GALEX SPECTROSCOPY OF SN 2005ay SUGGESTS ULTRAVIOLET SPECTRAL UNIFORMITY AMONG TYPE II-P SUPERNOVAE

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ABSTRACT

We present the initial results from our *GALEX* program designed to obtain ultraviolet (UV) spectra of nearby core-collapse supernovae (SNe). Our first target, SN 2005ay in the nearby galaxy NGC 3938, is a typical member of the SN II-P subclass. Our spectra show remarkable similarity to those of the prototypical Type II-P SN 1999em, and resemble also *Swift* observations of the recent Type II-P SN 2005cs. Taken together, the observations of these three events trace the UV spectral evolution of SNe II-P during the first month after explosion, as required in order to interpret optical observations of high-redshift SNe II-P, and to derive cross-filter *K*-corrections. While still highly preliminary, the apparent UV homogeneity of SNe II-P bodes well for the use of these events as cosmological probes at high redshift.

Subject headings: supernovae: individual (SN 2005ay) — ultraviolet: general

1. INTRODUCTION

In order to interpret optical observations of high-redshift supernovae (SNe), sampling the rest-frame ultraviolet (UV) radiation of these events, we need to have UV observations of local SNe of all types. Studies of high-redshift SNe promise, in turn, to shed light on key open questions, such as the evolution of cosmic metallicity, star formation at high redshift, and SN "feedback" processes shaping galaxy formation.

Type Ia SNe, famed for their cosmological utility as precision distance estimators, are the best studied of all SN subclasses in the rest-frame UV (e.g., Kirshner et al. 1993; Ellis et al. 2008; Foley et al. 2008a, 2008b). SNe Ia are broadly thought to result from thermonuclear explosions of white dwarf stars approaching the critical Chandrasekhar mass due to accretion from (or a merger with) a binary companion, and show remarkable homogeneity in their observational properties. How-

ever, UV studies may hint at unexplained dispersion in the rest-frame UV band (Ellis et al. 2008; Foley et al. 2008a, 2008b).

All other types of SNe (see Filippenko 1997 for a review) probably result from the gravitational collapse of short-lived, massive stars (e.g., Crockett et al. 2008; Li et al. 2007; Gal-Yam et al. 2007 and references therein). In general, core-collapse SNe are extremely heterogeneous in every observational respect, and, in particular, different types of core-collapse events have diverse UV properties (e.g., UV-bright Type IIn SN 1998S [Lentz et al. 2001] vs. UV-deficient Type Ic SN 1994I [Millard et al. 1999]). The dispersion in UV properties among objects within specific core-collapse SN subtypes is so far unknown.

Unfortunately, UV spectra of reasonable quality were obtained for only a handful of core-collapse SNe (see Panagia 2003, 2007 for reviews), and some of the best-observed events (notably SN 1987A; e.g., Eastman & Kirshner 1989) are quite peculiar. This observational deficit introduces significant uncertainties into the interpretation of high-redshift SN observations, which are forced to rely either on little-tested models for the UV spectrum of core-collapse events, or on the use of the few observed UV spectra for the entire population, neglecting possible dispersion in spectral evolution. The sparse database of UV core-collapse SN spectra continues to limit the scientific utility of large samples of core-collapse SNe at high redshifts. These include both samples currently assembled using the *Hubble Space Telescope* (*HST*; e.g., Dahlen et al. 2004; Riess et al. 2007) and from the ground (e.g., Poznanski et al. 2007b), and future data sets expected to emerge from a possible *JDEM* mission that includes a SN component and from deep infrared observations with the *James Webb Space Telescope*. Furthermore, in order to probe the physics of core-collapse SNe, broad spectral coverage, particularly of the UV range, where line blanketing by iron-peak elements plays a crucial role in the formation of the spectrum (e.g., Pauldrach et al. 1996), is essential. UV spectra are most sensitive to the metal content of the SN ejecta, a key probe of the nucleosynthetic evolution.

