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ON THE SPECTRUM AND SPECTROPOLARIMETRY OF TYPE Ic HYPERNOVA SN 2003dh/GRB 030329[1]

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ABSTRACT

Spectroscopic and spectropolarimetric observations of SN 2003dh/GRB 030329 obtained in 2003 May using the Subaru 8.2 m Telescope are presented. The properties of the supernova (SN) are investigated through a comparison with spectra of the Type Ic hypernovae SN 1997ef and SN 1998bw (hypernovae being a tentatively defined class of SNe with very broad absorption features: these features suggest a large velocity of the ejected material and possibly a large explosion kinetic energy). Comparison with spectra of other hypernovae shows that the spectrum of SN 2003dh obtained on 2003 May 8 and 9, i.e., 34–35 rest-frame days after the gamma-ray burst (GRB; for $z = 0.1685$), are similar to those of SN 1997ef obtained ∼34–42 days after the fiducial time of explosion of that SN. The match with SN 1998bw spectra is not as good (at rest 7300–8000 Å), but again spectra obtained ∼33–43 days after GRB 980425 are preferred. This indicates that the SN may have intermediate properties between SNe 1997ef and 1998bw. On the basis of the analogy with the other hypernovae, the time of explosion of SN 2003dh is then constrained to be between -8 and $+2$ days of the GRB. The Si and O P Cygni lines of SN 2003dh seem comparable to those of SN 1997ef, which suggests that the ejected mass in SN 2003dh may match that in SN 1997ef. Polarization was marginally detected at optical wavelengths. This is consistent with measurements of the late afterglow, implying that it originated mostly in the interstellar medium of the host galaxy.

Subject headings: gamma rays: bursts — nuclear reactions, nucleosynthesis, abundances — polarization — supernovae: general — supernovae: individual (SN 2003dh)

1. INTRODUCTION

Following the discovery of the energetic and bright Type Ic supernova SN 1998bw in the error box of GRB 980425, the argument for the association between at least some gamma-ray bursts (GRBs) and some Type Ic supernovae (SNe) has become a hot issue (Galama et al. 1998; Iwamoto et al. 1998; Kulkarni et al. 1998). Other bright and energetic Type Ic SNe have subsequently been discovered (e.g., SNe 1997ef and 2002ap; see Nomoto et al. 2001, 2003; Branch 2001; Mazzali et al. 2002), but in none of these cases was there strong evidence for association with a gamma-ray burst (GRB), leaving doubts about the reality of the case of SN 1998bw and GRB 980425.

The lack of association of all hypernovae with GRBs can be explained by asymmetry. GRBs could be produced by relativistic jets emerging from asymmetric hypernovae (e.g., Wang & Wheeler 1998; Iwamoto et al. 1998, 2000; Höflich, Wheeler, & Wang 1999; Woosley, Eastman, & Schmidt 1999; Nomoto et al. 2001, 2003; Wheeler 2001; MacFadyen, Woosley, & Heger 2001). It is generally assumed that the GRB is highly asymmetric and collimated more or less closely along the jet axis. There are also cumulative observational facts indicating that Type Ib/Ic SNe are intrinsically asymmetric (e.g., Wang et al. 2001, 2003; Mazzali et al. 2001; Maeda et al. 2002, 2003; Maeda & Nomoto 2003). Along with evidence for GRBs associated with some SNe, there is evidence for SNe associated with some GRBs. The bumps observed in some GRB afterglows may be underlying SN light curves seen rising to and passing maximum light (Bloom et al. 2002). However, spectral observations of the afterglows with bumps have not been possible (until GRB 030329

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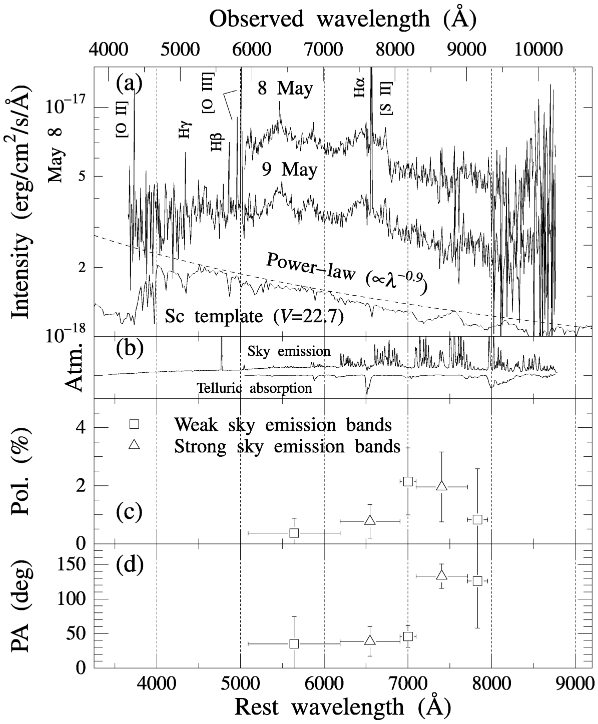

