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SPECTROSCOPIC DISCOVERY OF THE SUPERNOVA 2003dh ASSOCIATED WITH GRB 030329[1]

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ABSTRACT

We present early observations of the afterglow of GRB 030329 and the spectroscopic discovery of its associated supernova SN 2003dh. We obtained spectra of the afterglow of GRB 030329 each night from March 30.12 (0.6 days after the burst) to April 8.13 (UT) (9.6 days after the burst). The spectra cover a wavelength range of 350–850 nm. The early spectra consist of a power-law continuum ($F_\nu \propto \nu^{-0.9}$) with narrow emission lines originating from H II regions in the host galaxy, indicating a low redshift of $z = 0.1687$. However, our spectra taken after 2003 April 5 show broad peaks in flux characteristic of a supernova. Correcting for the afterglow emission, we find that the spectrum of the supernova is remarkably similar to the Type Ic "hypernova" SN 1998bw. While the presence of supernovae has been inferred from the light curves and colors of gamma-ray burst afterglows in the past, this is the first direct, spectroscopic confirmation that a subset of classical gamma-ray bursts originate from supernovae.

Subject headings: galaxies: distances and redshifts — gamma rays: bursts — supernovae: general — supernovae: individual (SN 2003dh)

1. INTRODUCTION

The origin of gamma-ray bursts (GRBs) has been a mystery since their discovery in the 1960s. It has only been since the *BeppoSAX* satellite (Boella et al. 1997) began providing rapid, accurate localization of several bursts per year that it has it been possible to study these events and their afterglows in detail. Optical observations of afterglows (e.g., GRB 970228: Groot et al. 1997; van Paradijs et al. 1997) have allowed redshifts to be measured for a number of GRBs (e.g., GRB 970508: Metzger et al. 1997), providing definitive proof of their cosmological origin. GRB 980425 was likely associated with SN 1998bw, and this was the first direct evidence that at least some GRBs result from the core collapse of massive stars (Galama et al. 1998). However, the isotropic energy of that burst was 10^{-3} to 10^{-4} times weaker (Woosley, Eastman, & Schmidt 1999) than classical cosmological GRBs, which placed it in a unique class. Indirect evidence of the connection between GRBs and massive stars has come from studies of the location of GRBs in their host galaxies (e.g., Holland & Hjorth 1999) and statistics on the types of galaxies that host GRBs (e.g., Hogg & Fruchter 1999). Chevalier & Li (1999) have shown that the afterglow properties of some GRBs are consistent with a shock moving into a stellar wind formed from a massive star.

Direct evidence of a classical GRB/supernova connection has been difficult to obtain because the typical redshift of a GRB is $z \sim 1$, meaning even powerful supernovae would peak at $R > 23$ mag. A number of GRBs have shown late deviations from a power-law decline (e.g., GRB 980326; Bloom et al. 1999), which are suggestive of a supernova peaking a few weeks after the burst. At $z = 0.36$, GRB 011121/SN 2001ke was a relatively nearby burst that showed a late-time bump and color changes consistent with a supernova (Garnavich et al. 2003c; Bloom et al. 2002). That burst was indeed the best evidence to date that classical, long gamma-ray bursts are generated by core-collapse supernovae, but it lacked a clear spectroscopic detection of a supernova signature. Detection of such a signature is reported in this Letter for GRB 030329.

The extremely bright GRB 030329 was detected by the French Gamma Ray Telescope, the Wide Field X-Ray Monitor, and the Soft X-Ray Camera instruments aboard the *High Energy Transient Explorer II* at 11:14:14.67 UT on 2003 March 29 (Vanderspek et al. 2003). The burst falls in the "long" category with a duration of more than 25 s. Peterson & Price (2003) and Torii (2003) reported the discovery of a very bright ($R \sim 13$), slowly fading (Uemura 2003) optical transient (OT), located at $\alpha = 10^{h}44^{m}50\overset{s}{.}0$, $\delta = +21°31'17\overset{''}{.}8$ (J2000.0) and identified this as the GRB optical afterglow. As a result of the brightness of the afterglow and its slow decay, photometric observations were extensive, making it one of the best-observed afterglows.

The afterglow was also very bright in X-rays (Marshall & Swank 2003), radio (Berger, Soderberg, & Frail 2003), submillimeter (Hoge et al. 2003), and infrared (Lamb et al. 2003).

[1] Based on data from the Multiple Mirror Telescope Observatory 6.5 m telescope, the Magellan 6.5 m Clay telescope, and the Fred Lawrence Whipple Observatory 1.5 m telescope.