To alleviate this problem is the main motivation for our target-of-opportunity *GALEX* program (GALEX-GI-44, cycle 1; GALEX-GI-67, cycle 2; GALEX-GI-61, cycle 3; GALEX-GI-
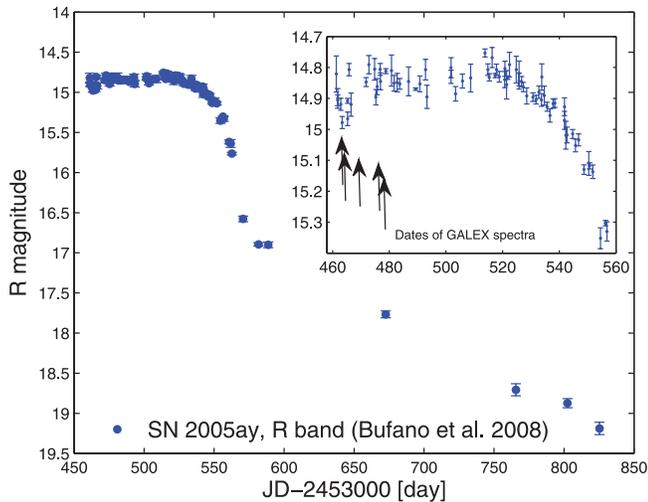
Fig. 1.—*R*-band light curve of SN 2005ay, showing the classical features of a Type II-P event, including the initial extended plateau, followed by a rapid decline period, and terminating in a radioactive decline phase. The *GALEX* data were obtained in the first 2 weeks of the plateau (see inset). The full multiband light-curve data, along with a detailed discussion of their calibration and error analysis, will be presented by F. Bufano et al. (in preparation).

20, cycle 4; PI Gal-Yam), designed to obtain multiepoch UV spectra of nearby core-collapse SNe. Here we report the first results from this program. In § 2 we describe our observations, and in § 3 we present our results. Discussion and conclusions follow in § 4. UT dates are used throughout the Letter.

2. OBSERVATIONS

SN 2005ay in the nearby galaxy NGC 3938 (heliocentric velocity $v = 809$ km s^{-1}) was discovered on 2005 March 27 by Rich (2005) and rapidly identified as a Type II supernova (Taubenberger et al. 2005; Gal-Yam & Smith 2005). Preexplosion limits (2005 March 19; Yamaoka & Itagaki 2005) indicate it was discovered shortly after explosion, leading us to trigger our *GALEX* target-of-opportunity program.

Following the activation of our *GALEX* program, we launched an intensive campaign to study SN 2005ay from the ground in optical and infrared (IR) wavelengths, to complement the *GALEX* UV study. We obtained dense multicolor photometry during the months after the SN discovery, and monitored its decline for approximately a year (Fig. 1). Numerous optical spectra show the evolution of this object in great detail, starting shortly after explosion (Fig. 2). Our observations confirm the identification of this event as a typical SN II-P (Tsvetkov et al. 2006), and will be reported in detail by F. Bufano et al. (in preparation). In this Letter we present the earliest *GALEX* UV spectra of SN 2005ay and compare it with additional examples from the literature (Fig. 3). The spectral similarity between these supernovae highlights an emerging picture of uniform UV properties of SNe II-P, the most common subclass of core-collapse SNe, and the first for which analysis based on a sample of events is possible.

The *GALEX* mission observed SN 2005ay in grism spectroscopy mode on 2005 April 2, 3, 8, 15, and 16. At that time, only the near-UV camera was operational, yielding a wavelength coverage of 1800–2900 Å. Reduction of these data required a custom approach, in order to properly remove the contribution from UV-
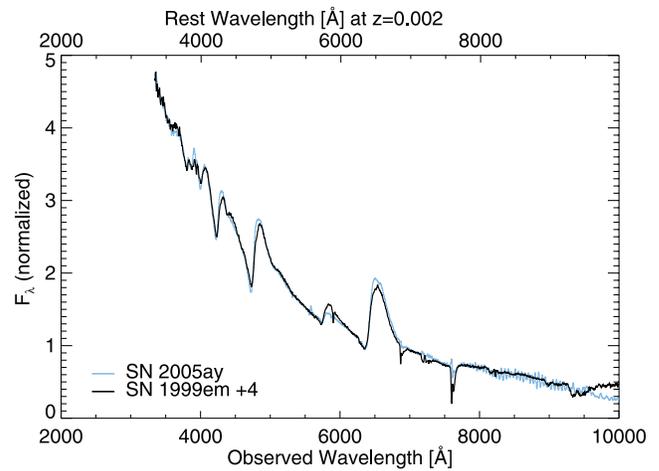

