

Astro2020 Science White Paper

Keeping an Ultraviolet Eye on Supernovae

- Thematic Areas:**
- Planetary Systems
 - Star and Planet Formation
 - Formation and Evolution of Compact Objects
 - Cosmology and Fundamental Physics
 - Stars and Stellar Evolution
 - Resolved Stellar Populations and their Environments
 - Galaxy Evolution
 - Multi-Messenger Astronomy and Astrophysics

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Abstract

As we look at near-term projects, the astronomical community will have incredible wide-field area and depth in the optical (thirty -meter telescopes, LSST) and the infrared (WFIRST, JWST). Missing from the U.S. plans are long-term replacements to the ultraviolet capabilities of the aging Hubble Space Telescope and Neil Gehrels Swift Observatory’s Ultra-Violet Optical Telescope (UVOT; Gehrels et al., 2004; Roming et al., 2005). It is imperative that we do not lose the ability to see in the ultraviolet over the same time period that time-domain astronomy makes its next leap into even larger samples of supernovae with LSST and WFIRST. The study of supernovae has had three primary roles: understanding the endpoints of stellar evolution, laboratories for explosion physics, and tools for cosmological measurements. Each is well-probed by ultraviolet observations.

1 Ultraviolet Probes of Supernova Physics

The ultraviolet flux dominates the spectral energy distribution of superluminous supernovae, interaction-driven type II_n and Ib_n supernovae, and the early phases of type II supernovae. A proper accounting of the bolometric luminosity requires measurements of that flux. The cooling of type II supernovae causes dramatic changes in the blackbody continua and the line absorption of different ionization levels of iron-peak elements (Dessart et al., 2009). For an accounting of the bolometric luminosity, broadband filters with a wide wavelength range of down to Ly-alpha is desirable. Also important is the flexibility of the observatory scheduling in allowing for target of opportunity observations with less than a week delay.

The temperature of the shock breakout and the subsequent adiabatic cooling of core-collapse supernovae is better constrained with ultraviolet observations, improving limits on the radius of the progenitor star. Similarly, the impact of a type Ia supernova ejecta with a companion is expected to have a distinct signature in the ultraviolet (Kasen, 2010). The predicted ultraviolet excess may have been detected in iPTF14atg (Cao et al., 2013) and SN2012cg (Marion et al., 2016). Several supernovae with early optical excesses, however, show no such excess (Miller et al., 2018; Hosseinzadeh et al., 2017). Constraining the type Ia supernova progenitor system is vital to understanding how the explosion observables might change through the history of the universe. This shock is most evident shortward of $\sim 2800 \text{ \AA}$, as the spectrum of the supernova ejecta is heavily line-blanketed at shorter wavelengths (Brown et al., 2012). Rapid response (< 1 day) is important if relying on ground-based discovery, while wide-field ultraviolet survey instruments could directly detect the emerging flux immediately after the explosion.

2 Understanding the Systematic Uncertainties of Type Ia Supernovae with Ultraviolet Observations

Ultraviolet observations are vital to understanding some of the most important astrophysical conditions affecting the use of type Ia supernovae as cosmological distance indicators. As sample sizes continue to grow, limiting systematic uncertainties will be critical to improving the cosmological constraints. Several of the astrophysical systematics are best probed in the ultraviolet. The ultraviolet is very sensitive to dust reddening. The reddening law appropriate for type Ia supernovae is surprisingly different than what is observed in the Milky Way (Krisciunas et al., 2007; Kessler et al., 2009). A further complication is disentangling the effect of dust reddening from intrinsic color variations (Wang et al., 2009; Foley et al., 2009; Mandel et al., 2014, 2017), both of

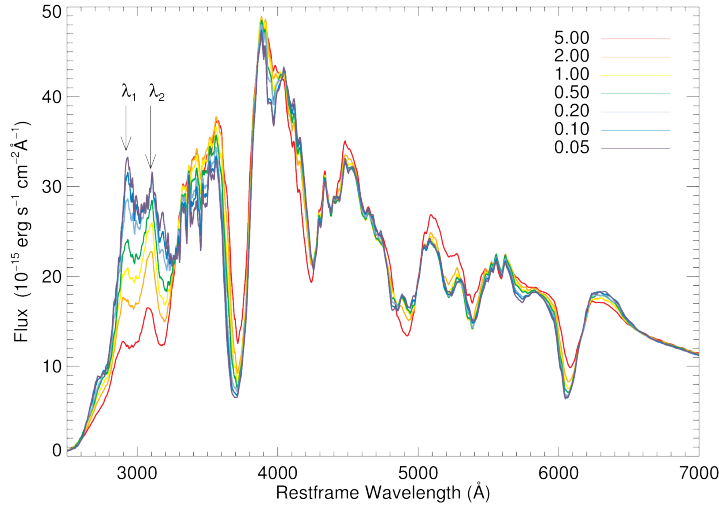


Figure 1: Theoretical models from Walker et al. (2012) with variations in the heavy metal abundances from a baseline model tuned to SN2005cf. λ_1 and λ_2 are conspicuous reverse fluorescence features which may aid in disentangling continuum variations from reddening variations.

which are strong in the ultraviolet (Brown et al., 2017, 2018).

The intrinsic color variations point to differences in the progenitors or the explosions of these objects prized for their homogeneity. The dispersion in luminosity increases to shorter wavelengths (Foley et al., 2008; Ellis et al., 2008; Brown et al., 2010; Foley et al., 2016), and different changes to the initial conditions could cause larger ultraviolet variations (see, e.g. Brown et al., 2015). Metallicity is the usual suspect which has been blamed separately for the differences in the mid-ultraviolet (Foley & Kirshner, 2013; Graham et al., 2015) and near-ultraviolet (Brown et al., 2018) spectra. One set of models from Walker et al. (2012) showing the significant difference in the ultraviolet is displayed in Figure 1. The degree to which an effect such as metallicity affects the magnitudes used for calibrating distances to type Ia supernovae must be known in order to make appropriate corrections to account for the systematic evolution of metallicity through the history of the universe or individual host galaxies.

