THE DEEPEST SUPERNOVA SEARCH IS REALIZED IN THE HUBBLE ULTRA DEEP FIELD SURVEY

LOUIS-GREGORY STROGLER AND ADAM G. RIESS
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; strolger@stsci.edu, ariess@stsci.edu

Received 2004 October 7; accepted 2005 November 23

ABSTRACT

The Hubble Ultra Deep Field Survey has provided the deepest optical and near-infrared views of the universe yet, and has enabled a search for the most distant supernovae, to \( z \sim 2.2 \). We have found four supernovae by searching spans of integrations of the Ultra Deep Field and the Ultra Deep Field Parallels taken with the Hubble Space Telescope paired with the Advanced Camera for Surveys and with NICMOS. Interestingly, none of these events were Type Ia supernovae (SNe Ia) above a redshift of 1.4, despite the substantially increased sensitivity per unit area to such objects over other surveys, including the Great Observatories Origins Deep Survey. However, we find that the low frequency of SNe Ia observed at \( 1.4 < z < 2.4 \) is statistically consistent with current estimates of the Type Ia supernova rate per unit volume, including the global star formation history combined with the nontrivial assembly time of SN Ia progenitors.

Key words: galaxies: evolution — supernovae: general — supernovae: individual (K0302-001, SN 2003lt, SN 2003lu, SN 2004R) — surveys

1. INTRODUCTION

The Hubble Ultra Deep Field (UDF) survey (GO 9978; principal investigator [PI] S. Beckwith) has provided the deepest view of the universe in the optical and near-infrared to date. Imaging was generally obtained with the Advanced Camera for Surveys (ACS) at a position located within the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004a) South field, centered at R.A. (J2000.0) = 03\(^{h}\)32\(^{m}\)59\(^{s}\)00, decl. (J2000.0) = \(-27^\circ54'29''1\). A total of 400 orbits were accumulated with the Hubble Space Telescope\(^1\) (HST) to achieve a 10\(\sigma\) detection threshold of approximately 29 mag (Vega) in the F435W, F606W, and F775W passbands and approximately 28 mag in the F850LP band. Deep near-infrared images were also obtained in the UDF target field (IRUDF; GO 9803; PI: R. Thompson) to further enhance the vast array of deep multiwavelength imaging for this region. The IRUDF was constructed by tiling several pointings with NICMOS camera 3 into a 3\(\times\)3 mosaic covering the inner \( \frac{1}{3} \) of the UDF in the F110W and F160W bands. In addition, in the process of collecting the IRUDF, another extremely deep optical field, an ACS “parallel field,” was accumulated through simultaneous observation with infrared imaging. This UDF ACS parallel (UDFP), although at a large angular separation from the UDF target center, did have overlap with the large, nearly 150 arcmin\(^2\) GOODS-South field.

The unparalleled depth and resolution of these HST surveys make them ideal for searching for very distant supernovae. In particular, the UDF, UDFP, and IRUDF surveys are unique in that they are the first surveys sensitive to Type Ia supernovae (SNe Ia) to \( z = 2.2 \).

With an elapsed time of less than 4 Gyr between the first generation of stars (\( z \sim 10 \)) and SNe Ia at \( z > 1.4 \), the observed number of these events at \( z > 1.4 \) could provide an important probe of the assembly time required by SN Ia progenitors (Strolger et al. 2004, hereafter S04). The rate at which SN Ia events occur is governed by the rate at which their progenitor stars form, and the time required for the SN Ia progenitor to develop into a SN Ia event. In the framework of cosmic time, these components are the star formation rate history and the population assembly time, or the delay time function (Dahlen & Fransson 1999; S04). Together, the star formation rate history and the delay time function describe a model for the SN Ia rate history [with comoving volume \( R_I(z) \)], which can be compared to observations of the SN Ia rate in different redshift regimes.

In principle, the observed discovery rate of SNe Ia at \( z > 1.4 \) could help to distinguish between viable models of \( R_I(z) \). In S04 it was shown that observations of the SN Ia rate over a large redshift range (encompassing most of the last \( \sim 10 \) billion years of the universe) are consistent with the combination of the Madgwick-Lilly star formation rate history from rest-frame U-band galaxy studies [hereafter SFR\(_U(z)\); see Giavalisco et al. 2004b] and a Gaussian distribution of delay times, with a mean of \( \sim 3.5 \) Gyr and a dispersion of \( \sim 1 \) Gyr.

However, in an apparent contradiction, it also has been recently shown that the SN Ia rate in galaxies at \( z < 0.1 \) does appear to increase toward later galaxy types; e.g., the SN Ia rate in irregular (dwarf) galaxies is approximately 10 times larger than in elliptical galaxies of the same total mass (Mannucci et al. 2005). This would seem to imply that the SN Ia rate more promptly traces the cosmic star formation rate history rather than being largely delayed from it. This is very difficult to resolve in light of the GOODS supernova data.

A simple test of the S04 model would be to push the limits of survey sensitivity well beyond those achieved in GOODS, and specifically look for high-redshift SNe Ia up to \( z \sim 2.2 \). One can then compare observed yields to those expected in this redshift regime from the S04 and other viable models of the SN Ia rate history. Such a survey has been achieved with HST and the Hubble UDF data.