Fig. 2.—Optical spectrum of SN 2005ay obtained on March 31 using the Dolores spectrograph mounted on the 3.58 m Telescopio Nazionale Galileo telescope in La Palma, Spain. Comparison with a database of SN spectra using the Superfit code (Howell et al. 2005) reveals a remarkable similarity to early spectra of the prototypical SN II-P event, SN 1999em (Leonard et al. 2002; a spectrum obtained 4 days postdiscovery is shown). The fit presented requires the application of a small negative reddening correction ($A_V \approx 0.05$ mag), indicating that SN 2005ay probably had lower dust extinction than SN 1999em, which itself was only slightly extinguished ($A_V \approx 0.35$ mag; Leonard et al. 2002). Alternatively, this could indicate a slightly higher temperature for SN 2005ay. The blue continuum and similarity to very early spectra of SN 1999em confirm the imaging indications that this object was discovered shortly (at most a few days) after explosion. Additional data and further discussion will be presented by F. Bufano et al. (in preparation).
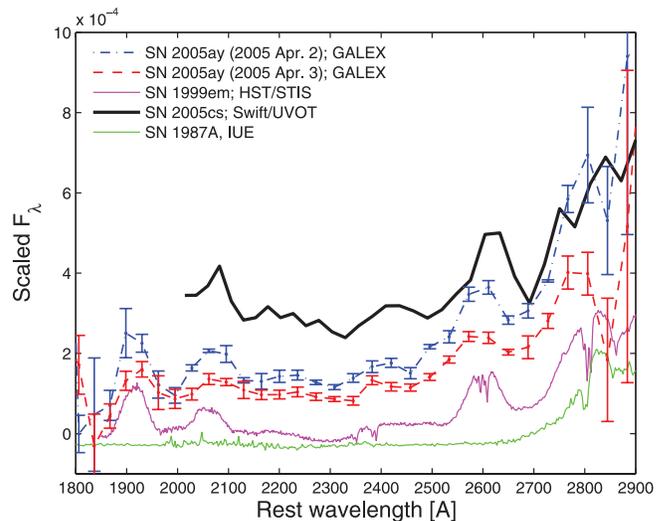

Fig. 3.—Comparison of the rest-frame UV spectra of Type II-P SN 1999em (*HST* STIS, *magenta*; Baron et al. 2000), SN 2005cs (*Swift* UVOT, *black*; Brown et al. 2007), and our new *GALEX* spectra of SN 2005ay (*red, blue*). The spectra have been arbitrarily scaled in flux for presentation purposes. The spectra of SNe 1999em and 2005ay were obtained ~12 days after explosion. The *Swift* spectrum of SN 2005cs was obtained somewhat earlier (6 days postexplosion) and we have adjusted its shape to match the spectral evolution of the SNe to day 12, so it should be considered approximate only; see text for details. Note the remarkable similarity in both continuum shape and observed features among these three events. In contrast, the spectrum of peculiar SN 1987A (*IUE, green*; Pun et al. 1995) obtained at a similar age (13 days after explosion) has no strong features bluer than the Mg II λ2800 line, perhaps reflecting the lower metallicity of its progenitor.

bright knots and residual small-scale structure in the nearby spiral arm of the host galaxy, NGC 3938. This process will be presented in detail by F. Bufano et al. (in preparation). In brief, we have obtained reference grism-dispersed images of the location of SN 2005ay on 2007 March 4–28, presumably including only negligible light from SN 2005ay, using an identical instrumental configuration. We performed digital image subtraction using the 2007 epoch as reference, and extracted our spectra from the background-subtracted reference frames. Figure 3 shows the combined spectra obtained on 2005 April 2 (4 *GALEX* orbits; total exposure time 5705 s) and 2005 April 3 (7 orbits; 9516 s). The spectra were binned to 30 Å resolution elements to increase the signal-to-noise ratio (S/N). Errors for each spectral bin were directly measured from the dispersion among consecutive orbits (1 σ errors are plotted in Fig. 3).

