

## IDENTIFICATION OF TYPE Ia SUPERNOVAE AT REDSHIFT 1.3 AND BEYOND WITH THE ADVANCED CAMERA FOR SURVEYS ON THE *HUBBLE SPACE TELESCOPE*<sup>1</sup>

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### ABSTRACT

We present discoveries of Type Ia supernovae (SNe Ia) at  $z > 1$  and the photometric diagnostic used to discriminate them from other types of SNe detected during the Great Observatories Origins Deep Survey (GOODS) *Hubble Space Telescope* Treasury Program with the Advanced Camera for Surveys (ACS). Photometric redshift measurements of the hosts combined with deep F606W, F775W, and F850LP imaging discriminates hydrogen-rich SNe II from SNe I at  $z > 1$  by exploiting the UV deficit in the energy distributions of SNe Ia. This sorting allows rapid follow-up of space-based discoveries. Subsequent spectroscopy of 11 GOODS SNe Ia obtained from the ground and with the grism on ACS confirmed the reliability of our photometric screening. We present the highest redshift spectrum of any SN published to date, SN Ia 2002fw at  $z = 1.3$  observed near maximum brightness with the ACS grism. The lack of UV flux for true SNe Ia provides an effective tool for our ongoing efforts to build a sample of SNe Ia at  $1.2 < z < 1.8$ , which will extend the useful range of the magnitude-redshift relation of SNe Ia.

*Subject headings:* cosmology: observations — supernovae: general

### 1. INTRODUCTION

The unexpected faintness of Type Ia supernovae (SNe Ia) at  $z \approx 0.5$  provides direct evidence that the expansion of the universe is accelerating, propelled by “dark energy” (Riess et al. 1998; Perlmutter et al. 1999). Augmented samples of SNe Ia extended to  $z \approx 1$  (Tonry et al. 2003; Blakeslee et al. 2003; N. Suntzeff et al. 2004, in preparation; B. Leibundgut et al. 2004, in preparation), as well as more detailed studies of SNe Ia (see Leibundgut 2001 and Riess 2000 for reviews), have strengthened the case for the existence of dark energy based on SNe. The new cosmic concordance model contains both dark matter and dark energy (i.e.,  $\Omega_M \approx 0.3$  and  $\Omega_\Lambda \approx 0.7$ ) and is sharply delineated by the convergence of three independent probes of the  $\Omega_M$ - $\Omega_\Lambda$  plane: the cosmic microwave background, SNe Ia at  $z < 1$ , and large-scale structure. However, when the number of constraints nearly equals the number of parameters little power remains to test the validity of the paradigm. Efforts to use the same measurements to fit an additional parameter, such the equation of state for dark energy, are vulnerable to systematic errors without redundant measurements.

A simple prediction of the new cosmological model is the weakening of dark energy relative to dark matter in proportion to  $(1+z)^3$ , leading to an earlier epoch dominated by dark matter, with decelerating expansion. If we fail to see deceleration, the evidence for dark energy is in doubt. The tools for this test are SNe Ia at  $z > 1$ , whose leverage to measure past

deceleration grows with redshift. SNe Ia at  $z > 1$  also create the opportunity to *amplify* the effects of any astrophysical contaminants such as chemistry, age, or strange dust that might contaminate the dark energy signal from SNe Ia.

To date, the reach of discovery from the ground has been limited to  $z < 1.2$  (Aldering et al. 1998; Coil et al. 2000; Tonry et al. 1999, 2003). Pursuit of SNe Ia to higher redshifts is inhibited by the bright night sky redward of  $\sim 8000 \text{ \AA}$ . Searches at bluer wavelengths are starved of photons by the intrinsic deficiency of SNe Ia in the UV. Even at  $1.0 < z < 1.2$ , detections of SNe Ia from the ground are often not reliable. Success requires unusually favorable conditions and daringly low significance thresholds for detections, but attempts can result in false discoveries, inconclusive spectra, or incomplete photometric records (e.g., SN 1999fo, SN 1999fu, and SN 1999fv; Tonry et al. 2003). Spectroscopic screening of low-confidence SN Ia candidates at  $z > 1$  is always time-consuming and often impractical and unsuccessful.