We have searched spans of images of the UDF, UDFP, and IRUDF observations for high-redshift SNe and have found a total of four events, none of which were at \( z > 1.4 \). In \$2\ we describe the UDF, UDFP, and IRUDF searches, show discovery and subsequent photometric data for the events found in the optical data, and present the evidence that shows the relatively low redshift of these events. In \$3\ we compare our null result at \( z > 1.4 \) to what would have been expected from a few viable SN Ia rate models.
2. THE SEARCHES, DISCOVERY DATA, AND ACS PHOTOMETRY

The UDF and UDFP images were searched by differencing stacks of images in the F850LP band, assembled as they were collected over the duration of the deep survey. A total of nine multitarget image stacks were created for the UDF field, and two image stacks were made for the UDFP. The image stacks were of varying depths and separated from one another with various baselines in time. The first stack for each field of both data sets was differenced with an overlapping area in either the ACS GOODS mosaic data (in the case of the UDF), or with ACS images obtained for GO 9352 (P. A. Riess) in the case of the UDFP. Each of the subsequent image stacks in both surveys were differenced with their preceding stacks. Similarly, the IRUDF images were searched by differencing two epochs of mosaicked images, each four orbits in depth and separated by approximately 77 days, in both the F110W and F160W passbands.

The image stacks for all data sets were produced using Multi-Drizzle (Koekemoer et al. 2002) by using the median of several exposures. This successfully rejected cosmic rays without rejecting transients that lasted substantially longer than the length of one exposure (\(\sim 1215 \text{ s} \)). The UDF and UDFP data sets were drizzled to 0\(^{0.05}\) pixel\(^{-1}\) in this preliminary investigation for SNe, and later redrizzled to 0\(^{0.03}\) pixel\(^{-1}\) for the final public release of the full-depth images. The IRUDF data were drizzled to 0\(^{0.09}\) pixel\(^{-1}\), chosen to be a multiple of the final UDF pixel scale.

Subtracted images were mined for candidate SNe by using automated computer algorithms and performing a close visual inspection of the residual images. The criteria for identifying potential SNe, and for rejecting possible confusion sources, were very similar to those used in S04. Each image stack of the UDF and UDFP only would be sensitive to motions larger than the point-spread function (PSF) (\(\sim 0^{\prime}.1\) FWHM in F850LP) over the accumulation time of the image stack (roughly 1 week). The proper motion of any candidate would have to be less than \(6 \times 10^{-4} \text{ arcsec hr}^{-1} (1.4 \times 10^{-3} \text{ deg yr}^{-1})\) to be misidentified. This would exclude any foreground solar system object, as it would need to be farther than 247,000 AU if orbiting the Sun at \(\sim 30 \text{ km s}^{-1}\), which is well beyond the current estimates of the extent of the solar system. Slow-moving Galactic stars could also be generally excluded on similar hypothetical grounds. In addition, variable stars would be excluded on the basis that they would appear in all epochs of observation, which is not expected for SNe, and by generally appearing unassociated with galaxies in the field. Furthermore, if there was a chance superposition, classic variable stars would be several orders of magnitude brighter than one would expect for SNe in these galaxies. Coronal flares by dMe stars would be clearly visible in bluer passbands (1–2 mag variations in the U band), but by nature the amount of variation drops rapidly toward redder passbands (only 0.1 mag in the V band) and would be undetectable in our search passband, F580LP (Abdul-Aziz et al. 1995; Osten et al. 2005). The variations of dMe stars cannot be mistaken with the 1–3 mag changes, or the duration of these changes, typically exhibited by SNe in these galaxies.

What remained in these subtracted images were true extragalactic transients (e.g., SNe and active galactic nuclei [AGNs]) and image artifacts such as misregistrations and variations in the PSF. As the field was fairly dense with galaxies, and well resolved in the ACS images, there were no significant misregistrations in the UDF and UDFP, except for stellar diffraction spikes that rolled with the change in telescope orientation between epochs of the surveys. The PSF in each median combined image stack was largely stable and unaffected by short-term exposure-to-exposure changes in the PSF (e.g., telescope breathing or focus drift). Therefore, one can be reassured that we have identified only extragalactic transients in the UDF and UDFP subtraction images.

In principle, our search was also sensitive to variable AGNs, variations within at most 1 pixel of the centroid of their host nuclei. However, none were detected down to our \(\sim 5 \sigma\) threshold, which on average corresponds to a magnitude limit of approximately 27 mag in the F850LP band. Other investigations that probe for much smaller optical variations (less than 3 \(\sigma\)) in galaxy nuclei do show evidence for lower level AGNs in the UDF target field (S. H. Cohen et al. 2006, in preparation), none of which have been undeniably identified with our differencing method.

We can be sure that variations identified in these surveys were SNe, especially in the ACS data sets. The NICMOS data sets, however, suffered from intrapixel sensitivity effects that severely limit the depth that can be probed, especially on bright sources. Camera 3 is poorly sampled at \(\sim 0.2\) pixel\(^{-1}\) and can produce as much as a 30% flux variation depending on if the peak of a PSF is centered on a given pixel or is offset toward the edges of the pixel (Storrs et al. 1999; Lauer 1999; Hook & Fruchter 2000). This flux variation in the pixel response function (PRF) is not removed in the flat-field correction and imposes an inherent limitation in these images. With many dithered exposures of the same field, it is possible to map the PRF (Storrs et al. 1999; Lauer 1999) and determine a correction to PSF photometry. Unfortunately, there are no easy means to deconvolve the PRF from the PSF. Therefore, differencing the two image stacks of the IRUDF necessarily results in a checkerboard pattern of under- and oversubtractions (measured at about \(\pm 15\%-20\%)\) on nearly all moderately bright sources. Faint and diffuse objects were generally cleanly subtracted. In Tables 1 and 2 we list the epoch stacks created for the UDF, UDFP, and IRUDF searches, with the mean date of the image stack, the total number of orbits, and the total exposure time of each stack.

To assess the sensitivity and completeness of the UDF, UDFP, and IRUDF searches, we performed Monte Carlo tests with planted PSFs meant to represent false SNe. In the case of the IRUDF, a PSF was generated from a few stars in the images and scaled to 1 count s\(^{-1}\) using zero points and aperture corrections provided by the NICMOS group at the Space Telescope Science Institute. The measured aperture photometry was then corrected for intrapixel sensitivity variations following a prescription detailed in Storrs et al. (1999).

