Swift UVOT Grism Observations of Nearby Type Ia Supernovae – I. Observations and Data Reduction

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ABSTRACT

Ultraviolet (UV) observations of Type Ia supernovae (SNe Ia) are useful tools for understanding progenitor systems and explosion physics. In particular, UV spectra of SNe Ia, which probe the outermost layers, are strongly affected by the progenitor metallicity. In this work, we present 120 Neil Gehrels Swift Observatory UV spectra of 39 nearby SNe Ia. This sample is the largest UV (λ < 2900 Å) spectroscopic sample of SNe Ia to date, doubling the number of UV spectra and tripling the number of SNe with UV spectra. The sample spans nearly the full range of SN Ia light-curve shapes (∆m15(B) ≈ 0.6–1.8 mag). The fast turnaround of Swift allows us to obtain UV spectra at very early times, with 13 out of 39 SNe having their first spectra observed ≳ 1 week before peak brightness and the earliest epoch being 16.5 days before peak brightness. The slitless design of the Swift UV grism complicates the data reduction, which requires separating SN light from underlying host-galaxy light and occasional overlapping stellar light. We present a new data-reduction procedure to mitigate these issues, producing spectra that are significantly improved over those of standard methods. For a subset of the spectra we have nearly simultaneous Hubble Space Telescope UV spectra; the Swift spectra are consistent with these comparison data.

Key words: supernovae: general – supernovae

1 INTRODUCTION

Type Ia supernovae (SNe Ia) are luminous distance indicators that were used to first discover the accelerating expansion of the Universe (e.g., Riess et al. 1998; Perlmutter et al. 1999). SNe Ia provide a direct route to probe the nature of the dark energy that drives the accelerated expansion. While SNe Ia are not perfect standard candles, they can be standardised via the tight relation between SN Ia light-curve width and luminosity (width-luminosity relation, WLR; Phillips 1993) and between SN Ia optical colour and luminosity (Riess et al. 1996) — more luminous SNe Ia are bluer and have broader, slower evolving light curves. After making these corrections, we are able to use these standardisable candles for cosmological inferences.

Observational evidence indicates that a SN Ia is the result of the thermonuclear explosion of an accreting carbon-oxygen white dwarf (WD) star in a close binary system (e.g., Hillebrandt & Niemeyer 2000; Hillebrandt et al. 2013; Maoz et al. 2014). Theoretically, the amount of 56Ni synthesised during the thermonuclear explosion affects the optical opacity and changes the “width” of a SN light curve, with slower declining SNe Ia having more opacity and higher luminosities (Hoeflich et al. 1996). Making empirical corrections based on light-curve width and colour, SNe Ia become exquisite distance indicators with a distance scatter below 8% (e.g., Conley et al. 2008; Wang et al. 2009a; Kelly et al. 2015). However, that remaining distance scatter is intrinsic scatter, beyond any measurement error, and must be related to physics unaccounted for in the standardisation.

Current SN cosmology analyses assume that SNe Ia across all redshifts have the same peak luminosity after standardising by the WLR. However, new observations showed that even after standardisation, luminosity still correlates with the large-scale host-galaxy environment (e.g., Kelly et al. 2010; Sullivan et al. 2010; Lampeitl et al. 2010; Pan et al. 2014). SNe Ia in galaxies of higher metallicities have (on average) higher corrected luminosities than those with lower metallicities. SNe Ia with identical progenitors except...
for metallicity are predicted to produce different amounts of $^{56}$Ni. Higher progenitor metallicity will result in a larger fraction of stable iron-group elements (IGEs) and less $^{56}$Ni in the SN explosion, and therefore fainter peak luminosity (Timmes et al. 2003).

Theoretical studies indicate that the higher progenitor metallicity will increase the IGEs in the outer layers of the SN, which will cause greater UV line blanketing (Lentz et al. 2000). Consequently, the progenitor metallicity will not change the optical spectral energy distribution (SED) of a SN Ia significantly, but will dramatically change its UV SED. This effect is also seen in recent observations of the “twin” SN 2011by and SN 2011fe (Foley & Kirshner 2013). The two SNe have nearly identical optical light-curve widths and spectra but very different UV spectra. Thus, the WLR is insufficient to calibrate the luminosity, resulting in increased Hubble-diagram scatter. The UV SED is essential to detect this metallicity effect.

The earliest UV observations of SNe date back to early 1980s, with a handful of SNe Ia observed by the International Ultraviolet Explorer (IUE) satellite (e.g., Cappellaro, Turatto, & Fernley 1995). The launch of the Hubble Space Telescope (HST) marked a milestone in obtaining high-quality UV spectra to study the progenitor composition and explosion mechanisms of SNe Ia (e.g., Maguire et al. 2012; Pan et al. 2015; Foley et al. 2016). However, the current HST sample is too small (e.g., 9 SNe in Foley et al. 2016) to cover all of the parameter space, such as light-curve width, ejecta velocity, and progenitor metallicity. Thus, we try to increase the sample of SNe Ia with UV spectra obtained with the Neil Gehrels Swift Observatory (Gehrels et al. 2004). A good amount of Swift UV spectroscopy has been published by recent studies (e.g., Bufano et al. 2009; Foley et al. 2012a; Brown et al. 2014; Smitka et al. 2016; Gall et al. 2017). Although HST has superior UV capabilities compared to Swift, the fast turnaround of Swift and its efficiency to obtain the data are unmatched. The earliest UV spectrum of a SN Ia published before this work was obtained from Swift (SN 2009ig; Foley et al. 2012a); it was observed $\sim 13$ days before the peak brightness. Extremely early observations with Swift are complementary to the existing HST UV sample.