From space, these challenges are largely mitigated. Gilliland & Phillips (1998) reported the detection of SN 1997ff by the Wide Field Planetary Camera 2 on the *Hubble Space Telescope* (*HST*). Using serendipitous follow-up of the field by the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS), Riess et al. (2001) showed that this SN was almost certainly of Type Ia at  $z \approx 1.7$  and its apparent magnitude consistent with deceleration. However, a single, sparsely observed SN is insufficient to guard against a spurious conclusion caused by lensing (Benítez et al. 2002) or an unexpected SN type.

An unprecedented opportunity to collect a significant sample of SNe Ia at  $1 < z < 2$  occurred in the 11th year of *HST* owing to three factors: the installation of a wider and faster Advanced Camera for Surveys (ACS; Ford et al. 2002), the refurbishment of NICMOS, and the periodic (45 day interval) multicolor imaging of two  $10' \times 15'$  fields with ACS by the Great Observatories Origins Deep Survey (GOODS) Treasury Program (Giavalisco et al. 2004). Each of the eight repeated epochs of the GOODS imaging was expected to yield one to two SNe Ia at  $z > 1.2$  as well as three to five other SNe. The ability to dis-

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criminate the SNe Ia at  $z > 1.2$  from other transients with high confidence is essential to avoid following the wrong objects, or squandering spectroscopic time, and to permit prompt *HST* monitoring via a preallocated program. The combined GOODS and SN “piggyback” program (GO-9352; principal investigator: A. G. Riess) constitutes the first program designed to discover and follow SNe from space.

We have used observed colors and photometric redshifts to identify likely SNe Ia at  $z > 1$  via their intrinsic UV deficit. Subsequent measurements using the grism on ACS have provided the spectroscopic confirmation at redshifts unreachable from the ground, including our first example and the highest redshift SN yet measured, in this case an SN Ia at  $z = 1.3$ . Here we report on a novel photometric method used to identify candidate SNe Ia at  $z > 1$  and demonstrate its spectroscopic confirmation. Elsewhere, we report details of the search for transients and their rates (Strolger et al. 2004; T. Dahlen et al. 2004, in preparation) as well as the constraints on cosmology and the nature of distant SNe Ia (Riess et al. 2004).

## 2. IDENTIFYING SNe Ia AT $z > 1$ : THE UV DEFICIT

The modern classification scheme of SNe includes at least seven primary subtypes (SNe IIL, IIP, IIb, IIn, Ia, Ib, and Ic) identified via the presence or absence of key features in their optical spectra (see Filippenko 1997 for a review). The major dichotomy of classification separates SNe with and without hydrogen (SNe II and I, respectively) in their spectra. Unfortunately, this historical convention fails to reflect current understanding, which recognizes a different, more physical bifurcation, that of explosion mechanism. SNe Ia are believed to arise from the thermonuclear disruption of a white dwarf and all other subtypes via core collapse in a massive ( $\geq 10 M_{\odot}$ ) star with varying degrees of mass loss (Wheeler & Harkness 1990; Filippenko 1997).

Explosive thermonuclear burning of the degenerate SN Ia progenitor produces  $0.3\text{--}1 M_{\odot}$  of iron-group metals. Owing to its high velocities and great abundance, Fe II resonantly scatters much of the thermal continuum flux in the UV ( $\lambda < 3300 \text{ \AA}$ ), imprinting a characteristic “UV deficit” in the spectral energy distributions (SEDs) of SNe Ia. In contrast, the most common form of core-collapse SNe, those with hydrogen-rich, electron-scattering atmospheres, are strong emitters in the UV. As shown in Figure 1, the UV deficit of SNe Ia provides a useful, photometric method to discriminate between the two most frequently observed subtypes of SN, SNe Ia and SNe II. Rest-frame optical ( $\lambda > 3300 \text{ \AA}$ ) color discrimination of SNe has been shown by Poznanski et al. (2002) to be of use for this purpose, although photometric differences are more subtle at these wavelengths than in the UV.