FIG. 1.—Observations of SN 2003dh/GRB 030329: (*a*) Flux spectra in which the telluric absorption has been corrected for, (*b*) spectra of sky emission lines and telluric absorptions for a reference of less-reliable wavelength regions, (*c*) degree of observed polarization, and (*d*) its P.A. in the equatorial coordinate. The flux has been binned to 10.8 Å widths. In (*a*), a template spectrum of an Sc-type galaxy (GISSEL98; Bruzual & Charlot 1993) of $V = 22.7$ (Zharikov et al. 2003) is shown, as well as a template GRB continuum having a power-law index $\beta = -0.9$ (Stanek et al. 2003) for comparison. The polarimetric data are properly binned and each bandwidth is indicated by a horizontal error bar. The vertical error bar denotes its mean error (1 σ).

and with the exception of GRB 021211; Della Valle et al. 2003) because of their faintness.

The recent gamma-ray burst GRB 030329 has now greatly advanced the issue of the GRB/SN association. The GRB was detected by the *High Energy Transient Explorer 2* at 2003 March 29.484 UT (Vanderspek et al. 2003), and its optical counterpart was promptly identified (Peterson & Price 2003; Torii 2003; Uemura et al. 2003; Price et al. 2003). In the afterglow spectrum a bright Type Ic SN 2003dh had been found (Stanek et al. 2003; Chornock et al. 2003; Zaritsky et al. 2003; Hjorth et al. 2003). This detection is probably the conclusive confirmation that indeed some SNe and some GRBs are produced by the same astrophysical cauldron. Its unusual brightness provided us with a unique opportunity to obtain spectroscopic and spectropolarimetric data of the SN about 40 days after the GRB. Polarimetry is effective for proving the asymmetric geometry of the explosion (e.g., Jeffery 1991; Höflich 1991; Kawabata et al. 2002). In this Letter, we report on observations obtained with the Subaru Telescope and attempt to derive some of the properties of SN 2003dh based on a comparison with those of other Type Ic hypernovae.

2. OBSERVATIONS

The spectroscopic and spectropolarimetric observations of SN 2003dh/GRB 030329 were obtained with the Faint Object Camera and Spectrograph (Kashikawa et al. 2002) attached to the 8.2 m Subaru Telescope on Mauna Kea. All the observations were carried out through a polarimetric unit that consists of a rotating superachromatic half-wave plate and a quartz Wollaston prism. Spectra are obtained at four wave-plate position angles (P.A.'s; 0°, 45°, 22°.5, and 67°.5) for spectropolarimetry or at one angle (0°) for spectroscopy. A 0''.8 width slit and two 300 lines mm^{-1} grisms were used; they produce 8 pixel ~11 Å resolution in both 5900–10240 Å (red) and 4200–6000 Å (blue). The spectropolarimetric data were obtained with the red grism on 2003 May 8.3 and 9.3 UT, and their total exposure times were 9120 and 7200 s, respectively. The spectroscopic data were obtained with the blue grism on May 9.4 with a 1200 s exposure time. These epochs correspond to 34–35 rest-frame days after the GRB, assuming a redshift of $z = 0.1685$ (Greiner et al. 2003).

The data were reduced in the standard manner. Nightly observation for unpolarized stars suggested that the instrumental polarization was negligible ($p \lesssim 0.1\%$), so we did not correct for it. The P.A. of the polarization was corrected with dome flat-field spectra obtained through a polarizing filter and using the observation of a polarized star, Hiltner 960.