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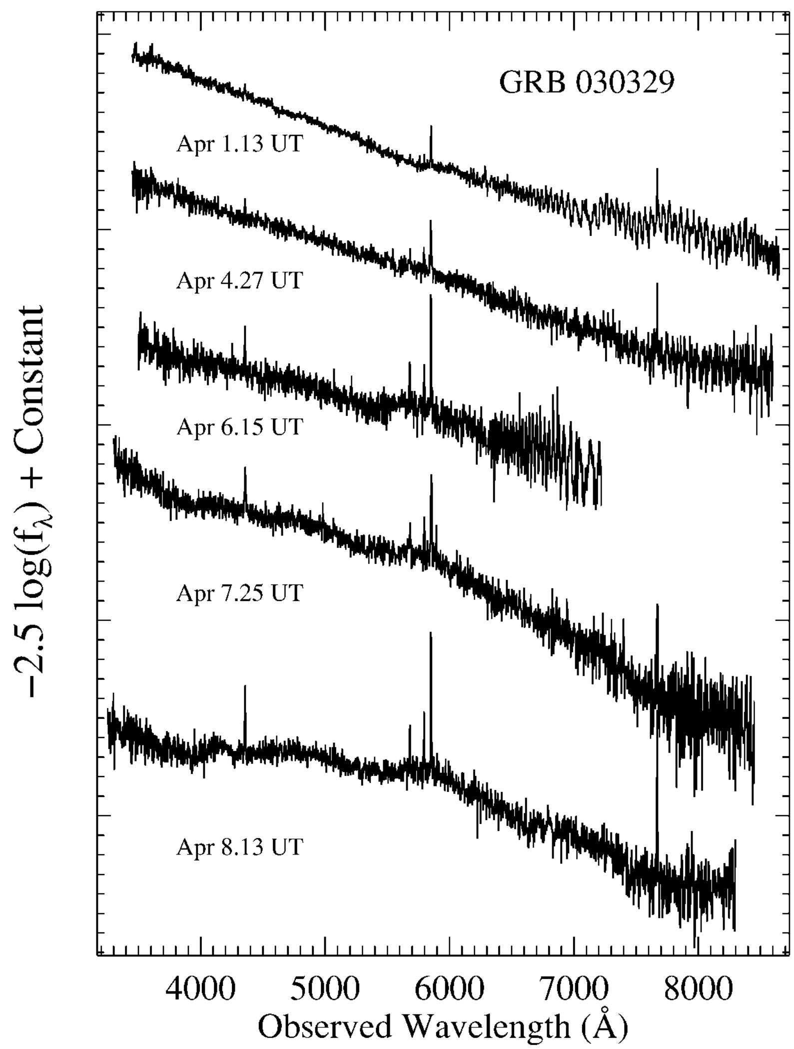

FIG. 1.—Evolution of the GRB 03029/SN 2003 spectrum, from April 1.13 UT (2.64 days after the burst) to April 8.13 UT (9.64 days after the burst). The early spectra consist of a power-law continuum ($F_\nu \propto \nu^{-0.9}$) with narrow emission lines originating from H II regions in the host galaxy at a redshift of $z = 0.168$. Spectra taken after April 5 show the development of broad peaks in the spectra characteristic of a supernova.

Using archival data, Blake & Bloom (2003) have put a 3 σ upper limit of $R = 22.5$ on the brightness of the host. Martini et al. (2003) were the first to report optical spectroscopy of the afterglow. Because the very bright OT overwhelmed the emission from the faint host galaxy, only a single emission line was detected and confirmed by Della Ceca et al. (2003), suggesting that this line may be due to [O II] provided a redshift of $z \approx 0.5$. However, a high-resolution Very Large Telescope spectrum by Greiner et al. (2003) revealed additional emission and also absorption lines that fixed the redshift at a very low $z = 0.1685$. This was later confirmed by Caldwell et al. (2003), making GRB 030329 the second nearest burst overall (GRB 980425 is the nearest at $z = 0.0085$) and the classical burst with the lowest known redshift.

