1 Introduction

1.1 Review of Type Ia Supernovae

We have seen in the last two classes that type Ia supernovae (SN-Ia), which form when an accreting carbon/oxygen white dwarf reaches the Chandrasekhar limit and explodes. The thermonuclear explosion has a characteristic spectrum and light-curve, and can be used as a standard candle. This feature is beneficial for cosmology, since this means they can be used to measure how the luminosity distance $D_L$ varies with redshift. With regard to their "standard" luminosity, observations indicate that while there is scatter in measured peak luminosity, this peak luminosity is related to the decline rate of the supernova’s light curve. The higher the peak luminosity, the slower the decline rate. Taking this relationship into account, photometrically sampling the light curve appropriately allows their use as standard candles.

1.2 Cosmology with Low-z Supernovae

Supernovae detected in host galaxies between $0.01 < z < 0.5$ have shown that the peak luminosity of SN-Ia appear dimmer than we would have expected from a decelerating matter-dominated universe. This result is consistent with a universe which is accelerating its expansion during recent epochs. Although, it has been suggested that alternative explanations exist, such as "gray dust" which may have the property of dimming the SNIa light without detectable reddening. Another potential mimic of this observed dimming could be any evolution in the SNIa properties with redshift, potentially to such evolving properties as metallicity or progenitor age.

We have seen that Hubble diagrams made using low-z SN-Ia are consistent with an accelerating universe, and may best be described by the equation of state of a cosmological constant, in other words, $w = P/\rho = -1$ (Wood-Vasey et al., 2007). However, in our mixed dark energy and dark matter universe we expect an earlier epoch during its expansion in which the matter density dominated and therefore the expansion was decelerating. At higher redshifts then we should see the opposite effect on the SN-Ia luminosity, meaning, for $z > 1$ we should see an apparent brightening in luminosity due to the deceleration of the universe. This also implies a "cosmic jerk", occurring at the transition redshift when the universe went from matter dominated and decelerating to dark energy dominated and accelerating.

Additionally, observations of SN-Ia at high redshift may provide some evidence for or against the gray dust or luminosity evolution theories which could explain the observed acceleration.
1.3 Cosmology with High-z Supernovae

2 Methods

We think we understand generally the form of SN-Ia SEDs, from many low-z observations and templates. Therefore to detect SN-Ia at \( z > 1 \) we must observe in the \( z \) band (850 nm), which corresponds to restframe U or B band to a limiting magnitude of about 26. At these wavelengths the atmosphere is too bright to observe deep enough from the ground. As SN-Ia are not UV emitters, observing in a bluer band is not possible. So observing from space with Hubble is the best option.

But, SN-Ia are unpredictable and transient objects, requiring time-sensitive followup observations to adequately sample the light curve, as well likely requiring spectroscopy to confirm the redshift, and that its a type 1a. And observing at high-z is even more time consuming since the images must be deeper.

To overcome these obstacles, the Hubble Higher-z Supernova Search (HHZSS) teamed up with the Great Observatories Origins Deep Survey (GOODS) mission on HST, to piggyback on their observing time to make extremely deep maps of the Hubble Deep Field North (HDF-N) and Chandra Deep Field South (CDF-S). The observations of the GOODS fields were organized as follows to accomodate this collaboration:

- Observing epochs for the deep images were split into intervals spaced by 45 days. (this is approximately the risetime for a SN-Ia at \( z = 1 \), which is about 20 days in the restframe.) Deep blank field observations are now also rolling searches for Supernovae!
- Each epoch was scheduled so that they occurred 3-4 days prior to the request deadline for HST’s ”Target of Opportunity” observing time, so that followup observations could be made (confirmation of redshift and type Ia status with spectra, photometric sampling of light curve.)
- A fast pipeline was set up to reduce data as soon as it returned from HST. The pipeline identified transients using image differencing, ruled out cosmic rays and hot pixels, subject to a SNIa color-selection technique (Riess et al. 2004b, and see below), all within 24 hours of the observation.

These characteristic methods optimized the survey for detecting SN-Ia at \( z > 1 \). See Strolger et al. (2004) for more details on the pipeline.

The goal of this study was to study the expansion of the universe from a redshift of 1.8 to the present, and also the equation of state, \( w = P/\rho \) of dark energy. Additionally, this dataset provided an opportunity to observe any evolution of the equation of state with redshift, \( w(z) \). The data includes 23 SNIa at \( z > 1 \) discovered with HST, and additionally 170 lower-z SNIa, some also discovered with HST, and the rest from previous SNIa surveys including the Calan-Tololo Survey (Hamuy et al. 2006), CfA surveys I,II (Riess et al., 1999, Jha et al. 2004), and the high-z SN search team at CTIO (Schmidt et al. 1998).