Although SNe Ia may be routinely discovered and identified via photometric means, misidentification is possible. Core-collapse SNe with negligible hydrogen (SNe Ib and Ic) also have weak UV flux. However, such SNe are less common in the field than hydrogen-rich core-collapse SNe by a factor of  $\sim 3$  (Cappellaro et al. 1997; Cappellaro, Evans, & Turatto 1999; W. Li and A. V. Filippenko 2003, private communication), and most are fainter than SNe Ia by 1–3 mag, effectively reducing their discovery rate in a magnitude-limited survey (e.g., Li et al. 2001). More troublesome is a subset of SNe Ic, which attain optical luminosities comparable to those of SNe Ia and would be the chief contaminant to SNe Ia identified in magnitude-limited surveys in the optical. However, past surveys of this

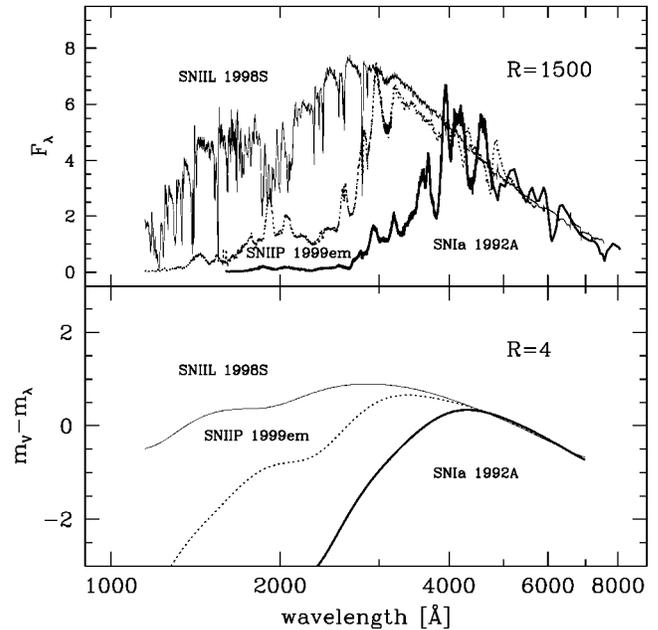


FIG. 1.—*Top*: High-resolution spectra of three representative young SNe: SN Ia 1992A (Kirshner et al. 1993) and a blue SN II (SN 1998S; Lentz et al. 2001) and a redder SN II (SN 1999em; Baron et al. 2000) from 1200 to 7000  $\text{\AA}$  normalized in the optical. *Bottom*: Low-resolution sampling of the same spectra showing the color differences in the UV. Fe II resonantly scatters much of the thermal continuum flux of SNe Ia in the UV ( $\lambda < 3300 \text{ \AA}$ ), imprinting a characteristic UV deficit not seen in the hydrogen-rich photospheres of common SNe II.

nature demonstrate that the degree of contamination is small. Ultraluminous SNe Ic constitute only a few percent of SNe found by the Calán-Tololo Survey (Hamuy et al. 1996; Clocchiatti et al. 2000), the Abell Cluster Search (B. P. Schmidt 2003, private communication), the Lick Observatory Supernova Search (Filippenko et al. 2001; W. Li and A. V. Filippenko 2003, private communication), and the Nearby SN Factory Search (P. Nugent 2003, private communication), or in compilations of past surveys (Richardson et al. 2002). Heavily reddened core-collapse SNe could mimic the colors of an SN Ia in the UV, but the total absorption would severely reduce their detection rate at  $z > 1$ . Without a significant evolution in the relative rates of SN types or their photometric properties, the expected frequency of misidentification of candidate SNe Ia targeted by this diagnostic would be less than one in 10, although the rate may rise at higher redshifts. Because cosmological measurements from SNe Ia are statistical in nature, modeling of the frequency of contamination can be used to correct a sample, but the best defense against sample contamination is spectroscopic screening.