For the IRUDF data, we placed one false SN of a given magnitude at the centers of a randomly selected set of 50 detected objects (to \(\sim 5 \sigma\)), subtracted the images, and then attempted to recover the false SNe by visual inspection (without prior knowledge of the locations of each planted false SN). This method was iterated to successively fainter magnitudes (in steps of 0.2 mag) until none of the planted SNe were recovered. The resulting histograms of percent recovered per magnitude bin are shown in Figure 1.

The sensitivity in each epoch of the IRUDF was determined from the magnitudes of objects in the difference frame. These magnitudes represent the flux difference of two image stacks in the locations of these objects. We use an analytical function to describe the efficiency in detecting objects of a given magnitude in the subtracted frame (\(m\)):

\[
e(m) = \frac{T}{1 + e^{(m-m_0)/S}},
\]  

(1)
### Table 1
Predicted Yield of SNe Ia from UDF and UDFP Surveys

| Field       | Mean Date | Number of Orbits | Exposure Time (s) | 5 σ Limit (mag) | Baseline (days) | $R_{\text{ud}(z)}$ Models |
|-------------|-----------|------------------|-------------------|-----------------|-----------------|---------------------------|
| GoodS       | 2003 Feb 11 | 5                | 10500             | ...             | ...             | ...                       |
| 0924–1002   | 2003 Sep 28 | 18               | 43740             | 27.3            | 229             | 1.06 (0.04), 1.26 (0.21), 3.43 (0.44) |
| 1002–1008   | 2003 Oct 5  | 18               | 43740             | 27.4            | 7               | 0.04 (0.00), 0.07 (0.02), 0.17 (0.05) |
| 1010–1014   | 2003 Oct 12 | 18               | 43740             | 27.4            | 7               | 0.04 (0.01), 0.08 (0.03), 0.20 (0.07) |
| 1016–1029   | 2003 Oct 22 | 20               | 48600             | 27.5            | 11              | 0.07 (0.01), 0.13 (0.06), 0.33 (0.13) |
| 1204–1211   | 2003 Dec 7  | 16               | 38480             | 26.7            | 8               | 0.04 (0.00), 0.07 (0.02), 0.17 (0.05) |
| 1212–1218   | 2003 Dec 15 | 18               | 49140             | 27.4            | 8               | 0.04 (0.01), 0.08 (0.03), 0.20 (0.06) |
| 1204–1211   | 2003 Dec 15 | 18               | 49140             | 27.4            | 8               | 0.04 (0.01), 0.08 (0.03), 0.20 (0.06) |
| 1016–1029   | 2003 Nov 23 | 4                | 10752             | 25.6            | 77              | 0.40 (0.04), 0.61 (0.17), 1.60 (0.37) |
| UDF Total   | ...        | ...              | ...               | ...             | ...             | ...                       |
| GOODS       | 2003 Feb 11 | 2                | 4200              | ...             | ...             | ...                       |
| 0924–1002   | 2003 Sep 28 | 18               | 4600              | 26.1            | 202             | 0.61 (0.01), 0.65 (0.06), 1.77 (0.13) |
| 1002–1008   | 2003 Oct 5  | 18               | 4600              | 26.1            | 202             | 0.61 (0.01), 0.65 (0.06), 1.77 (0.13) |
| 1010–1014   | 2003 Oct 12 | 18               | 4600              | 26.1            | 202             | 0.61 (0.01), 0.65 (0.06), 1.77 (0.13) |
| 1016–1029   | 2003 Oct 22 | 20               | 4600              | 26.1            | 202             | 0.61 (0.01), 0.65 (0.06), 1.77 (0.13) |
| 1204–1211   | 2003 Dec 7  | 16               | 4600              | 26.1            | 202             | 0.61 (0.01), 0.65 (0.06), 1.77 (0.13) |
| 1212–1218   | 2003 Dec 15 | 18               | 4600              | 26.1            | 202             | 0.61 (0.01), 0.65 (0.06), 1.77 (0.13) |
| 1204–1211   | 2003 Dec 15 | 18               | 4600              | 26.1            | 202             | 0.61 (0.01), 0.65 (0.06), 1.77 (0.13) |
| UDFP Total  | ...        | ...              | ...               | ...             | ...             | ...                       |
| GOODS       | 2003 Feb 11 | 2                | 4200              | ...             | ...             | ...                       |
| 0831–0901   | 2003 Aug 31 | 2                | 4600              | 26.1            | 202             | 0.61 (0.01), 0.65 (0.06), 1.77 (0.13) |
| 0911–0913   | 2003 Sep 12 | 9                | 20700             | 26.8            | 12              | 0.07 (0.01), 0.11 (0.03), 0.30 (0.08) |
| UDFP Total  | ...        | ...              | ...               | ...             | ...             | ...                       |
| Overall Total | ...        | ...              | ...               | ...             | ...             | ...                       |

**Note.**—The expected number of SNe Ia in the UDF+UDFP for each model per template-search pair are shown over all redshifts, with the expected number at $z > 1.4$ shown in parentheses. The numbers are summed for each survey field and for the entire survey.

where $T$ is the maximum efficiency, $m_c$ represents a cutoff magnitude at which $\epsilon(m)$ drops below 50% of $T$, and $S$ controls the shape of the roll-off. We find that $T = 0.98, m_c = 25.60$, and $S = 0.20$ well describes the efficiency histogram for the F110W passband, and $T = 0.97, m_c = 24.20$, and $S = 0.21$ parameterizes the efficiency in the F160W passband (see Fig. 1).