3. DISCUSSION

3.1. *UV Homogeneity*

In Figure 3, we compare our rest-frame-UV spectra of SN 2005ay with those of two other SNe II-P, SN 1999em and SN 2005cs, which are the only other II-P events with high-S/N rest-frame UV spectra. SN 1999em was discovered on 1999 October 28.9, and the estimated explosion date is ~5.3 days before discovery (Leonard et al. 2002). The *HST* spectrum reproduced here (Baron et al. 2000) was obtained on 1999 November 5, about 12 days after explosion. SN 2005cs was discovered on 2005 June 29, approximately 2 days postexplosion (Dessart et al. 2008). The *Swift* spectrum reproduced here was obtained on 2005 July 3, ~6 days postexplosion (Brown et al. 2007). Tsvetkov et al. (2006) estimate the explosion date of SN 2005ay as 2005 March 23 ± 2 days. From spectral comparison with SN 1999em (Fig. 2) we find that the March 31 spectrum of SN 2005ay has, consistently, an age of ~9 days after explosion. So our *GALEX* spectra reported in Figure 3 were obtained 11–13 days postexplosion. This estimate is also consistent with available preexplosion limits (§ 2).

Since the UV spectra of SNe evolve rapidly, in order to compare our *GALEX* spectra with those from the literature we had to adjust the *Swift* spectrum of SN 2005cs (obtained ~6 days postexplosion) to approximately match those of the other events, both of which happen to have been obtained at a similar epoch (11-13 days postexplosion). We performed this adjustment using two alternative methods, giving consistent results. First we interpolated the *Swift* photometry reported by Brown et al. (2007) and Dessart et al. (2008) in the *U*, *UVW*1, and *UVW*2 bands (central wavelengths 3465, 2600, and 1928 Å, respectively; see Brown et al. 2007 for additional bandpass details), which bracket our wavelength range, to 6 and 12 days postexplosion. We then adjusted the spectral shape of the early spectrum to match the evolution of the spectral energy distribution of the SN, measured from *Swift* photometry.

Alternatively, we used an additional spectrum obtained by *Swift* ~11 days after explosion, of much lower S/N (see Brown et al. 2007). However, assuming that the spectral shape of this later spectrum is correct, even if individual features cannot be reliably measured, we can adjust the day 6, high-S/N spectrum to match the shape of the day 11 spectrum. This yields consistent results with those obtained using the UV photometry (see above) and we plot the adjusted spectrum in black in Figure 3. A more detailed discussion of the *Swift* spectra of SN 2005cs will appear in F. Bufano et al. (in preparation). Obviously, both of these procedures introduce additional uncertainties to the spectral

shape of SN 2005cs, which should therefore be regarded as approximate only (in contrast to the other spectra in Fig. 3 that have not been modified from their observed form).

UV spectra are particularly sensitive to effects of dust extinction. Since the estimated extinction for the three events in question is uncertain but small ($E_{B-V} \lesssim 0.1$ mag; Leonard et al. 2002, Baron et al. 2000; Pastorello et al. 2006; Brown et al. 2007; Dessart et al. 2008; Tsvetkov et al. 2006; this work, Fig. 2), we have made no correction for extinction to the spectra in Figure 3, and postpone a more detailed discussion of this issue to F. Bufano et al. (in preparation).

Inspecting Figure 3, we note the remarkable similarity among the spectra of these three SNe. Identical spectral features are prominent, such as the Mg II P Cygni profile around 2800 Å, as well as the emission "bumps" around 2600, 2200, 2070, and 1900 Å. This similarity is independent of the overall spectral shape and suggests that similar physical conditions occur at the photospheres of these SNe. The continuum shape is also almost identical when SN 1999em and SN 2005ay are compared, with SN 2005cs a close match as well, considering the additional uncertainty introduced to compensate for the earlier observation (see above).

This apparent homogeneity is in stark contrast to the wide diversity among UV spectra of other subtypes of core-collapse SNe, exemplified by a comparison with the UV spectrum of the peculiar Type II SN 1987A (from Pun et al. [1995] via the SUSPECT database[16]), often considered a close relative of SNe II-P. The clearly different spectral shape blueward of the Mg II 2800 Å line may reflect the peculiar metallicity, compact progenitor, and high ejecta expansion velocity seen in SN 1987A (e.g., Mazzali & Lucy 1990). The homogeneity among UV spectra of normal SNe II-P is reminiscent of that observed among UV spectra of standard Type Ia supernovae (e.g., Foley et al. 2008a).