However, the slitless design of the Swift observations makes the spectrum more likely to be contaminated by nearby background sources. This not only complicates the data reduction, but also makes the interpretation of Swift datasets difficult. Traditional methods using Swift/UV-Optical Telescope (UVOT; Roming et al. 2004) grism data-reduction software (UVOTPY; Knuij 2014) have been widely used, but they become less reliable when.
reducing spectra that are seriously contaminated by nearby background sources. A more effective decontamination technique has been developed by Smitka et al. (2016). However, their method requires a template observation of the galaxy with the same spacecraft roll angle at late times (usually > 1 yr after SN explosion), which weakens the advantage of Swift (i.e., its fast turnaround). A relatively fast and correct reduction of early-time data is useful for assessing and scheduling the follow-up observations of young transients.

In this work, we present a SN sample that is more than three times larger than that of the HST UV sample. We improve the Swift UVOT grism data-reduction procedure to better extract SN spectra. This allows us to produce more accurate Swift spectra, which we will exploit in future analyses.

A plan of the paper follows. In Section 2 we introduce the selection and observations of our SN Ia sample. Section 3 discusses the data-reduction techniques. We present the spectra in Section 4 and summarise our results in Section 5. Throughout this paper, we assume $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and a flat universe with $\Omega_M = 0.3$.

2 OBSERVATIONS

2.1 SN sample selection

Most of the SNe in our sample were observed as part of our dedicated Guest Investigator programs (GI–04047, GI–5080130, PI Filippenko; GI–8110089, GI–1013136, GI–1215205, PI Foley). However, the full sample contains all SNe Ia observed with the UVOT/UV grism by Swift (excluding spectra that are not useful for further analysis; see below for more details).

The UVOT has a relatively small aperture (30 cm), and so only relatively nearby SNe Ia are sufficiently bright (distance modulus $\mu \lesssim 35 \text{ mag}$, corresponding to $V_{\text{max}} \lesssim 15 \text{ mag}$) to produce high-quality spectra in reasonable exposure times. We desired spectra of the SNe before or near peak brightness, and therefore most SNe in the sample were discovered 1–2 weeks before peak brightness.

The sample presented here contains 120 Swift/UVOT Grism spectra of 39 SNe Ia, with 20 SNe observed through our Swift programs and another 19 SNe selected from the Swift data archive that have UV spectra. The complete list of SNe in this work can be found in Tables 1 and 2. Besides these 120 spectra, there are 17 observations from which we cannot extract any useful data or that were highly contaminated by background sources. We summarise them in Table 4.

In Figure 1, we present the redshift, $\Delta m_{15}(B)$ (the $B$-band decline 15 days after peak brightness), number of spectra per SN, and rest-frame phase distributions of our sample. The median redshift of the sample is 0.0079, with the closest object having $z = 0.0006$ ($D = 3.3 \text{ Mpc}$; SN 2014J) and the most distant SN having $z = 0.0214$ ($D = 93 \text{ Mpc}$; SN 2009dc). The $\Delta m_{15}(B)$ of our sample ranges from 0.6 to 1.8 mag (median of 1.1 mag), with three objects classified as super-Chandra SNe Ia having $\Delta m_{15}(B) = 0.72$ (SN 2009dc), 0.59 (SN 2011aa), and 1.08 mag (SN 2012dn). We lack sufficient data to measure $\Delta m_{15}(B)$ of 7 SNe.

A large fraction of the SNe in our sample (24 out of 39) have multiple epochs of UV spectra, with a median of 2 spectra per SN. This makes our sample particularly useful in studying UV spectral evolution. The SN phase is relative to the epoch of peak optical brightness. For the 6 SNe where we do not have light curves, the epoch of peak brightness is estimated by fitting the optical spectra with SNID (Blondin & Tonry 2007). The median phase (in the rest frame) of the first observation of a SN and all spectra is $-4.5$ and $-1.9$ days, respectively. Among the 39 SNe, 13 have spectra $\gtrsim 1$ week before peak brightness, 29 have pre-peak spec-

Figure 2. Upper panel: Swift data image of SN 2012cg. Lower panel: Same as upper panel, but with annotations. The first-order spectra from the SN and its host galaxy are marked with green arrows. The zeroth-order light from the SN and its host galaxy are marked with blue arrows. All zeroth-order images from nearby bright stars are marked in cyan. The image is 17′×17′.
Figure 3. Rotated and expanded version of the SN 2012cg image shown in Figure 2. The top, middle, and bottom panels mark the SN and host-galaxy spectra, the SN extraction aperture, and the background regions, respectively.

Figure 4. **Upper panel**: Comparison of interpolated background spectra by varying the offset (in pixels) of the background channel relative to the SN aperture as shown in Figure 3. Here the background spectra with offsets of 3 (the value ultimately chosen for this spectrum), 10, 15, 20 pixels are shown as black, red, blue, and green curves, respectively. **Bottom panel**: The resulting SN spectra for the background offsets shown in the upper panel plotted in their corresponding colours. Savitzky-Golay smoothed spectra are overplotted, as thick lines, in both panels.