GOODS provides the means to use this photometric discriminant for SNe Ia at  $z > 1$ . SNe in GOODS were discovered by image subtraction in 2000 s exposures in ACS F850LP, a passband that includes the rest-frame optical (*UBVRI*) up to  $z \approx 1.5$  and allows for the detection of SNe Ia up to  $z \approx 1.8$ . Simultaneous imaging in F775W and F606W provides a useful measurement of the UV flux at  $z > 1$ . As shown in Figure 2, the expected F775W–F850LP and F606W–F850LP colors of SNe Ia and SNe II diverge at  $z > 1.0$  and  $z > 0.7$ , respectively, with apparent differences reaching 1–3 mag. SNe Ia at  $z > 1.3$  are expected to be so faint in F606W that such SNe should appear as “dropouts.” The survey limit of F850LP  $\approx 25.8$  mag

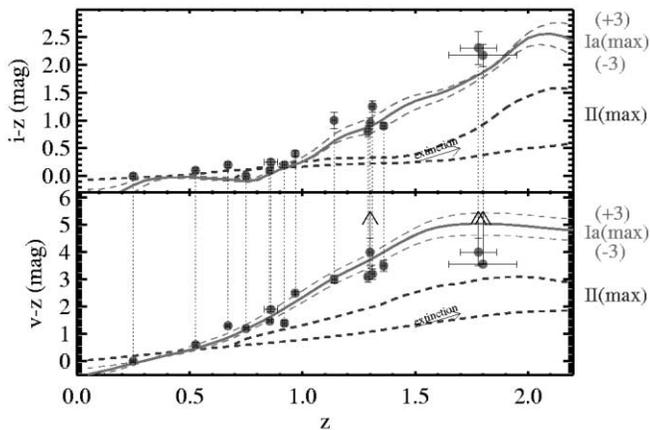


Fig. 2.—Finding and classifying SNe Ia with ACS via the UV deficit. The expected  $i-z$  (i.e., F775W–F850LP) and  $v-z$  (i.e., F606W–F850LP) colors of SNe Ia and SNe II near maximum brightness (calculated from the SEDs in Fig. 1) compared to the observed colors of candidate SNe Ia found in GOODS data. SNe Ia are readily distinguishable from SNe II by their red colors. Reddened SNe II would be too faint for this magnitude-limited sample. SNe shown at  $z < 1.5$  were independently confirmed to be SNe Ia.

(see Strolger et al. 2004 for more precise values) restricts the discovery of SNe at  $z > 1.2$  to  $M_B < -17.5$  mag and at  $z > 1.5$  to  $M_B < -18.5$  mag.

Within 6–18 hr after a repeat visit of the Chandra Deep Field–South or Hubble Deep Field–North, each GOODS epoch was differenced with the preceding epoch to identify SNe. Follow-up spectroscopy of most candidates with  $F850LP < 24$  mag was attempted from the ground with the Keck and Magellan telescopes during the next new moon and are reported elsewhere (Riess et al. 2004). Candidates whose host photometric redshift indicated a high likelihood of  $z > 1.2$  and whose colors indicated a good match to the UV deficit of an SN Ia at the host redshift were targeted for follow-up with *HST* using ACS direct imaging, NICMOS, and in some cases ACS grism spectroscopy. All likely SNe were reported in the IAU Circulars within 72 hr of discovery, 43 to date (Giavalisco et al. 2002; Riess et al. 2002, 2004; Strolger et al. 2002; Casertano et al. 2003; Ferguson et al. 2003; Dahlen et al. 2003). A complete listing of the GOODS SNe and their classifications can be found in Strolger et al. (2004). Here we focus on the initial identification via the apparent UV deficit of 15 candidate SNe Ia in three redshift intervals:  $z < 1.0$ ,  $1 < z < 1.5$ , and  $z > 1.5$ .

