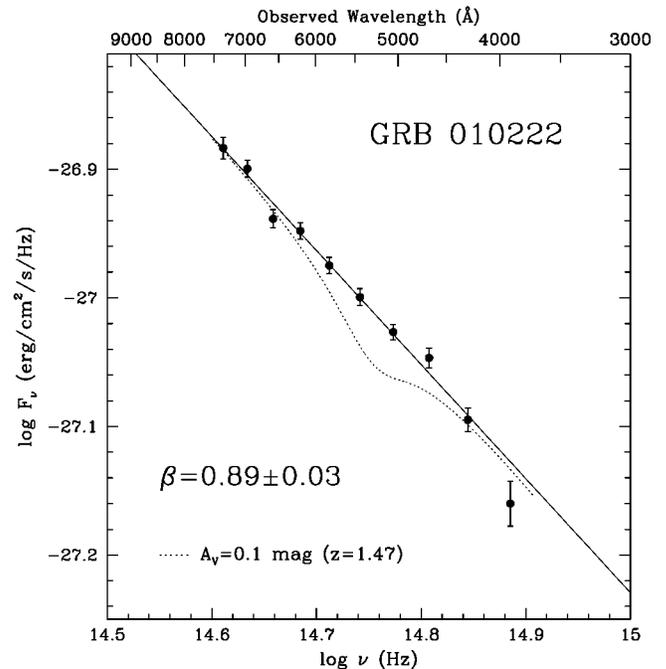


FIG. 3.—Continuum flux of the OT associated with GRB 010222 based on the FLWO 1.5 m spectrum. The observed flux has been corrected to match the FLWO 1.2 m photometry from the same epoch (Stanek et al. 2001). The solid line shows the best-fit continuum slope, $F_\nu \propto \nu^{-\beta}$, with $\beta = 0.89 \pm 0.03$. The dotted line shows the effect of 0.1 mag of visual extinction from the host galaxy, assuming an $R_V = 3.1$ extinction law and $z = 1.477$ for GRB 010222. The lack of a dust feature like the $\lambda 2175$ bump suggests either that there is very little extinction from the $z = 1.477$ system or that the extinction law differs from the standard Galactic extinction law.

spectral slope is rather steep in comparison to early observations of other bright GRB afterglows. For example, GRB 990510 had a $\beta \approx 0.5$ less than 1 day after the burst (Stanek et al. 1999), and GRB 991216 had $\beta \approx 0.6$ after a correction for large Galactic extinction (Garnavich et al. 2000). On the other hand, GRB 000926 exhibited a very steep spectral slope with an index of 1.5, which was attributed to significant dust extinction along the line of sight (Price et al. 2001).

The steep spectral slope for GRB 010222 may also indicate significant extinction from dust in the host galaxy. Furthermore, jet models by Sari, Piran, & Halpern (1999) predict a shallower spectral index than we observe given the reported light-curve decline rates (for details, see Stanek et al. 2001), also suggesting significant extinction. However, as shown in Figure 3, the spectrum exhibits no clear evidence for the $\lambda 2175$ “bump,” typical of Galactic interstellar dust (Cardelli et al. 1989), which falls in the observed spectral region for $z = 1.477$. Such a feature would be easily detectable even at levels $A_V \approx 0.1$ mag. Thus, we conclude that there is no significant extinction from Galactic-type dust in the $z = 1.477$ absorption system. However, substantial extinction from dust with an extinction law like that found in the SMC could still account for the steep

spectral slope, as such dust does not show a significant $\lambda 2175$ feature (Prévot et al. 1984). An SMC-like extinction curve may be a more natural choice if GRBs come from young stellar environments, since dust in starburst galaxies tends to lack the $\lambda 2175$ bump (Gordon, Calzetti, & Witt 1997).

In summary, through photometric and spectroscopic observations of GRB 010222 soon after the burst at the FLWO 1.2 and 1.5 m telescopes, we have been able to identify the associated OT and constrain its redshift, $z \geq 1.477$. We further argue that the $z = 1.477$ absorption system seen in the OT spectrum is likely the host galaxy itself. If the steep spectral index of the OT is a result of extinction in the $z = 1.477$ system, the extinction law differs from standard Galactic extinction.

We are grateful to the entire *BeppoSAX* team for the quick turnaround in providing precise GRB positions to the astronomical community as well as to Scott Barthelmy and the GRB Coordinates Network (GCN). That these results could be obtained with small aperture telescopes is entirely due to the speed in which positions are reported and disseminated.

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