Figure 5. Spatial profile of the SN and background perpendicular to the SN trace (a “cross cut”) for the data presented in Figure 3 (black curve). The red dashed lines define the aperture used to extract the SN spectrum. The regions used to define the background are marked by hashed green regions. The interpolated background used for final background subtraction is shown as a blue dashed line. In this example, the size of the target aperture is set to 13 pixels (1.8σ). The size of each background region is 3 pixels. The upper and lower background regions are offset by 3 pixels from the edge of the target aperture.

2.2 Swift observations

The spectroscopic observations were performed by the Swift UVOT (Roming et al. 2004). The UVOT provides UV and optical spectroscopy with either slitless UV-grism or V-grism. In this work, we focus on the UV-grism observations,
with a wavelength coverage of $\sim 1700$–$5000$ Å and the UV response optimised in the 2000–3400 Å region.

Owing to the slitless design of the UVOT for spectroscopy, the data image contains both zeroth-order and higher-order emission (see Figure 2 for an example). We asked our targets to be observed under the “clocked mode” when possible. Observing in clocked mode reduces the contamination from zeroth-order images of field stars (e.g., those marked in the lower panel of Figure 2) where the first-order light falls on the detector - and comes close to a slit spectrograph in the occulted region.

Given the brightness of our targets, we requested an average exposure time $T_{\text{exp}} = 15$ ks in our own programs to obtain a good UV spectrum near peak brightness; however, such long exposures were rarely obtained because of various observing constraints. The exposure times ranged from 0.6 to 18 ks with a median of 8.5 ks.

3 DATA REDUCTION

Compared to typical slit spectroscopy, the slitless design of the Swift UVOT grism makes the target spectrum more likely to be contaminated by nearby background sources. Although “clocked mode” is adopted for most of our observations, higher-order spectra (e.g., from either the host galaxy or field stars) could still overlap or fall close to our targets, affecting the background subtraction.

The other major complication for slitless spectra is that the entire galaxy along the dispersion direction, instead of the region directly coincident with the SN, will contaminate the spectrum. These regions are spatially offset from the SN and other regions of the galaxy, and therefore light from nearby wavelengths can contaminate the SN spectrum (effectively “smearing” the galaxy spectrum in the wavelength direction). Smitka et al. (2016) attempted to address these problems by observing a template image of the galaxy long after the SN faded in nearly the same configuration (e.g., clocking, pointing, and roll angle) as the original data image.

They measure the background at the same location in the template image and then subtracted that from the target spectrum. This decontamination technique is effective in reducing any contamination in the SN spectrum. However, the template image can only be obtained after the SN has faded away (usually $\gtrsim 1$ yr after peak brightness). Given the fast turnaround of Swift, it would be ideal to be able to perform an effective data reduction on a shorter timescale. Moreover, the exposure time for the template spectrum must be long (i.e., comparable to that of the data image), so as to not adversely affect the SNR of the final host-subtracted SN spectrum.

We developed our own pipeline to reduce UVOT grism data, building upon the Swift UVOTPY software (Kuin 2014; Kuin et al. 2015). We follow the standard procedures in UVOTPY, such as target extraction, background subtraction, wavelength calibration, and flux calibration. However, our pipeline measures the background in a different way. Instead of creating a smoothed background image by averaging the regions above and below the target spectrum, we extract background spectra above and below the target with customisable offsets and sizes and then subtract the interpolated (at the position of the target) background spectrum.

We illustrate the target and background extractions in Figure 3. The top panel shows the first-order spectrum of SN 2012cg from Figure 2. The contamination from the host spectrum is clearly seen above the SN trace. The aperture used to extract the SN spectrum is marked in the panel. For bright objects, we generally adopt an aperture size similar to that of the UVOTPY default (i.e., 2.5 $\sigma$). Here the aperture size is controlled by $\sigma$, the standard deviation of a Gaussian distribution used to fit the count rate. Smaller apertures are recommended for fainter sources or those with nearby contamination. For SN 2012cg, as displayed in Figure 3, we use an aperture size of 1.8 $\sigma$.

When using smaller apertures, we rescale the flux to match that of the default aperture size which was used for flux calibration and coincidence-loss correction.

We demonstrate the background extraction in the bottom panel of Figure 3. The two apertures used to extract the background spectra above and below the target are shown in the panel. They are offset from the target along the dispersion axis to trace the curvature of the spectrum. The background spectrum can be sensitive to the offset of the apertures from the target. Because of the contamination from the underlying host-galaxy spectrum, the flux of the background spectrum can vary by a factor of $\sim 2$ depending on different offsets, altering the final target spectrum significantly; this effect is shown in Figure 2. To accurately estimate the local background, we generally extract the background spectrum as close to the SN as possible, selecting an aperture size that does not overlap with the SN aperture. This is achieved by inspecting the “cross cut” of the spectrum (i.e., the spatial flux distribution perpendicular to the trace; see Figure 4). For SN 2012cg, we offset the background apertures from the edge of the target aperture by 3 pixels to not only remove the host-galaxy light, but also not to include the SN light. Larger offsets result in incorrect background subtraction and increase the contamination from the host galaxy.