For flux calibration, we observed spectrophotometric standard star Feige 34 (Massey & Gronwall 1990) with a wide (2''.0) slit in a moderate seeing condition (1''.0). In the target observation, the 0''.8 width of the slit was comparable to or narrower than the target image sizes (FWHM = 1''.0–1''.6 on May 8 and 0''.7–0''.8 on May 9), causing a nonnegligible loss of light. We estimated it from stellar image profiles in unfiltered images taken for telescope guiding. It was approximately 39% (May 8) or 24% (May 9), and we corrected for it by artificially scaling up the flux. The absolute value of the flux, however, is still lower than the result from Zharikov, Chavushyan, & Mujica (2003) of $R = 20.88$ on May 8.15 UT by 0.45–0.50 mag. The discrepancy could originate from an underestimation of the point-spread function of the stellar image or insufficient calibrations, but the situation is unclear and we have not performed any further correction. Since the Galactic extinction toward the star is likely to be relatively negligible ($E_{B-V} = 0.025$; Schlegel, Finkbeiner, & Davis 1998), we did not correct for it either.

In Figure 1 we show the derived spectra of SN 2003dh/GRB 030329 in which several narrow emission lines are visible that can be attributed to H II regions within the host galaxy. There is no significant variation in the SN spectra over the 2 days.

3. SPECTRAL COMPARISON WITH OTHER HYPERNOVAE

Stanek et al. (2003) compared the early spectrum of SN 2003dh with those of SN 1998bw and found a close resemblance between them. They pointed out that the expansion velocities in 1998bw and 2003dh on April 8 are significantly higher than in other hypernovae, such as SN 1997ef (Iwamoto et al. 2000) and SN 2002ap (Mazzali et al. 2002; Kinugasa et al. 2002).

Using our spectra, we performed a similar comparison. We find that the spectra of SN 1998bw obtained between 19 and 29 days after B maximum (Patat et al. 2001), i.e., between 33 and 43 rest-frame days after the explosion of the SN, are a good match for the May spectra of SN 2003dh (Fig. 2*a*). However, an even better match is obtained using the spectra of SN 1997ef at a similar epoch (34–42 days; Fig. 2*b*). In particular, the spectra of SN 2003dh are different from those of SN 1998bw in the red, where in SN 1998bw the O I λ7774 and Ca II IR triplet lines blend, while in SN 1997ef they do not. This is an indication that SN 1997ef is less energetic than SN 1998bw, as the velocities attained are smaller. Thus SN 2003dh on May 8–9 may also be less energetic than SN 1998bw, although SN 2003dh had shown a comparable expansion velocity in its early phase (Stanek et al. 2003). On the basis of comparisons of earlier and later spectra,

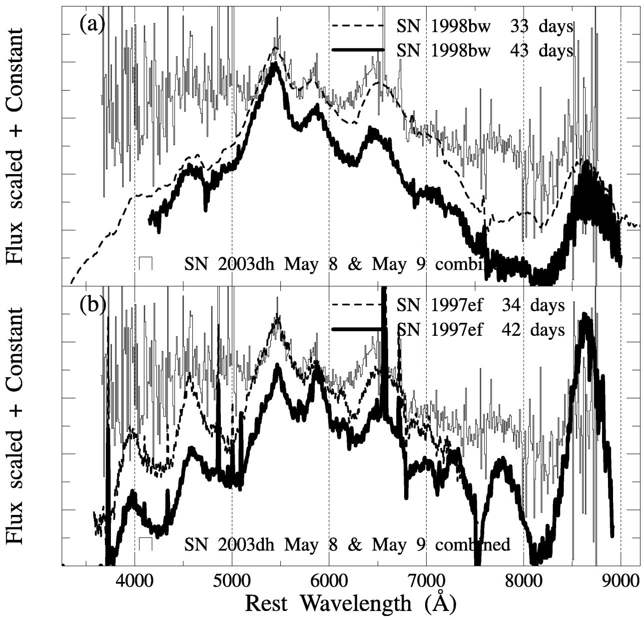

FIG. 2.—Comparison of SN 2003dh spectrum with other hypernovae: (*a*) SN 1998bw (Patat et al. 2001) and (*b*) SN 1997ef (Mazzali et al. 2000). The SN 2003dh spectrum is an average of both May 8 and 9 spectra. These show a global resemblance between the spectrum of SN 2003dh and those of the other hypernovae. However, the match seems better with SN 1997ef around the O I λ7774 line.

the total kinetic energy of SN 2003dh may therefore lie between those of SNe 1997ef and 1998bw.