### 3. HIGH, HIGHER, HIGHEST

For four SNe Ia with  $0.2 < z < 1$ , the apparent magnitude of  $21 \text{ mag} < F850LP < 23.5 \text{ mag}$  made it possible to get a spectroscopic confirmation in a few hours on a 6–10 m telescope (three others were confirmed in ACS grism images). Each of these spectra provides conclusive identification as an SN Ia, as well as the indicated redshift, and is presented elsewhere (Strolger et al. 2004; Riess et al. 2004). In all cases, the measured photometric redshifts and colors were consistent with the spectroscopic identification, as shown in Figure 2. However, because the effective rest-frame wavelength of the F606W bandpass remains redward of 3300 Å at  $z < 1$ , the observed colors do not sample the UV deficit and were therefore insufficient to distinguish the transients as probable SNe Ia from colors alone.

For five transients, the observed colors and the photometric

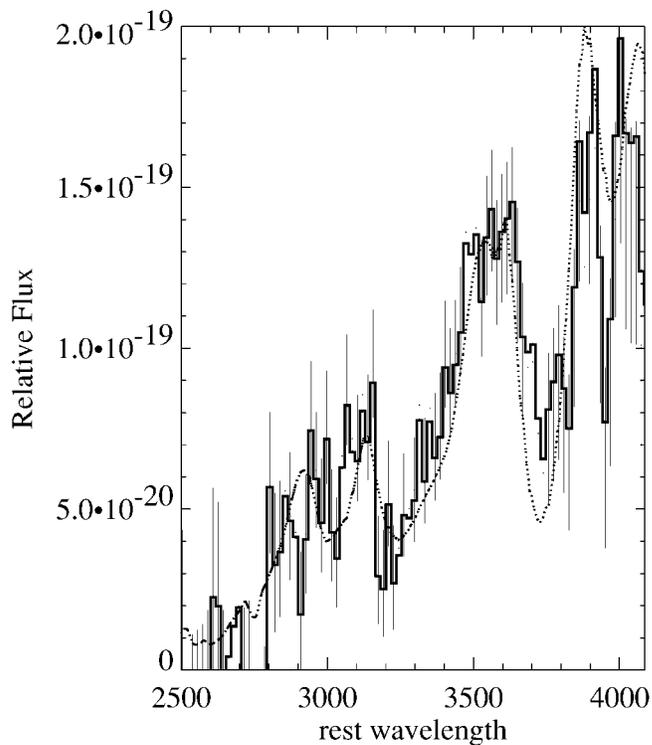


Fig. 3.—Spectrum of SN Ia 2002fw at  $z = 1.3$  as observed in 15 ks through the grism filter with ACS on *HST* compared to SN Ia 1981B at maximum light. Identifiable absorption features in the spectrum of SN 2002fw include the Ca II H and K absorption blend at rest-frame 3700 Å and the blueshifted Si II  $\lambda 4130$  absorption.

redshifts of the hosts were consistent with being SNe Ia at  $1 < z < 1.5$  and inconsistent with being SNe II. In this redshift interval, the observed colors were highly indicative of SN type, allowing us to select these as likely SNe Ia for target of opportunity (ToO) monitoring with *HST* in advance of spectral confirmation and without delays or gaps in the photometric record. Four of the five were spectroscopically confirmed as SNe Ia at a redshift consistent with the initial photometric estimate, as shown in Figure 2 (Riess et al. 2004).

The deep imaging obtained by GOODS before the discovery of SN 2002fw indicated  $1.1 < z < 1.5$  with 95% confidence for its host galaxy. The measured colors of SN 2002fw at discovery of  $F775W-F850LP = 0.80 \pm 0.05 \text{ mag}$  and  $F606W-F850LP = 3.0 \pm 0.1 \text{ mag}$  were consistent with an SN Ia at the photometric redshift (but not an SN II), precipitating a prompt *HST* monitoring (ToO). In Figure 3, we present the *HST* spectroscopy of SN 2002fw, an SN Ia at  $z = 1.3$  and the first high-redshift SN Ia harvested from the GOODS program (see § 3). The spectrum was obtained in 15 ks of exposure with the ACS Wide Field Camera and the grism filter, beginning 10 days after the discovery image. Similar ACS grism data were obtained for other SNe Ia in this redshift range and will be shown elsewhere (Riess et al. 2004).