After the target extraction and background subtraction, we wavelength- and flux-calibrate each spectrum following.
Figure 7. Upper-left panel: Signal-to-noise ratio (SNR) of the Swift sample as the function of redshift. Here we select the spectrum closest to the peak brightness (within 5 days) of each SN for comparison. The SNRs are determined for 2300–2800 Å (mid-UV) and 2900–4000 Å (near-UV) and displayed as blue squares and red triangles, respectively. Upper-right panel: Same as the upper-left panel, but scaling the SNR to that expected with a $T_{\text{exp}} = 15$ ks exposure (see Section 4.2 for details). The inverse-square law, flux $\propto D^{-2}$ (or SNR $\propto D^{-1}$), is overplotted (the vertical position is arbitrary). Here the variable $D$ represents the luminosity distance of the SN. Middle-left panel: The SNR of the Swift sample as a function of $V$-band peak brightness. As in the upper panels, the SNR is determined from the near-peak spectrum of each SN. Middle-right panel: Same as the upper-right panel, but with $V$-band peak brightness. Lower-left panel: The SNR of the Swift sample as a function of rest-frame phase. We select the SNe which have multi-epoch observations to show the temporal variation of SNR. Here the SNR is determined for the entire spectral range (2300–5000 Å). The vertical dotted line marks the epoch of peak brightness. Lower-right panel: Same as the lower-left panel, but scaling the SNR to that expected with a $T_{\text{exp}} = 15$ ks exposure.
the procedures in UVOTPY. Given the large uncertainty in wavelength calibration (the accuracy is \(\sim 9\,\text{Å} \) for the UV grism clocked mode (Knia et al. 2015), we shift the zeropoint of the wavelength solution for each individual exposure by cross-correlating the spectrum to that of another spectrum (either an HST or a ground-based spectrum) at a similar phase.

Each epoch of spectroscopy usually consists of several short exposures, with each observed under slightly different conditions that slightly change the flux and wavelength of the spectrum. Therefore, we repeat the same reduction procedure with each individual exposure before combining all spectra into a single spectrum. If no comparison spectrum is available, we simply shift the wavelength of all the exposures to match the mean value. The shift of our Swift spectra ranges from \(~30\) to \(+30\,\text{Å}\), with an average of \(-6\,\text{Å}\) relative to the HST spectra.

For bright zeroth-order contamination (e.g., field stars) falling close to the target spectrum, our pipeline can identify those sources (through the background spectrum) more easily than the old method, but it is generally inferior to reductions using a template spectrum (i.e., Smitka et al. 2016). We cross-check bright sources \((B < 18\,\text{mag})\) from the USNO-B1.0 catalog (Monet et al. 2003) and remove the affected pixels when producing the final spectrum.

4 RESULTS

4.1 Comparison of data-reduction methods

Figure 6 shows a comparison of spectra reduced using the method described in Section 3 to the same spectra reduced using the default UVOTPY software and the Smitka et al. (2016) decontamination method. The spectrum produced through our method agrees well with that from Smitka et al. (2016). However, the spectrum reduced by the default pipeline is clearly offset in flux from the other two spectra. This is likely caused by incorrect host-galaxy subtraction (see Figures 3 and 4). The default UVOTPY method underestimates the underlying background, resulting in a spectrum with higher flux at all wavelengths (i.e., with additional light from the host galaxy). Our new method removes the host contamination and performs the background subtraction more correctly.

We display the reductions of all 120 spectra in Figures 10 through 16 using the improved method. Here we trimmed each spectrum to show only the UV flux redward of 2300 Å, as the SNR of Swift spectra generally deteriorates dramatically below \(~2300\,\text{Å}\).

4.2 Data quality

The SNR of each spectrum depends on many factors such as the exposure time \((T_{\text{exp}})\), distance to the SN, the amount of host-galaxy extinction, and phase. The sensitivity of the Swift UV grism peaks at \(~2800\,\text{Å}\). However, because of a SN Ia SED peaks near 4000 Å at maximum brightness, the SNR also increases from the UV to the optical (in terms of the effective wavelength). Here we report the SNR of each spectrum as a function of redshift, luminosity, rest-frame phase, and wavelength. The large range of \(T_{\text{exp}}\) (a factor of \(~10\)) for our sample complicates the comparison of other properties. To compensate for these differences, we also calculate the SNR scaled to that expected with a \(T_{\text{exp}} = 15\,\text{ks}\) exposure. This is achieved by multiplying the SNR by a factor of \(\sqrt{15\,\text{ks}/T_{\text{exp}}}\) (assuming the noise is dominated by Poisson noise). This simple approximation ignores other factors such as the varying background for different SNe and detector noise, but it is sufficient for our purposes.

To investigate the effect of distance on the SNR, we select only the spectrum nearest to the peak brightness (within 5 days from the peak) for each SN. The result is shown in the upper panels of Figure 7. Not surprisingly, the SNR of the spectrum shows strong correlation with the redshift, in a sense that SNe at higher redshift (thus more distant) tend to have lower SNR than those of more nearby SNe. We find that the trend generally follows the same direction as an inverse-square law (although with large dispersion), where the SN brightness is expected to be inversely proportional to the square of its luminosity distance (or the SNR is inversely proportional to the luminosity distance).