Quantifying the effect of metallicity on distance estimates may require ultraviolet spectroscopy (2500-3500 Å) to disentangle multiple effects within a broadband UV filter (see, e.g. Brown et al., 2015) of type Ia supernovae in the nearby Hubble flow ($z > 0.02$) so that the physical characteristics determined by the ultraviolet spectra can be correlated directly with luminosities determined from Hubble-flow distances.

3 Comparing Supernovae Through Cosmic Time in the Rest-Frame Ultraviolet

Through metallicity or other effects, the evolution of supernovae through the history of the universe is best probed in the rest-frame ultraviolet for all supernova types. It is true that rest-frame ultraviolet observations can be obtained from ground-based optical observations of high-redshift supernovae. To compare supernovae across redshifts, however, a sample of supernovae at each redshift must be observed in the same rest-frame wavelength ranges. Type Ia supernovae have been followed to longer wavelengths to understand the redshifted optical bands which are already understood. Past a redshift of $z=1.7$, however, the observable range runs out. For the maximal range, one should begin at even shorter wavelengths. Observer-frame ultraviolet observations of nearby objects can be compared to progressively redder bands for higher redshift objects to observe the rest-frame ultraviolet.

An excellent example is shown in Figure 2. The extreme ultraviolet luminosity of Gaia16apd can be redshifted out to $z\sim 20$ (or whenever the first superluminous supernovae explode) and be detectable by the James Webb Space Telescope. A larger sample of nearby objects is needed where a full range of X-ray-UV-optical-NIR-radio data can be obtained of the supernovae and their host galaxies so that the physics of these explosions and whether they change through the history of the universe can be explored.

4 Studying Rare Objects in the Ultraviolet

While many approaches to supernovae already have large samples and the statistical gain has diminishing returns as the \sqrt{N} , there are still aspects of transient science which still have a linear growth or better in the science return. Rare transients which represent explosions in a short-duration phase of stellar evolution or initial conditions will be found in greater numbers. Identifying those unusual objects and being able to trigger ultraviolet observations will give the broader picture of the temperature and energy of these explosions.

Despite the large numbers of transients found, there are still unique objects being discovered, many of which reveal unique behavior in the ultraviolet. ASASSN-15lh was thought to be the most luminous supernova ever discovered (Dong et al., 2016). The ultraviolet luminosity was evidence of a high temperature and showed an unprecedented rebrightening in the ultraviolet (Brown et al., 2016). Subsequent work points to evidence of it being a tidal disruption event of a star by a spinning black hole at the center of its host galaxy (Leloudas et al., 2016; Krühler et al., 2018). Such an extremely luminous

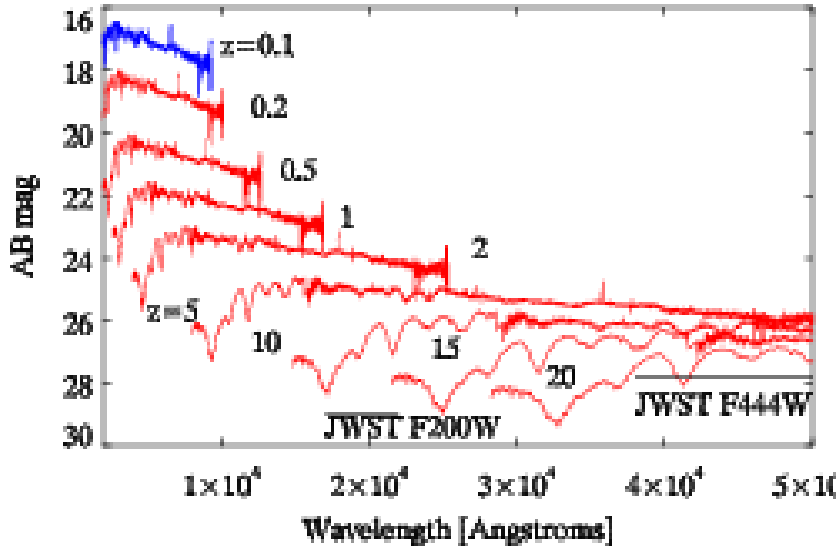


Figure 2: Ultraviolet spectrum of Gaia16apd with the photons redshifted and the flux attenuated by the distance. Such a luminous explosion would be detected from the earliest generations of stars.

object should be more easily found in flux-limited surveys, so such events must be extremely rare. AT2018cow is another ultraviolet-luminous transient which has been explained by both tidal disruption and stellar explosion interpretations (Perley et al., 2019; Kuin et al., 2019; Margutti et al., 2019). These two objects strikingly demonstrate that new and peculiar types of objects are still being discovered even after the thousands of supernovae already observed. Additionally, the electromagnetic counterpart of the binary neutron star merger was found to peak in the near-ultraviolet (see, e.g. Evans et al., 2017). Multi-messenger astronomy is supported by multi-band electromagnetic observations across a wide wavelength range.

These supernova science cases highlight some areas where important developments can be made by ultraviolet observatories, especially those with a wider field of view for prompt detection of shock breakouts and the early phases of supernovae, rapid follow-up capabilities to take advantage of ground-based discoveries, and/or higher sensitivity in the mid-ultraviolet ($\lambda < 2800 \text{ \AA}$) for spectroscopic studies of objects in the nearby Hubble flow. Ultraviolet observatories should be part of comprehensive long-term plans to have multi-wavelength eyes on the transient universe.

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