The false-star tests for the F850LP passband data of the UDF and UDFP surveys were performed using the methods used in S04. These Monte Carlo tests show efficiency function parameters nearly identical to those used in S04, with $T = 1$ and $S = 0.38$, but with adjusted 50% efficiency cutoff magnitudes ($m_c$) corresponding to the 5 $\sigma$ sensitivity limits for the difference of a given pair of stacks (also shown in Tables 1 and 2). These limits are in good agreement with those expected from the exposure times of the search and template images using the ACS exposure time calculators. The typical brightness threshold for detection in the F850LP-band template-search subtraction was $m_c = 27$ mag. An illustration of the sensitivity threshold can be seen in Figure 2.

### Table 2
Predicted Yield of SNe Ia from IRUDF Survey

| Field   | Mean Date | Number of Orbits | Exposure Time (s) | 5 $\sigma$ Limit (mag) | Baseline (days) | $R_{\text{ud}(z)}$ Models |
|---------|-----------|------------------|-------------------|------------------------|-----------------|---------------------------|
| F110W   | 2003 Sep 7 | 4                | 10752             | ...                    | ...             | ...                       |
| Stack 2 | 2003 Nov 23 | 4                | 10752             | 25.6                   | 77              | 0.40 (0.04), 0.61 (0.17), 1.60 (0.37) |
| F160W   | 2003 Sep 7 | 4                | 10752             | ...                    | ...             | ...                       |
| Stack 2 | 2003 Nov 23 | 4                | 10752             | 24.2                   | 77              | 0.26 (0.03), 0.48 (0.22), 1.17 (0.43) |

**Note.**—The expected number of SNe Ia in the UDF+UDFP for each model per template-search pair are shown over all redshifts, with the expected number at $z > 1.4$ shown in parentheses.
Despite the intrapixel sensitivity limitations of the IRUDF survey, no candidate SNe were discovered in the deep IRUDF imaging. However, four SNe were discovered in the UDF and UDF Pi images, none of which would have been detected in the IRUDF, as they were either outside the imaging area of the IRUDF or detected after the completion of the IRUDF imaging. Following their detection in the F850LP band, we measured Vega-based aperture magnitudes for the four SNe from difference images made in the F606W, F775W, and F850LP bandpasses, using aperture corrections and photometric error estimations described in S04. The discovery images for all four SNe are shown in Figure 3, and the positional and photometric data are listed in Tables 3 and 4.

In all cases we used photometric redshifts (phot-z) determined from the multiwavelength GOODS data to estimate the redshifts of the host galaxies (Mobasher et al. 2004). Spectroscopic confirmation has not been obtained for these SNe. We also generally lack the photometric data and age constraints necessary to assuredly identify the SN types using the identification confidence scheme detailed in S04 and color selection methods described in Riess et al. (2004a). However, we can still use these techniques to reject combinations of SN type and redshift space; specifically, we can reject the faint and red signature of SNe Ia at very high redshifts.

Three of the SNe were identified in the UDFP field. K0302-0012 was discovered in the GOODS follow-up images from GO 9352, and not detected 7 months later (to within 5σ) in the UDFP images. The host of K0302-001 was very faint, with F606W ≤ 28 mag within a 0.2 radius, and very blue, virtually undetectable at F850LP ≤ 27.5 in the same aperture. The galaxy could not be sufficiently detected in any of the deep multiwavelength ground-based data assembled for GOODS (spanning U through

---

2 This designation reflects the new IAU standard for possible faint SNe. See http://cfa-www.harvard.edu/iau/CBAT_PSN.html.

---

**Fig. 1.** Efficiency of the IRUDF survey in recovering false SNe placed in the centers of galaxies in the field. The fraction of recovered fake SNe per magnitude bin is shown as a histogram in the F110W and F160W passbands and is approximated by the function \( e(\Delta m) \propto (1 + e^{\Delta m})^{-1} \).

**Fig. 2.** Example of the average survey sensitivity in the F850LP band. A region of the 1224–1230 image stack is shown after differencing it with the previous image stack. Fake SNe have been added at various magnitudes. Below the image are radial profiles (circles; lines are Moffat fits to the profiles) of the 24 and 27 mag fake SNe, with approximate S/Ns of 100 and 7, respectively. SNe above \( \approx 27.1 \) mag (which corresponds to the 5σ limit) were virtually undetectable in this survey.
and was only identified in two ACS bands: F606W and F775W. The lack of photometric measurements of the host galaxy, especially in the red and near-infrared wavelengths, made it difficult to constrain its photometric redshift using the Bayesian photometric redshift method (Benitez 2000). The phot-z estimate derived of the host of K0302-001 lacked a significant peak and had a broad 95% confidence interval of 1.03 < z < 2.22.

However, the photometry of the SN was more illuminating. The magnitude and colors (specifically the red F606W – F850LP

| SN             | R.A. (J2000.0) | Decl. (J2000.0) | North (arcsec) | East (arcsec) | Redshift |
|----------------|----------------|-----------------|----------------|---------------|----------|
| K0302-001      | 03 32 37.10    | −27 56 53.6     | −0.27          | 0.13          | 1.3 (1.2–1.4) |
| 2003lt         | 03 32 42.88    | −27 55 52.5     | 0.45           | 0.20          | 1.0 (0.74–1.26) |
| 2003lu         | 03 32 36.17    | −27 55 01.4     | −0.28          | 0.43          | 0.11 (0.0–0.24) |
| 2004R          | 03 32 41.30    | −27 46 13.6     | −0.10          | −0.11         | 0.80 (0.56–1.04) |

Notes.— Offsets are from the nucleus of the host galaxy to the SN. Maximum likelihood photometric redshifts are listed with the 95% confidence intervals in parentheses. Coordinates supersede those announced in the IAU Circular. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
color of 3.33 mag; see Riess et al. 2004a) match those of the five SNe Ia measured by Riess et al. (2004b) at or near maximum at z ≈ 1.3. Results from Riess et al. (2004a, 2004b) demonstrate that ~95% of SNe with these photometric characteristics, when discovered at maximum light, are correctly identified as SNe Ia, with the other 5% being SNe IIb or IIc. A firm conclusion we can make is that this SN was too bright and too blue to have been a SN Ia (of any previously seen luminosity and color) at z > 1.4.