As noted above, the SNR of the spectrum also depends on the wavelength. Here we calculate the SNR in two separate regions: 2300–2800 Å (mid-UV) and 2900–4000 Å (near-UV). We find that the SNR decreases dramatically at shorter wavelengths. The SNR in the near-UV is on average \(~10\) times higher than that in the mid-UV region.

We show the SNR of the (near-peak) spectrum as a function of SN V-band peak brightness in the middle panels of Figure 7. Most of the SNe in our sample are brighter than \(V = 15\,\text{mag}\) at peak, with the brightest object having \(V \approx 10\,\text{mag}\) (SN 2011fe) and the faintest object having \(V \approx 15.6\,\text{mag}\) (SN 2016eoa). The relation also appears to be tighter than that with redshift, and thus will be useful for scheduling future observations, in estimating the SNR of the spectrum given the exposure time and SN magnitude. Note that SN 2014J has \(V \approx 10.6\,\text{mag}\) at peak, which is the second brightest object in our sample (in terms of V-band peak brightness). However, its spectrum has a low SNR \((\sim 1\) in mid-UV) due to large extinction \((A_V \approx 2\,\text{mag})\). We also compare our samples with SNe in the Swift data (e.g., Foley et al. 2016) to study the SNR variations.

In the bottom panels of Figure 7, we show the dependence of SNR on the SN phase. By examining the SNe which have multi-epoch observations in our sample, we find the trend that the SNR of pre-peak spectra generally rises with phase and peaks at the maximum light. It then decreases after the peak when the SN gets fainter at later phases. This trend is consistent with the SN Ia light curve, where the peak luminosity is generally \(~3–4\,\text{mag}\) brighter than that right after the SN explosion (e.g., Zheng et al. 2013). The resulting variation on SNR of the spectrum can be as large as a factor of \(\gtrsim 10\) (assuming a fixed \(T_{\text{exp}}\)).

4.3 Comparison to HST UV sample

Compared to Swift, the current HST SN Ia UV sample that probes blueward of 2900 Å is relatively small (e.g., 9 SNe in Foley et al. 2016). The addition of 39 SNe Ia observed by Swift greatly increases the number of SNe with UV data. Here we compare these samples. The top panel of Figure 8 compares the SN phase distributions of the Swift and HST samples.
Swift tends to observe SNe at earlier phases than HST, with medians phases of −1.9 and +5.5 days, respectively. There are 6 Swift-observed SNe Ia with their first UV spectrum ≥10 days before peak brightness. In contrast, only 2 HST-observed SNe Ia have UV observations ≥10 days before peak brightness. As earlier observations provide critical progenitor information (e.g., Pan et al. 2015), Swift can be a powerful resource for studying SN Ia physics.

The bottom panel of Figure 8 compares the ∆m15(B) distributions of the Swift and Foley et al. (2016) HST samples. The Swift sample has a larger range of ∆m15(B) and several more examples for specific values of ∆m15(B). In particular, our Swift sample contains several slowly declining SNe Ia (e.g., ∆m15(B) < 0.8 mag). This will greatly increase the resolution and precision of parameter space when constructing data-driven models of SN Ia UV spectra (e.g., Foley et al. 2016).

For the subset of SNe that were observed at similar phases with both Swift and HST, we can directly compare the Swift data reduction to the well-calibrated HST data. Figure 9 displays the 6 SNe Ia which have high-SNR UV spectra and similar phases for both Swift and HST observations. The Swift spectra have been normalised to match the HST spectra in the region 3000–3500 Å (for SN 2017cbv, whose HST spectrum only covers λ < 3100 Å, we use 2500–3000 Å). We present the spectra in both linear and logarithmic scales in the figure. The spectra are generally well matched, further indicating that the Swift spectral reductions are accurate.

Compared to Swift, HST covers a similar wavelength range in the UV, but the HST spectra have consistently higher SNR.

5 SUMMARY

In this work, we present Swift/UVOT observations and reductions of 120 spectra of 39 nearby SNe Ia. This is the largest existing sample of SN Ia UV spectra that probe blueward of 2900 Å. The new sample doubles the number of SN Ia UV spectra and triples the number of SNe Ia with UV spectra.

We outline an improved method to reduce the Swift spectroscopic data and perform the reductions. This method achieves a more precise background subtraction than the original reduction pipeline. Our new method can effectively reduce the contamination from background sources, which is critical for the slitless observations of Swift UVOT.

Compared to the HST sample, the Swift sample is larger in both number of SNe and number of spectra. The Swift sample has a broad ∆m15(B) distribution, spanning the entire range for SNe Ia. The Swift sample also has significantly more SNe at the earliest phases, with the median phase of the first observation of a SN and all spectra being –4.5 and –1.9 days, respectively.

SN Ia UV spectra are critical to understanding the progenitor systems and explosion mechanisms of SNe Ia. With the addition of Swift UV spectra, we are building a sample which has the statistical power to investigate the UV properties of the SN Ia sample. A detailed analysis of these data will be presented in the second paper of this series (Pan et al., in preparation).

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Figure 9. UV through optical spectra (2300–5000 Å) of 6 SNe Ia observed with both Swift/UVOT (black curves) and HST/STIS (red curves). For each SN, we display the flux with both linear (upper subpanel) and logarithmic (lower subpanel) scales. Note that for SN 2017cbv, the HST spectrum only covers $\lambda \lesssim 3100$ Å.