The combined set of rest-frame UV spectra now available for SNe II-P (SN 1999em, SN 2005cs, and SN 2005ay) samples the UV spectral evolution of such events between 6 days (the earliest *Swift* observation of SN 2005cs) and 25 days (our last *GALEX* spectrum of SN 2005ay) after explosion. Assuming these events are representative of the population of SNe II-P, the data suffice to describe the UV evolution of these objects throughout the interesting UV-bright period after explosion (F. Bufano et al., in preparation).

3.2. *Implications*

The use of SNe II-P as an alternative cosmological distance indicator to SNe Ia has been advocated for many years (e.g., Kirshner & Kwan 1974; Wagoner 1977; Schmidt et al. 1994; Hamuy & Pinto 2002; Baron et al. 2004). Nugent et al. (2006) have recently demonstrated that SN II-P distances can be measured, with existing facilities, out to cosmological distances, and that an independent cosmological measurement is feasible. A possible advantage of SNe II-P for cosmological use is that these events, arising from the explosion of relatively low-mass red supergiant stars (e.g., Hendry et al. 2006; Li et al. 2007 and references therein) are much more common (per unit volume) than SNe Ia, and should occur in abundance out to high redshifts, where such massive stars are formed in great numbers. SNe Ia, in contrast, may show a decline in rate above $z \approx 1.5$ (Dahlen et al. 2008; although see Poznanski et al. 2007b), which, if real, may reflect

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[16] See http://suspect.nhn.ou.edu.

a metallicity "floor" required for these events to take place (Kobayashi et al. 1998), or a long delay time between the formation of SN Ia progenitors and their explosion (Strolger et al. 2004).

Since optical detectors still offer the most powerful combination of efficiency, low sky background, and relatively wide fields, taking advantage of the benefits of SNe II-P for cosmology at high redshifts may require the use of optical surveys, sampling the rest-frame UV, to discover high-redshift SNe II-P. A UV spectral homogeneity as suggested by our data, if confirmed, would allow the use of UV spectral templates to discover and photometrically identify high-redshift SNe II-P (e.g., Poznanski et al. 2002, 2007a; Riess et al. 2004). Furthermore, accurate photometry could be derived using cross-filter K-corrections which take into account the effects of spectral features using template spectra (S-corrections; Stritzinger et al. 2002). This would apply at least to those SNe II-P within the luminosity range spanned by the objects we considered, i.e., between the less-luminous SN 2005cs (Pastorello et al. 2006) to the normal SN 1999em. Much fainter (e.g., SN 1997D, SN 1999br; Pastorello et al. 2004) or much brighter ones (e.g., SN 1992am; Hamuy 2003) may have different UV spectra, and additional observations to test the correlation between UV spectral shape and luminosity are definitely required.

Another important application of high-redshift supernova surveys is to measure supernova rates, which probe the star formation rate and cosmic metal production. SNe that decline quickly in the UV would be detectable for shorter periods in rest-frame UV surveys, and thus a small number of detections is translated into a higher true rate, while a smaller correction needs to be applied to SNe that remain bright in rest-frame UV longer. Properly calculating these corrections for SNe at different redshifts, for which the same survey band samples different spectral ranges within the rest-frame UV, requires detailed knowledge about the spectral evolution of SNe, one of the goals of our *GALEX* program. As shown here, for SNe II-P, the most common type of core-collapse subtypes, we have made good progress in achieving this goal.

4. CONCLUSIONS

We are carrying out a spectroscopic survey of nearby core-collapse SNe using *GALEX* grism spectroscopy in target-of-opportunity mode. About 1–2 nearby events are observed each year, increasing our knowledge of the spectral evolution of core-collapse SNe of the various subtypes. Our collaboration also provides supporting IR and optical observations of our *GALEX* targets. We have presented first results from this project—spectra of the nearby Type II-P SN 2005ay. Combined with additional observations of two similar objects from the literature, we trace the UV spectral evolution of SNe II-P and find a remarkable similarity among these objects, the most common type of core-collapse SNe and the only subtype with a sample of events having UV spectroscopic measurements. Such rest-frame UV homogeneity, if supported by additional objects, indicates that the use of these SNe as cosmological probes is a promising prospect.

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