SN 2003It was discovered in the first UDF stack (mean date 2003 August 31) and undetected in the GOODS follow-up comparison images. It was also well detected in the second UDF stack of mean date 2003 September 12. Its host galaxy, which was well detected in all GOODS data, had a well-constrained phot-z of z = 1.0 (0.74 < z < 1.26 to 95% confidence). The photometry and colors of SN 2003It were consistent with those for a SN Ia discovered ~80 days from maximum light at z ≈ 1.0, which is also consistent with the phot-z of the host but inconsistent with tested SN Ia scenarios (varying age, light-curve shape, and extinction) above redshift 1.4.

SN 2003It was found in the second UDF stack and not detected in the first UDF stack. The single F850LP-band measurement alone does not allow for a restriction in SN type and redshift space. However, the phot-z for the bright and well-detected host was z = 0.11 (0.0 < z < 0.25 to 95% confidence), and therefore, we can reject the possibility that this was a SN Ia at z > 1.4.

The only SN detected in several epochs of the UDF target field observations was SN 2004R, discovered in the last six-orbit stack obtained 2004 January 13. It was not detected, to within 5 σ, in the 12-orbit stack obtained 2003 December 24–30. A review of the data from 2004 January 1–11 revealed that the SN was rapidly rising in the F850LP and F775W bands but declining in the F606W band. The phot-z for the host galaxy was again well constrained at z = 0.8 (0.56 < z < 1.04 to 95% confidence). The photometry and colors for SN 2004R were generally consistent with our Type II-P SN model (constructed from SN 1999em) caught prior to rest-frame B-band maximum light, and with a host extinction of A_{F850LP} ≈ 1.5 mag (assuming a Galactic extinction law) at the photometric redshift. The data were inconsistent with tested SN Ia models at z > 1.4.

To summarize, our search of the UDF, UDFP, and IRUDF data resulted in the detection of four SNe of largely unknown types. However, we have plausibly rejected the possibility that any were SNe Ia at z > 1.4.

### 3. COMPARISONS TO PREDICTED RATE MODELS

The sample of SNe Ia from GOODS has shown for the first time a distinct rise in the SN Ia rate with volume in the range 0.5 < z < 1.0 over measurements made at lower redshifts (Dahlen et al. 2004; see also Fig. 4 of this paper). These measurements are statistically inconsistent with a constant or nearly constant R_{Ia}(z), as could have been inferred from measures of the SN rate at z ≤ 0.5 (Blanc et al. 2004).

There is now an apparent discrepancy in the SN Ia rate measurements at z ~ 0.5. At this redshift, the SN Ia rate measured from the GOODS data was nearly twice the value of measurements made in the ground-based high-z supernova search programs (Pain et al. 2002; Tonry et al. 2003). Naturally, it would seem that completeness was not the primary goal for these ground-based programs and was generally sacrificed for the sake of favorable SNe Ia with low background contamination for optimal spectroscopic confirmation and precise distance measurements. Indeed, a recent careful reexamination of the data from the fall 1999 campaign of the High-z Supernova Search project (Tonry et al. 2003), and the fall 2001 Institute for Astronomy survey (Barris et al. 2004) shows preliminary evidence of many additional SNe, resulting in an increase by a factor of 2 in the SN Ia candidates, and thus a likely increase in the rates determined from these data to values consistent with the GOODS measurements (B. J. Barris & J. L. Tonry 2004, private communication).

Perhaps the most intriguing result on the SN rates from the GOODS sample has been the dearth of SNe Ia discovered at z > 1. Dahlen et al. (2004) have found that there is a steep decline in the rate at 1.2 < z < 1.6 in comparison to the rate at z = 1.0, a result seemingly at odds with the lack of such a decline in the global star formation rate in this redshift range. However, S04 and Dahlen et al. (2004) have shown that R_{Ia}(z) is

![Fig. 4.—Type Ia SN rate history, as measured by several authors (symbols; Cappellaro et al. 1999; Hardin et al. 2000; Strolger et al. 2003; Reiss 2000; Madgwick et al. 2003; Blanc et al. 2004; Tonry et al. 2003; Pain et al. 2002; Dahlen et al. 2004). Vertical bars represent statistical errors, and horizontal bars on the Dahlen et al. 2004) data take into account the completeness estimates of the GOODS SN survey. Also shown are the tested models for the SFR(z) (the best-fit S04 model (solid line), the SFR_{I0}(z) model (dashed line), and the SFR_{I0}(z) model (dotted line)).