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REFERENCES

Amanullah R. et al., 2014, ApJ, 788, L21
Blondin S., Tonry J. L., 2007, ApJ, 666, 1024
Brown P. J. et al., 2005, ApJ, 635, 1192
Brown P. J. et al., 2014, ApJ, 787, 29
Brown P. J., Landez N. J., Milne P. A., Stritzinger M. D., 2017, ApJ, 836, 232
Bufano F. et al., 2009, ApJ, 700, 1456
Cappellaro E., Turatto M., Fernley J., eds., 1995, ESA Special Publication, Vol. 1189, IUE-ULDA Access Guide No. 6: Supernovae
Childress M. J. et al., 2015, MNRAS, 454, 3816
Childress M. J. et al., 2016, PASA, 33, e055
Conley A. et al., 2008, ApJ, 681, 482
Folatelli G. et al., 2013, ApJ, 773, 53
Folatelli G. et al., 2010, AJ, 139, 120
Foley R. J. et al., 2012a, ApJ, 744, 38
Foley R. J. et al., 2014, MNRAS, 443, 2887
Foley R. J., Kirshner R. P., 2013, ApJ, 769, L1
Foley R. J. et al., 2012b, ApJ, 753, L5
Foley R. J. et al., 2016, MNRAS, 461, 1308
Foley R. J. et al., 2017, ArXiv e-prints
Friedman A. S. et al., 2015, ApJS, 220, 9
Gall C. et al., 2017, ArXiv e-prints
Gehrels N. et al., 2004, ApJ, 611, 1005
Goobar A. et al., 2014, ApJ, 784, L12
Hillebrandt W., Kroemer M., Röpke F. K., Ruiter A. J., 2013, Frontiers of Physics, 8, 116
Hillebrandt W., Niemeyer J. C., 2000, ARA&A, 38, 191
Hoeftich P., Khokhlov A., Wheeler J. C., Phillips M. M., Suntzeff N. B., Hamuy M., 1996, ApJ, 472, L81
Hosseinzadeh G. et al., 2017, ApJ, 845, L11
Kelly P. L., Filippenko A. V., Burke D. L., Hicken M., Ganeshalingam M., Zheng W., 2015, Science, 347, 1459
Kelly P. L., Hicken M., Burke D. L., Mandel K. S., Kirshner R. P., 2010, ApJ, 715, 743
Krisciunas K., Suntzeff N. B., Espinoza J., Gonzalez D., Miranda A., Sanchez P., 2017, Research Notes of the American Astronomical Society, 1, 36
Kuin N. P. M. et al., 2015, MNRAS, 449, 2514
Kuin P., 2014, UVOTPY: Swift UVOT grism data reduction. Astrophysics Source Code Library
Lampeitl H. et al., 2010, ApJ, 722, 566
Lentz E. J., Baron E., Branch D., Hauschildt P. H., Nugent P. E., 2000, ApJ, 530, 966
Maguire K. et al., 2012, MNRAS, 426, 2359
Maguire K. et al., 2013, MNRAS, 436, 222
Maoz D., Mannucci F., Nelemans G., 2014, ARA&A, 52, 107
Monet D. G. et al., 2003, AJ, 125, 984
Munari U., Henden A., Belligoli R., Castellani F., Cherini G., Righetti G. L., Vagnozzi A., 2013, NA, 20, 30
Pan Y.-C. et al., 2015, MNRAS, 452, 4307
Pan Y.-C. et al., 2014, MNRAS, 438, 1391
Perlmutter S. et al., 1999, ApJ, 517, 565
Phillips M. M., 1993, ApJ, 413, L105
Riess A. G. et al., 1998, AJ, 116, 1009
Riess A. G., Press W. H., Kirshner R. P., 1996, ApJ, 473, 88
Roming P. W. A. et al., 2004, in Proceedings of the SPIE, Vol. 5165, X-Ray and Gamma-Ray Instrumentation for

Astronomy XIII, Flanagan K. A., Siegmund O. H. W., eds., pp. 262–276
Shappee B. J. et al., 2016, ApJ, 826, 144
Silverman J. M., Ganeshalingam M., Filippenko A. V., 2013, MNRAS, 430, 1030
Silverman J. M., Ganeshalingam M., Li W., Filippenko A. V., Miller A. A., Poznanski D., 2011, MNRAS, 410, 585
Smartt S. J. et al., 2015, A&A, 579, A40
Smitka M. T., Brown P. J., Kuin P., Suntzeff N. B., 2016, PASP, 128, 034501
Smitka M. T., Brown P. J., Suntzeff N. B., Zhang J., Zhai Q., Wang X., Mo J., Zhang T., 2015, ApJ, 813, 30
Stritzinger M. et al., 2010, AJ, 140, 2036
Sullivan M. et al., 2010, MNRAS, 406, 782
Timmes F. X., Brown E. F., Truran J. W., 2003, ApJ, 590, L83
Wang X. et al., 2009a, ApJ, 699, L139
Wang X. et al., 2009b, ApJ, 697, 380
Yamanaka M. et al., 2014, ApJ, 782, L35
Zhang J.-J., Wang X.-F., Bai J.-M., Zhang T.-M., Wang B., Liu Z.-W., Zhao X.-L., Chen J.-C., 2014, AJ, 148, 1
Zheng W. et al., 2013, ApJ, 778, L15
Table 1. Summary of Swift UVOT grism observations of the SN Ia sample in this work.