2. OBSERVATIONS

From the moment the low redshift for the GRB 030329 was announced (Greiner et al. 2003), we started organizing a campaign of spectroscopic and photometric follow-up of the afterglow and later the possible associated supernova. Spectra of the OT associated with GRB 030329 were obtained over many nights with the 6.5 m Multiple Mirror Telescope (MMT), the 1.5 m Tillinghast telescope at the Fred Lawrence Whipple Observatory (FLWO), and the Magellan 6.5 m Clay telescope. The spectrographs used were the Blue Channel (Schmidt et al. 1989) at the MMT, FAST (Fabricant et al. 1998) at the FLWO 60 inch (1.5 m) telescope, and LDSS2[12] at Magellan. The observations were reduced in the standard manner with IRAF[13] and our own routines. Spectra were optimally extracted (Horne 1986). Wavelength calibration was accomplished with HeNeAr lamps taken immediately after each OT exposure. Small-scale adjustments derived from night-sky lines in the OT frames were also applied. We used Feige 34 (Stone 1977) and HD 84937 (Oke & Gunn 1983) as spectrophotometric standards. We attempted to remove telluric lines using the well-exposed continua of the spectrophotometric standards (Wade & Horne 1988; Matheson et al. 2000). The spectra were in general taken at or near the parallactic angle (Filippenko 1982). The relative fluxes are thus accurate to ∼5% over the entire wavelength range. Figure 1 shows a subset of our spectra. The initial report on

[12] J. Mulchaey 2001, http://www.ociw.edu/magellan_lco/instruments/LDSS2/.

[13] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

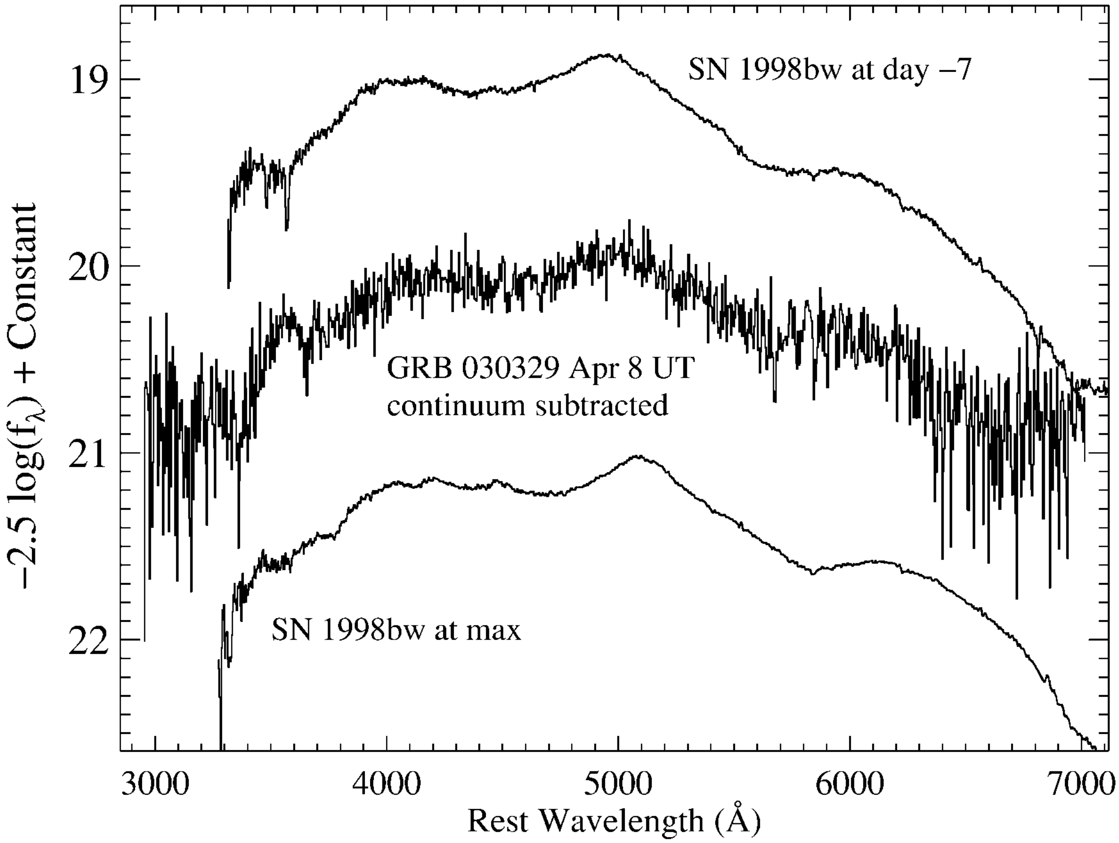

FIG. 2.—MMT spectrum of April 8 with the smoothed MMT spectrum of April 4 scaled and subtracted. The residual spectrum shows broad bumps at approximately 5000 and 4200 Å (rest frame), which is similar to the spectrum of the peculiar Type Ic SN 1998bw a week before maximum light (Patat et al. 2001). The match is not as good for SN 1998bw at maximum light, especially at the red end of the spectrum.

some of these data was presented by Martini et al. (2003) and Caldwell et al. (2003). Circulars by Matheson et al. (2003a, 2003b) and Garnavich et al. (2003a, 2003b) reported the first detection of the supernova associated with GRB 030329 (see § 3).