### Table 4: Photometric Data

| SN       | Filter | JD + 2,450,000 | Magnitude |
|----------|--------|----------------|-----------|
| K0302-001| F850LP | 2680.22        | 24.38 ± 0.03 |
| F775W    | 2680.96 | 25.29 ± 0.03 |
| F606W    | 2680.25 | 25.18 ± 0.12 |
| F850LP   | 2895.71 | 26.19 ± 0.04 |
| F775W    | 2885.32 | 27.26 ± 0.11 |
| F606W    | 2878.52 | 30.2 ± 0.8    |
| 2003It   | F850LP | 2895.71        | 26.33 ± 0.04 |
| 2003It   | F850LP | 3006.95        | 27.54 ± 0.26 |
| 2004R    | F850LP | 3014.59        | 27.69 ± 0.13 |
| 2004R    | F850LP | 3017.13        | 26.46 ± 0.06 |
| 2003lu   | F775W  | 3005.89        | 27.91 ± 0.26 |
| 2003lu   | F775W  | 3009.21        | 27.09 ± 0.12 |
| 2003lu   | F775W  | 3013.70        | 27.48 ± 0.07 |
| 2003lu   | F775W  | 3017.45        | 27.15 ± 0.05 |
| 2003lu   | F606W  | 3000.40        | 27.82 ± 0.07 |
| 2003lu   | F606W  | 3007.75        | 27.85 ± 0.06 |
| 2003lu   | F606W  | 3013.70        | 27.85 ± 0.06 |
| 2003lu   | F606W  | 3016.28        | 28.04 ± 0.08 |
| 2003lu   | F606W  | 3019.15        | 28.20 ± 0.09 |

**Note:** Magnitudes are given in the Vega-based system and are listed with their photometric errors.
likely a reflection of the SFR$_{\text{Ia}}(z)$, which has been delayed by an assembly time function, or delay time function, which is the distribution of times required for SN Ia progenitors to go from formation to explosion. S04 found that the difference in the evolution of the SFR$_{\text{Ia}}(z)$ and the $R_{\text{Ia}}(z)$ can be well modeled as a Gaussian delay time function with a mean delay of $\sim 3.5$ Gyr and a dispersion that is a small fraction of the delay. Subsequently Dahlen et al. (2004) found that based on the model delay, the fraction of stars in the range of $3\sim 8 M_\odot$ that will explode as SNe Ia is about 5%.

Past searches for SNe Ia in high-redshift clusters with HST by Gal-Yam et al. (2002) show rates that are similar to field SN Ia rates, indicating some similarity in their rate evolution. Unfortunately, these cluster rate measurements at $z > 0.1$ are not precise enough, nor sufficiently well sampled in redshift space, to definitively compare their SN Ia rate history to those measured in non-clustered environments.

An anecdotal anomaly in the consideration of the decline in $R_{\text{Ia}}(z)$ at $z > 1$ is the serendipitous discovery of SN 1997ff (Gilliland et al. 1999; Riess et al. 2001). The depth of the discovery images for SN 1997ff was only marginally deeper than for a single epoch of GOODS, and the SN itself, although likely magnified by as much as $\sim 0.2$ mag (Jönsson et al. 2006), was discovered well above this detection threshold. The significantly larger duration and survey area of the UDF+UDF search suggests that the number of such SNe Ia at $z > 1$ in the UDF data should exceed those found by Gilliland et al. (1999) by a factor of $\sim 5$. Yet, when dealing with such small, pencil-beam surveys, the survey yields are subject to the chance of low-number Poisson statistics, and therefore the number of expected SNe serves more as a probability for finding SNe Ia than a true expectation value.

In the § 2 we concluded that our searches of the UDF, UDFP, and IRUDF data had failed to yield any SNe Ia at $z > 1.4$. To test the significance of this null result, we have simulated the yield that was expected in these data sets, given a set of viable $R_{\text{Ia}}(z)$ models. The GOODS data best-fit $R_{\text{Ia}}(z)$ model of S04 was defined by

$$R_{\text{Ia}}(z) \Rightarrow R_{\text{Ia}}(t) = \nu \int \text{SFR}_U(t) \Phi(t_d) \, dt,$$

where the rate history in redshift space is related to the rate history in time space, $R_{\text{Ia}}(t)$. It is a convolution of the star formation rate history $[\text{SFR}_U(t)]$ and the SN Ia delay time function $\Phi(t_d)$, with a constant ($\nu$) that reflects the efficiency with which progenitor systems of SNe Ia actually become events. The number of expected SNe per redshift interval was determined by

$$N_{\text{Ia}}(z) = R_{\text{Ia}}(z) \tau_{\text{c}}(z)(1 + z)^{-1} \frac{\Theta}{4\pi} \Delta V(z),$$

where $\tau_{\text{c}}$ is the “control time” probability function, which takes into account the survey efficiency with difference magnitude (described in § 2), $\Theta$ is the area surveyed, and $\Delta V(z)$ is the volume element in a $\Delta z$ shell about $z$ for an assumed flat universe ($\Omega_k = 0$). The expected number of SNe Ia at $1.4 < z < 2.4$ is then

$$N_{\text{Ia}}(1.4 < z < 2.4) = \sum_{z=1.4}^{2.4} N_{\text{Ia}}(z) \Delta z.$$

In Mannucci et al. (2005) it is shown that the SN Ia rate in low-z galaxies (per unit mass) does appear to correlate with the rate of star formation (also per unit mass). Therefore, for comparison we have also calculated the yield expected from a $R_{\text{Ia}}(z)$ that is directly proportional (i.e., without delay) to the extinction corrected SFR$_U(z)$ model used in S04,

$$R_{\text{Ia}}(z) \propto \int \text{SFR}_U(z) \, dz,$$

but with an explosion efficiency for the SN Ia progenitor mass range of 10% (instead of 5%) as required to match SN Ia rate measurements at $z < 0.2$ by various authors (see Fig. 4).

Recently, based on the results of Mannucci et al. (2005), Scannapieco & Bildsten (2005) have hypothesized that the SN Ia rate is actually made up of both delayed and prompt components. Their SN Ia rate model is nearly entirely dominated by the prompt component in the early epochs of the universe. Therefore, at $z > 1.4$ their prediction of the SN Ia rate should be identical to the values expected from equation (5).