| SN Name     | Host            | Redshift | $\Delta m_{15}(B)^	ext{v}$ (mag) | UT Obs. Date          | $T_{\text{exp}}$ (s) | $T_{\text{exp}}$ used$^\text{c}$ (s) | Phase (day) | Ref. |
|-------------|-----------------|----------|----------------------------------|-----------------------|----------------------|---------------------------------------|-------------|------|
| SN 2005am   | NGC 2811        | 0.0079   | 1.45(03)                         | 2005-03-08.02         | 2781.73              | 1097.31                               | 0.0         | Brown et al. (2009) |
| SN 2005cf   | MCG-01-39-03    | 0.0065   | 1.05(03)                         | 2005-06-04.71         | 1897.12              | 1897.12                               | -7.9        | Wang et al. (2009)  |
| SN 2009ig   | NGC 5728        | 0.0093   | 1.21(00)                         | 2009-02-13.16         | 3956.35              | 3956.35                               | 0.0         | Friedman et al. (2015) |
| SN 2009Y    | NGC 5728        | 0.0093   | 1.21(00)                         | 2009-02-27.57         | 14024.93             | 12737.63                              | -4.0        | Folatelli et al. (2013) |
| SN 2009an   | NGC 4332        | 0.0092   | 1.44(00)                         | 2009-09-03.36         | 14753.74             | 12650.73                              | -4.5        | Friedman et al. (2015) |
| SN 2009dc   | UGC 10064       | 0.0214   | 0.72(03)                         | 2009-09-03.36         | 14753.74             | 12650.73                              | -4.5        | Silverman et al. (2013) |
| SN 2010ev   | NGC 3244        | 0.0092   | 1.12(02)                         | 2010-07-12.13         | 17820.81             | 6325.86                               | 5.0         | Gutiérrez et al. (2016) |
| SN 2011B    | NGC 2655        | 0.0047   | 1.38(10)                         | 2011-01-15.20         | 10263.21             | 9654.62                               | -6.0        | Brown et al. (2017)  |
| SN 2011aa   | UGC 3906        | 0.0124   | 0.59(07)                         | 2011-09-04.71         | 10454.98             | 6633.80                               | -9.3        | Friedman et al. (2015) |
| SN 2011ao   | IC 2973         | 0.0107   | 1.00(00)                         | 2011-03-09.48         | 6004.08              | 6633.80                               | -2.5        | Silverman et al. (2013) |
| SN 2011by   | NGC 3972        | 0.0028   | 1.14(03)                         | 2011-11-05.50         | 9560.79              | 9560.79                               | 0.6         | Brown et al. (2014)  |
| SN Name   | Host        | Redshift | $\Delta m_{15}(B)^a$ | UT Obs. Date        | $T_{\text{exp}}$ | $T_{\text{exp \ used}}$ | Phase | LC ref.  |
|-----------|-------------|----------|----------------------|---------------------|-----------------|------------------------|-------|----------|
| SN 2011fe | NGC 5457    | 0.0008   | 1.11(00)             | 2011-08-28.52       | 9437.18         | 9437.18                | −13.8 | Munari et al. (2013) |
| SN 2011iv | NGC 1404    | 0.0065   | 1.69(05)             | 2011-12-05.26       | 8015.13         | 3048.35                | −5.7  | Foley et al. (2012b) |
| SN 2012cg | NGC 4424    | 0.0014   | 1.04(00)             | 2012-05-23.38       | 17685.15        | 15126.62               | −12.6 | Munari et al. (2014) |
| SN 2012dn | ESO 462-G016| 0.0101   | 1.08(03)             | 2012-07-23.28       | 3811.96         | 1188.78                | −1.5  | Brown et al. (2014)  |
| SN 2012fr | NGC 1365    | 0.0055   | 0.85(05)             | 2012-11-03.34       | 5927.61         | 5927.61                | −9.1  | Chang et al. (2014)  |
| SN 2012ht | NGC 3447    | 0.0036   | 1.39(05)             | 2012-12-26.35       | 13501.33        | 13501.33               | −8.3  | Yamanaka et al. (2014) |
| SN 2013aa | NGC 5643    | 0.0040   | 0.80(03)             | 2013-02-19.73       | 5625.08         | 5625.08                | −1.3  | Maguire et al. (2013) |
| SN 2013cg | NGC 2891    | 0.0080   | ...                  | 2013-05-12.95       | 11846.95        | 11846.95               | 0.0   | Spectrum² |
| SN 2014J  | NGC 3034    | 0.0007   | 0.95(01)             | 2014-01-25.67       | 11245.94        | 8649.39                | −6.3  | Foley et al. (2014)  |
| iPTF14bdn | UGC 8503    | 0.0156   | 0.84(05)             | 2014-06-08.70       | 7272.02         | 7272.02                | −5.7  | Smitka et al. (2015) |
| ASASSN-14lp| NGC 4666    | 0.0051   | 0.80(05)             | 2014-12-13.54       | 16848.62        | 16848.62               | −11.2 | Shappee et al. (2016) |
| SN 2016ccz| MRK 685     | 0.0150   | 1.00(02)             | 2016-05-28.87       | 11505.85        | 11505.85               | −1.2  | Foley et al. (2017)  |
| SN 2016coj| NGC 4125    | 0.0045   | 1.33(03)             | 2016-06-07.02       | 12877.91        | 7549.49                | −2.1  | Foley et al. (2017)  |
| SN 2016eiy| ESO 509-IG064| 0.0087  | ...                  | 2016-08-05.58       | 6697.64         | 4556.10                | 0.6   | Spectrum² |
| SN 2016ekg| PGC 67803   | 0.0171   | ...                  | 2016-08-06.31       | 7185.58         | 6105.81                | −0.7  | Spectrum² |
| SN 2016eoa| NGC 0083    | 0.0208   | 1.35(03)             | 2016-08-17.51       | 13133.66        | 13133.66               | 1.8   | Foley et al. (2017)  |
| SN 2016ff | UGC 430     | 0.0114   | 1.49(05)             | 2016-08-28.87       | 6315.70         | 5408.91                | 2.4   | Swope² |
| SN 2016gb | ESO 555-G029| 0.0097   | ...                  | 2016-10-04.44       | 11189.93        | 7405.62                | −2.5  | Spectrum² |
| SN 2016fd | UGC 9165    | 0.0175   | ...                  | 2016-12-13.42       | 11628.96        | 11628.96               | 5.3   | Spectrum² |