3. RESULTS

The brightness of the OT and its slow and uneven rate of decline, with episodes of increased brightness (well documented by many GCN circulars), allowed us to observe the OT every night since the GRB event (so far until April 9 UT), thus providing a unique opportunity to look for spectroscopic evolution over many nights. The early spectra of the OT of GRB 030329 (Fig. 1, *top*) consist of a power-law continuum typical of GRB afterglows, with narrow emission features identifiable as Hα, [O III], Hβ, and [O II] at $z = 0.1687$ (Greiner et al. 2003; Caldwell et al. 2003) probably from H II regions in the host galaxy. These lines can be used to estimate the star formation rate within the spectrograph slit (Kennicutt 1998). Preliminary analysis of the [O II] flux suggests a low star formation rate of ~0.1 $M_\odot$ yr^{-1} (Caldwell et al. 2003), but a more detailed analysis is possible after the afterglow has faded.

A fit to the early spectra provides a power-law index of $\beta = -0.94 \pm 0.01$ for April 1 and -0.93 ± 0.01 for April 4 (statistical errors only). This is consistent with the spectral slope of -0.94 found using Sloan Digital Sky Survey photometry taken March 31/April 1 (Lee et al. 2003). Correcting for low Galactic extinction of $E(B-V) = 0.025$ (Schlegel et al. 1998) lowers the slope to -0.85, which is a typical spectral index for GRB afterglows (e.g., Stanek et al. 2001).

Beginning April 6, our spectra showed the development of broad peaks in flux, characteristic of a supernova. The broad bumps are seen at approximately 5000 and 4200 Å (rest frame). At that time, the spectrum of GRB 030329 looked similar to that of the peculiar Type Ic SN 1998bw a week before maximum light (Patat et al. 2001). Over the next few days, the SN features became more prominent as the afterglow faded and the SN brightened toward maximum.

To discern the spectrum of the SN component, we assume that the spectral slope of the afterglow light did not evolve significantly in time. This allows us to subtract the afterglow-dominated spectrum obtained on April 4 UT (see Fig. 1) from the supernova-dominated spectrum of April 8. The resulting spectrum is shown in Figure 2. For comparison, spectra of SN 1998bw at maximum and a week before maximum are also shown (Patat et al. 2001). The similarities of the GRB 030329 supernova to SN 1998bw are striking, while the match to other “hypernovae” such as SN 1997ef (Iwamoto et al. 2000) and SN 2002ap (Mazzali et al. 2002) is not as good. The primary difference is that the feature around 4400 Å (rest frame) in the GRB 030329 supernova and SN 1998bw is very broad, while in SN 1997ef and SN 2002ap the feature is sharp and well defined. This is likely an indication that the expansion velocities in 1998bw and the GRB 030329 supernova are significantly higher than in the other two events.

The evolution of the GRB 030329/SN 2003dh is still ongoing. In a future paper (T. Matheson et al. 2003, in preparation), we will discuss in more detail the properties of the afterglow of GRB 030329, in itself a very unusual event, and long-term spectroscopic and photometric evolution of the SN 2003dh. With this future paper, we will also release our data for this GRB/SN via anonymous ftp.

We have shown convincing spectroscopic evidence that a supernova was lurking beneath the optical afterglow of the classical, long burst GRB 030329. The supernova spectrum was very similar to the Type Ic hypernova SN 1998bw, which was associated with the intrinsically weak GRB 980425. With two confirmed cases, it is tempting to link only Type Ib/c events with GRBs. However, the Type IIn hypernova 1997cy (Germany et al. 2000) may have triggered a GRB, and the blue color of SN 2001ke near maximum was consistent with some hydrogen-rich events (Garnavich et al. 2003c).

The 4400 Å feature in the spectrum of GRB 030329 is significantly broader than those seen in hypernovae SN 1997ef and SN 2002ap, neither of which was clearly associated with a GRB event. While the presence of supernovae have been inferred from the light curves and colors of GRB afterglows in the past, this is the first direct, spectroscopic confirmation that some and maybe all classical gamma-ray bursts originate from supernovae.

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