Such comparisons are quantitatively somewhat uncertain. However, in this case they suggest that SN 2003dh exploded in the range (−8, +2) days of GRB 030329, based on the similarity in the spectral evolution to both SNe 1998bw and 1997ef.

Although, in the direct comparison with SNe 1997ef and 1998bw, SN 2003dh has a continuum excess in the blue region ($\lambda \lesssim 5000$ Å; see Figs. 2*a* and 2*b*), it can be naturally explained by an underlying host galaxy and/or a residual afterglow continuum. For example, using χ^2-fitting to SN 1998bw, we can plausibly extract the SN spectrum having little or no excess under the assumption that the host galaxy type is a starburst as shown in Figure 3. (In this Letter, we use only the SN 1998bw spectrum for a fit because of much lower contamination in the 1998bw host galaxy than in the 1997ef host galaxy. Further analyses also using SN 1997ef spectra will appear in future work.) This seems almost consistent with the result in which an Sc-type galaxy template (assuming a Large Magellanic Cloud– or Small Magellanic Cloud–like dwarf galaxy of $V = 22.7 \pm 0.3$; Eracleous, Schaefer, & Gerardy 2003; Fruchter et al. 2003; e.g., Fig. 1*a*) is subtracted from the observation (Fig. 4). In the decomposed spectrum, the Si II λλ6347, 6371 line in SN 2003dh appears to be comparable to the corresponding feature in both SNe 1997ef and 1998bw. Figure 4 also suggests that the O I λ7774 line in SN 2003dh is comparable to that in SN 1997ef. Since O dominates the composition of the ejecta (see Nomoto et al. 2001, 2003; Nakamura et al. 2001), this may be taken to imply that the mass of the ejecta of SN 2003dh matches in SN 1997ef (∼10 $M_\odot$; Mazzali, Iwamoto, & Nomoto 2000).

4. POLARIMETRY

The result of our polarimetry is shown in Figures 1*c* and 1*d*. In the rest wavelength range 5000–7000 Å, it is found that

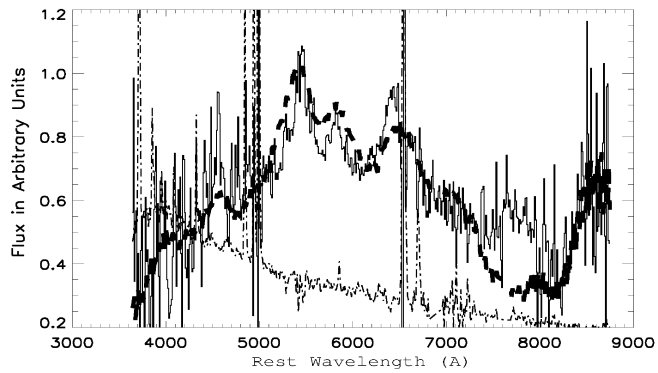

FIG. 3.—SN 2003dh spectrum after subtraction of a starburst galaxy spectrum. They are derived using χ^2-fitting to the SN 1998bw spectrum 36 days after explosion. The thick dashed line shows the best-matching SN 1998bw spectrum, the dash-dotted line is the subtracted host spectrum, and the continuous line is the decomposed SN 2003dh spectrum.

the observed polarization is not significant ($P < 1\%$), although the alignment of P.A. around 40° suggests that the polarization is nonzero. In the interstellar polarization catalog (Heiles 2000), 30 stars are found within 15° around SN 2003dh. They mostly show only $P \lesssim 0.1\%$. The maximum polarization is found to be $P = 0.2\%$ for HD 87737 ($d = 456$ pc), and the most distant star, HD 91316 ($d = 792$ pc), shows $P = 0.17\%$. This is consistent with the Galactic extinction toward the SN ($E_{B-V} = 0.025$) and the well-established relation of $P_{\max} \lesssim 9E_{B-V}$ (Serkowski, Mathewson, & Ford 1975). The interstellar polarization in our Galaxy is likely to be negligible compared with the error in our data.