*Note:* The table continues with additional entries.
Table 3. Summary of Swift UVOT grism observations of the SN Ia sample in this work. (continued)

| SN Name   | Host    | Redshift | ∆m_{15}(B) | UT Obs. Date | T_{exp} | T_{exp} used | Phase | LC ref.       |
|-----------|---------|----------|------------|--------------|---------|-------------|-------|--------------|
| SN 2017cbv | NGC 5643 | 0.0040   | 1.06(00)   | 2017-03-12.53 | 11914.14 | 5005.92     | −16.5 | Hosseinzadeh et al. (2017) |
|           |         |          |            | 2017-03-17.58 | 11081.64 | 9239.51     | −11.5 |             |
|           |         |          |            | 2017-03-24.48 | 12373.66 | 12373.66    | −4.6  |             |
| SN 2017erp | NGC 5861 | 0.0062   | ···         | 2017-06-17.35 | 8495.45  | 4743.82     | −7.1  | Swope         |
|           |         |          |            | 2017-06-19.18 | 10173.46 | 8581.91     | −5.3  |             |
| SN 2018aoz | NGC 3923 | 0.0058   | ···         | 2018-04-12.82 | 2323.53  | 2323.53     | −2.2  | Spectrum      |

a The B-band decline 15 days after the peak brightness.
b The total exposure time of the exposures actually used for data reduction and SNR calculation in this work.
c The reference of SN photometric properties adopted in this work.
d The epoch of peak brightness is estimated from the optical spectrum observed on May 26, 2013 UT under the ANU WiFeS SuperNova Programme (AWSNAP; Childress et al. 2016).
e The epoch of peak brightness is estimated from the optical spectrum observed on July 26, 2016 UT under the Public ESO Spectroscopic Survey for Transient Objects (PESSTO; Smartt et al. 2015) program.
f The epoch of peak brightness is estimated from the optical spectrum observed on Aug. 01, 2016 UT by KANATA 1.5-m telescope.
g The epoch of peak brightness is estimated from the optical spectrum observed on Apr. 02, 2018 UT by FLOYDS-S telescope.

Table 4. Summary of Swift UVOT grism observations of the SNe Ia NOT included in this work owing to either extremely low SNR or serious background contamination in the UV.

| SN Name   | UT Obs. Date | Swift Obsid |
|-----------|--------------|-------------|
| SN 2005am | 2005-03-09   | 30010007    |
|           | 2005-03-18   | 30010036    |
|           | 2005-03-22   | 30010051    |
|           | 2005-03-24   | 30010075    |
| SN 2005hk | 2005-11-08   | 30338004    |
| SN 2007sr | 2007-12-21   | 31073004    |
|           | 2007-12-22   | 31073007    |
|           | 2007-12-23   | 31073010    |
|           | 2007-12-24   | 31073013    |
| SN 2010ev | 2010-07-05   | 31751001    |
| SN 2014J  | 2014-01-23   | 33124001    |
| SN 2016gfr| 2016-09-21   | 34732002    |
| OGLE16dha | 2016-09-30   | 34742002    |
|           | 2016-10-05   | 34742004    |
| SN 2018gv | 2018-01-23   | 10521003    |
|           | 2018-01-23   | 10521005    |
| SN 2018xx | 2013-02-23   | 10572004    |
Figure 10. *Swift* UVOT grism observations of SNe Ia. The red dashed line marks the level of zero flux.
Figure 11. Swift UVOT grism observations of SNe Ia (continued).
Figure 12. Swift UVOT grism observations of SNe Ia (continued).
Figure 13. Swift UVOT grism observations of SNe Ia (continued).
Figure 14. *Swift* UVOT grism observations of SNe Ia (continued).
Figure 15. Swift UVOT grism observations of SNe Ia (continued).
Figure 16. Swift UVOT grism observations of SNe Ia (continued).