It has been suggested that rest-frame $U$-band galaxy observations, at best, provide only a lower limit to the actual cosmic star formation history, and that mid- to far-infrared data provide a more accurate measure (Chary & Elbaz 2001). Although this is still controversial, we have also tested the yield expected from a $R_{\text{Ia}}(z)$ that is proportional to a star formation rate history derived from infrared data (Chary & Elbaz 2001),

$$R_{\text{Ia}}(z) \propto \int \text{SFR}_{\text{IR}}(z) \, dz,$$

again, without delay and with a progenitor efficiency of 10% to match the low-z SN Ia rates.

The expected number of SNe Ia from each tested model, over all redshift ranges and in the considered $1.4 < z < 2.4$ range, are tabulated and summed for all image stacks of the UDF and UDFP surveys in Table 1 and for the IRUDF in Table 2. In Figures 5 and 6 we show the redshift distribution (total number in each redshift bin) expected by each $R_{\text{Ia}}(z)$ model in the F850LP, F110W, and F160W bands. Due to the long delays required by the progenitors in the S04 model, and as the universe was only 4.5 billion years old at $z = 1.4$ (assuming $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_k = 0.7$), few early-forming progenitors would have had sufficient time to explode by $z = 1.4$, and therefore, it is foreseeable that the S04 model would expect few, if any, SNe Ia in the tested redshift regime. Indeed, the S04 best-fit $R_{\text{Ia}}(z)$ model expects $\sum_{z=1.4}^{2.4} N_{\text{Ia}}(z) \Delta z$. This is the correct form of the equation, which has a typographical error in S04.
The power to reject the S04 model based on a single high-$z$ observation was less than 4% of the time. The S04 best-fit IRUDF model had high Poisson probabilities of 87%, 96%, and 97% assigned to this outcome in the F850LP, F110W, and F160W bands, respectively.

However, interestingly, a null result could have also been expected from the other tested $R_{\mu}(z)$ models, although at lower probabilities. The SFR$_{\mu}(z)$ model had expectation values of 0.69, 0.17, and 0.22 events in each passband, and thus had 50%, 84%, and 81% Poisson probabilities for zero observed events in the F850LP, F110W, and F160W bands. And although the greatest expected yield would come from the SFR$_{IR}(z)$ model, with 1.49, 0.37, and 0.43 expected in each passband, respectively, a zero yield could still be expected in the tested redshift range with probabilities of 23%, 69%, and 65%. All of the models show that a zero yield would be within 99% most probable outcomes, and only one, the SFR$_{IR}(z)$ model for the F850LP data, has a zero yield outside the 68% most probable outcomes.

It is interesting to consider what the relative agreement with the tested models would have been had a single SN Ia at $z > 1.4$ been discovered in the IRUDF data. If one high-$z$ SN Ia had been found in each of the F110W and F160W bands (individually considered), then it would have been unlikely that the S04 best-fit $R_{\mu}(z)$ represents the true SN Ia rate history, as such an outcome would be expected less than 4% of the time. The S04 best-fit $R_{\mu}(z)$ could therefore have been rejected to >96% confidence. The power to reject the S04 model based on a single $z > 1.4$ SN Ia in the F850LP-band data is much less significant, down to 88%.

One high-redshift SN Ia would have been an expected outcome of both the SFR$_{\mu}(z)$ and SFR$_{IR}(z)$ models, in each survey passband, at the 1−2 $\sigma$ confidence interval.

Although these UDF surveys offer support for the S04 best-fit $R_{\mu}(z)$ model, it is clear that our null result cannot reject any of the tested, viable models for the supernova rate history to a significant (greater than 99%) confidence. In fact, a theoretical SN rate history would need to predict five or more SNe Ia at $1.4 < z < 2.4$ in these surveys to be rejected at greater than 99% confidence by the zero yield of this survey. Such a hypothetical model would suggest that the average SN Ia rate in the high-$z$ range would be approximately 150 times larger than the SN Ia rate measured in the local ($z \leq 0.1$) universe. This is very inconsistent with trends inferred from measured SN Ia rates over any redshift interval and is likely to be rejected based on theoretical considerations of the low [O/Fe] ratios it would predict for stars and the interstellar medium of local galaxies.

Despite the fact that the UDF surveys cannot discern our tested SN Ia rate models, the null yield at least provides a limit on the SN Ia rate in the tested redshift regime. The average SN Ia rate at $z > 1.4$ cannot exceed approximately $6 \times 10^{-3}$ yr$^{-1}$ Mpc$^{-3} h_{70}^3$. Yet this limit does not allow for a full exploration of limits on the constituents of the SN rate, particularly the function of event assembly times. If SNe Ia were instantaneous events, not at all delayed from star formation, we would find that the star formation rate could not exceed an average of approximately $3 M_{\odot} $ yr$^{-1}$ Mpc$^{-3} h_{70}^{-3}$ at $z > 1.4$ and remain consistent with SN Ia rate measures at all redshifts (assuming the ratio of events per unit formed stellar mass remains constant over time). However, this hypothetical rate is more than an order of magnitude higher than most measures of the star formation rate history in this cosmic epoch, including those by Chary & Elbaz (2001), Lanzetta et al. (2002), Giavalisco et al. (2004b), and Bunker et al. (2004).

Without useful constraints on the SFR$_{IR}(z)$, it is impossible to derive meaningful boundaries on the delay time function of SN Ia events. The effective purpose of the delay time function is to shift the center of the SFR$_{IR}(z)$ distribution to lower redshifts and to skew the shape of the function. The convoluted result only reduces the strength of the SN Ia rate in high-redshift regimes, even more so for exceptionally long mean (or characteristic) delay times. Conversely, further constraints on the SFR$_{IR}(z)$ at very early epochs could be imposed once a model for the delay time function has been adopted. Unfortunately, there is not yet a consensus on the delay time function, mainly because the actual progenitors of SNe Ia remain largely ambiguous.