Various authors have reported significant polarization of the GRB 030329/SN 2003dh object at the earliest stages. The degree of polarization and its P.A. in the *R* band (center wavelength corresponding to about 5560 Å in rest frame) were 0.90% ± 0.39% and 109° ± 12° on March 30.8 UT (Efimov et al. 2003), 1.97% ± 0.48% and 83°.2 on March 31.1 (Magalhaes et al. 2003), and 0.5% ± 0.1% and 73° ± 5° on April 2.1 (Covino et al. 2003). In this period, the optical flux was dominated not by the SN component but by the GRB afterglow, and the variable polarization could be attributed to the asymmetric fireball scenario (e.g., Ghisellini & Lazzati 1999). However, the gradual rotation of P.A. with wavelength found by Covino et al. (2003) suggests the existence of a mildly polarized ($P \lesssim 0.5\%$) component having P.A. ≃ 0°–73°, which is consistent with our value ∼40°. This is consistent with a constant polarization component

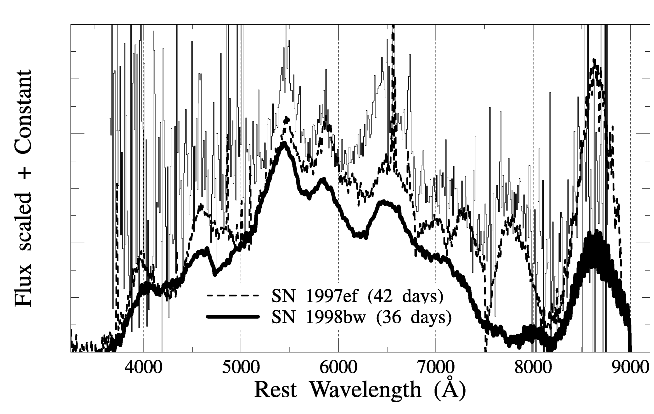

FIG. 4.—Comparison between the SN 2003dh spectrum from which a template spectrum of an Sc-type galaxy (e.g., Fig. 1) has been subtracted and those of other hypernovae.

due to interstellar matter in the host galaxy (dichroic absorption and/or scattering). The similarity of the polarization P.A. of our data at 5000–7000 Å and the P.A. of elongation of the host galaxy (230° = 50°; Fruchter et al. 2003) also suggest that a considerable fraction of the polarization is due to interstellar polarization in the host galaxy.

The low intrinsic polarization of SN 2003dh can be explained in terms of a mild asphericity of the explosion along the line of sight (e.g., Höflich 1991), but this does not imply that the explosion was highly spherically symmetric. If the explosion is spheroidal (e.g., prolate) and we view it nearly along the axis of the symmetry, only a small departure from asymmetry about the line of sight is expected, and thus only small polarization is expected. It has been known that core-collapse SNe usually show large polarization, and their explosions are likely to be asymmetric (Wang et al. 1996, 2001; Leonard & Filippenko 2001). The presence of the GRB and the hypernova spectrum suggests that the viewing angle nearly aligns with the axis of the prolate explosion as suggested for SN 1998bw/GRB 980425 (e.g., Höflich et al. 1999; Patat et al. 2001; Maeda et al. 2002).

We should also note the possible polarization at 7000–8000 Å, which has a P.A. orthogonal to that of the polarization at wavelengths 5000–7000 Å. SN 2002ap, which is at present the only hypernova that has been well observed with spectropolarimetry, also had distinct polarization features ($\Delta P \sim$ 1%–2%) at O I or Ca II triplet absorption troughs (Kawabata et al. 2002; Leonard et al. 2002; Wang et al. 2003). However, Figure 1*c* shows that the significance of the polarization at 7000–8000 Å is low ($P/\sigma_P < 2$). The contamination of residual sky emission lines could degrade the quality in the wavelength region. We conclude that the significance of the polarization in SN 2003dh on May 8 and 9 is not high compared with other core-collapse SNe.

5. CONCLUSIONS

Our observations confirm that the supernova component SN 2003dh of GRB 030329 evolves in the same manner as other Type Ic hypernovae, e.g., SNe 1997ef and SN 1998bw. Polarization was marginally detected for the SN at optical wavelengths, but it seems to be mainly (perhaps totally) of interstellar origin in the host galaxy. The low intrinsic polarization would be consistent with the scenario of the highly collimated jet model of the GRB afterglow if the viewing angle is well aligned with the axis of asymmetric explosion. However, this suggestion is tentative. Future bright SNe/GRBs should also be monitored spectropolarimetrically.

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