Two SNe were discovered whose photometric redshifts and colors were indicative of SNe Ia at  $z > 1.5$ . In both cases, the  $F775W-F850LP$  color was between 2.0 and 2.5 mag, consistent with the UV deficit of SNe Ia and strongly inconsistent with the bluer colors of SNe II. The absence of either SN in the F606W images to the detection limit of point sources (with known position) limits  $F606W-F850LP > 3.2 \text{ mag}$  for each,

consistent with SNe Ia and inconsistent with SNe II. Elsewhere, we present the follow-up observations of these SNe and provide further constraints on their type and distance (Riess et al. 2004).

#### 4. DISCUSSION

The UV deficit is a useful tool to identify likely SNe Ia for rapid follow-up observations. For GOODS, careful consideration was given to select passbands that could use this diagnostic to discriminate SNe I from SNe II at  $z > 1$ . Monte Carlo simulations of the selection of SNe Ia at  $z > 1$  indicate that the frequency of “false positives” (i.e., non-SNe Ia or SNe Ia at  $z < 1$ ) would be less than 10% for expected transients. Furthermore, in each actual case, we can calculate the likelihood of a misidentification taking into account the photometric measurements, their uncertainties, and the quality of the fit. The expectedly high level of success in identifying SNe Ia at  $z > 1$  allowed us to select suitable candidates and commit to rapid follow-up with *HST* in advance of any additional confirmation. The subsequent spectroscopy confirmed statistically and on an individual basis the good likelihood of selecting SNe Ia via their UV deficit.

A few SNe were discovered at  $z > 0.7$  whose blue color could be used to reject a classification of SN Ia and matches well with classification as a young SN II (e.g., F606W–F850LP = 0.0–1.0 mag and  $z = 0.9$ ; see Fig. 2). However, the signal-to-noise ratio required to confirm spectroscopically the photometric evidence for young candidate SNe II at these redshifts far exceeds that of SNe Ia because of both the weakness of features and the candidate’s relative faintness, and we did not get enough data to confirm this classification.

Owing to its high redshift, the well-measured part of the spectrum of SN 2002fw extends from 2500 to 4200 Å (see Fig. 3). For comparison, we have superposed the spectrum of the prototypical SN Ia 1981B at maximum extended to the UV by *IUE* (Branch et al. 1985). Overall, the agreement between the two is excellent both in color and for specific features. Only minor differences are apparent, consistent with the intrinsic variation of SN Ia abundances and explosion velocities. Notable and pro-

nounced absorption features in the spectrum of SN 2002fw include the Ca II H and K feature at rest-frame 3700 Å and the blueshifted Si II  $\lambda$ 4130. In the UV region of the spectrum, a rise blueward of 3200 Å is well discerned owing to blending of high-velocity Fe II absorption. Our line identifications are from Kirshner et al. (1993) and Mazzali et al. (1993). The defining feature of SNe Ia, Si II  $\lambda$ 6355 (typically blueshifted to 6150 Å) cannot be discerned because of the high redshift of the SN. However, as discussed by Coil et al. (2000) for SN 2002fv ( $z = 1.2$ ), the absorption feature near 4000 Å due to Si II  $\lambda$ 4130 is sufficient to establish SN 2002fw as an SN Ia (although not as useful at later times as Si II  $\lambda$ 6355) and not an SN Ib/Ic.

Light curves are a critical component of measuring distances to SNe Ia. They constrain the age of SN Ia observations, an individual calibration of each SN’s luminosity, and the extinction of each SN Ia (via the color excess), a prerequisite for calibrating their distances. For  $z > 1$  objects, this requires observations in the near-IR with NICMOS. Elsewhere (Riess et al. 2004), we present the distances measured for the GOODS SNe Ia based on their light curves and colors as well as the implied cosmological constraints.

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