It should be noted that there is significant evidence for uncertainty in the estimates of galaxy volume densities for specific populations in the GOODS fields (Somerville et al. 2004), and the survey presented in this paper covers a smaller area of the GOODS-South field. However, the SFR$_{IR}(z)$ model (in the $z > 1$ regime) used in this analysis was also determined from GOODS data, and therefore should be subject to the same variances. The SFR$_{IR}(z)$ model, by contrast, was determined from several local surveys and through theoretical modeling of the evolution of the galaxy infrared luminosity function (Chary & Elbaz 2001). Therefore, we expect cosmic variance to distort the predicted SN Ia rate in this observed volume (from 15%−20%) when applying the global average SFR$_{IR}(z)$ to this small field.

Our choice of the lower bound on the redshift range tested, $z > 1.4$, was based on the redshift range in which the completeness of the UDF surveys (in the F850LP band) become significant over the GOODS SN survey. However, our results are not very sensitive to the precise definition of the uniquely high-redshift space of this survey.

In addition, other baselines and combinations of images in the UDF surveys could have been selected that would have increased the expected number of SNe Ia in the desired redshift range (see Fig. 7). Ignoring the first image pair of the survey (using >7 month old templates), the average baseline between observations in the F850LP band was roughly 13.5 days, to a
Progress in determining the rates of SNe Ia and their associated timescales for assembly is most likely to come by “piggybacking” such studies on the now numerous and major efforts to find and measure SNe to constrain dark energy parameters. Such cosmology-driven SN surveys are designed as wide, open field surveys and are well suited to deriving the SN field rates, when completeness is carefully considered. These surveys generally avoid galaxy clusters as search targets because nearly half of the yield of SNe Ia found in such surveys are located behind the clusters (Gal-Yam et al. 2002; Reiss et al. 1998), where contamination by lensing is unavoidable. In addition, potential evolutionary differences between cluster- and field-born SNe Ia could add systematic errors to cosmological determinations and to SN Ia progenitor analyses.

4. SUMMARY

The UDF, UDFP, and IRUDF observations yielded four SNe over the 5 month duration of the survey. None were SNe Ia at $z > 1.4$. We find the dearth of SNe Ia at high redshift in this survey to be consistent with the GOODS best-fit $R_{14}(z)$ from S04. However, it is also a likely result from other plausible $R_{14}(z)$ models with no delay from star formation because of the relatively small area probed in this survey. Surveys such as the GOODS more than compensate for the loss in depth by the increased survey area and are vastly superior programs for differentiating between SN Ia rate models. Future data sets with $HST$ such as the Cycle 12 programs by A. Riess and S. Perlmutter (PIs for GOs 9727 and 9728, respectively) and the Probing Acceleration Now with Supernovae (GO-10189; PI: A. Riess) in Cycle 13 will allow for much more precise measurement of the SN Ia rate in the $z > 1$ regime. In combination with the GOODS data, they will provide the best available measures of the empirical distributions of SN Ia delay times and the comparison to star formation rate models.

We thank Tomas Dahlen and our anonymous referee for their beneficial discussions. We also thank Steven Beckwith, Roger Thompson, Bahram Mobasher, Anton Koekemoer, Louis Bergeron, Rogier Windhorst, and Rychard Bouwens. Financial support for this work was provided by NASA through programs GO-9728, GO-9978, and GO-9803 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

REFERENCES

Jönsson, J., Dahlen, T., Goobar, A., Gunnarsson, C., Mörtssell, E., & Lee, K. 2006, ApJ, 639, 991
Koekemoer, A. M., Fruchter, A. S., Hook, R., & Hack, W. 2002, in The 2002 $HST$ Calibration Workshop: Hubble after the Installation of the ACS and the NICMOS Cooling System, ed. S. Arribas, A. Koekemoer, & B. Whitmore (Baltimore: STScI), 337
Lanzetta, K. M., Yahata, N., Pascarelle, S., Chen, H., & Fernández-Soto, A. 2002, ApJ, 570, 492
Lauer, T. R. 1999, PASP, 111, 1434
Magsick, D. S., Hewett, P. C., Mortlock, D. J., & Wang, L. 2003, ApJ, 599, L33
Mannucci, F., della Valle, M., Panagia, N., Cappellaro, E., Cresci, G., Maiolino, R., Petrosian, A., & Turatto, M. 2005, A&A, 433, 807
Mobasher, B., et al. 2004, ApJ, 600, L167
Osten, R. A., Hawley, S. L., Allred, J. C., Johns-Krull, C. M., & Roark, C. 2005, ApJ, 621, 398
Pain, R., et al. 2002, ApJ, 577, 120
Reiss, D. 2000, Ph.D. thesis, Univ. Washington
Reiss, D. J., Germany, L. M., Schmidt, B. P., & Stubbs, C. W. 1998, AJ, 115, 26
Riess, A. G., et al. 1998, AJ, 116, 1

Riess, A. G., et al. 2001, ApJ, 560, 49
———. 2004a, ApJ, 600, L163
———. 2004b, ApJ, 607, 665
Scannapieco, E., & Bildsten, L. 2005, ApJ, 629, L85
Somerville, R. S., Lee, K., Ferguson, H. C., Gardner, J. P., Moustakas, L. A., &
Giavalisco, M. 2004, ApJ, 600, L171

Storrs, A., Hook, R., Stiavelli, M., Hanley, C., & Freudling, W. 1999, Camera 3
Intrapixel Sensitivity (STScI Rep. NICMOS-99-005; Baltimore: STScI)
Strolger, L.-G. 2003, Ph.D. thesis, Univ. Michigan
Strolger, L.-G., et al. 2004, ApJ, 613, 200 (S04)
Tonry, J. L., et al. 2003, ApJ, 594, 1