2.1 Color-Based Method for selecting SNIa

SNIa can be distinguished from other types of transients, such as SN of type II, by taking advantage of their inherent restframe UV deficit, at \( \lambda < 3300\AA \), see figure 1. This UV deficit is caused by
resonant scattering of UV thermal continuum photons by FeII. Recall that iron group metals make up between $0.3 - 1 M_{\text{sun}}$ of the progenitor. Type II SN on the other hand, are UV emitters. The biggest contaminator to the resulting set of candidate SNIa are SN of type Ic, which are weak UV emitters. But, in other studies, the fraction of contamination has been small, on the order of only a few percent. Follow up spectroscopy removes this fraction from the HST data used for cosmology. See figure 3 for an example of how the UV deficit is translated into observed colors, and distinguished from type II SN. Also, for more information on the color-selection technique, see Riess et al. (2004b).

Figure 1: SED for a variety of supernova types, and the basis for color-selection of type-Ia supernovae, (Riess et al., 2004b).

3 Luminosity Distance

We have previously seen that the luminosity distance to the SNIa can be used to study cosmology. We can calculate the luminosity distance once we have ‘turned’ the SNIa lightcurve into a standard candle, via the multi-color light curve shape fitting method, which takes into account the peak luminosity - lightcurve decline rate relation. By taking the lightcurves observed in several bands, the luminosity distance can be fit using a variety of routines which exist. This study uses the one called MLCS2k2 (Jha et al. 2004), which can take advantage of rest-frame U band lightcurves if
available. These fitting routines include some attempts to correct light curves for host galaxy dust content, although in general the host galaxy dust properties remains a source of uncertainty in this field.

The luminosity distance is then calculated via the distance modulus, $\mu = m - M = 5 \log d_L + 25$, where $m$ is apparent magnitude, $M$ is absolute magnitude (from the lightcurve fitting), and $d_L$ is the luminosity distance.

4 Results for Cosmology

To carry out the analysis with implications for cosmology, they break the SNIa sample into the 'gold' sample, their most confident set of SNIa, the 'silver' sample contains the less confidently detected set, (although all accepted SNIa survive a very strict set of selection criteria). Unless otherwise noted, the gold sample was used to calculate cosmological parameters.

Assuming a flat universe, which is a valid assumption given results from other cosmological experiments such as WMAP, the authors find that their SNIa results are consistent with $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$. Confidence intervals are shown in figure 3.

Also by plotting up the Hubble diagram for the full SNIa sample, a variety of models can be rejected (Figures 4,5). Here, the data is plotted along with the best-fitting flat universe, with $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$. In the inset, you can also see how the data compares with the simple
'gray dust' model, and a simple SNIa evolution model, evolving with redshift, and their HST dataset rules these models out. The data appears to be following a model with cosmic deceleration in the past, with current cosmic acceleration.

Additionally, they have made a simple check of any evolution of the SED of their SNIa sample with redshift. In figure 6, they have made a composite (average) SED from their low-z sample (black) and high-z sample (gray) and find no evidence of an evolution in SNIa evolution. This is interesting because this is the first time a comparison of $z > 1$ and low-z SNIa SEDs have been made, and its not well understood if there should be some evolution due to metallicity of the progenitors, or host galaxy properties. This study seems to suggest we are safe to assume no evolution.

Additionally, they have plotted the evolution of the hubble parameter and change in scale factor as a function of $z$ (see figure 5). Pure acceleration and deceleration models are ruled out, and they find a model with past deceleration and subsequent acceleration to be a good fit. In particular, they find that the deceleration parameter with the form $q(z) = q_0 + z \frac{dq}{dz}$ fits well with $q_0 = -0.6$ and $\frac{dq}{dz} = 1.2$, and a transition redshift between the matter dominated and dark energy dominated epoch to be $z_{DE} = 0.43 \pm 0.07$. A comparison between the 2004 dataset and new 2007 dataset shows that they have reduced their uncertainty in the Hubble parameter from 50% to 20%.
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4.1 Dark Energy

Now, time to try to constrain the equation of state of dark energy, \( w = P/\rho \), and also how may change with redshift. Many studies have shown that it is consistent with a cosmological constant,
namely \( w = -1 \). To study how it changes, it is necessary to parametrize \( w \) so we can quantify how it varies with \( z \). Here, they consider three possible parametrizations. First, the static equation of state, \( w(z) = w_o \), and also a simple parameterization, \( w(z) = w_o + z \frac{dw}{dz} \). This simple parametrization has the unattractive feature that for large \( z \), \( w(z) \) diverges. Therefore, they use a third parametrization, \( w(z) = w_o + w_a \frac{z}{1+z} \), which does not diverge at large \( z \), but at the expense of requiring a stiffer behavior of \( w \). For this parametrization, the cosmological constant has values \((w_o, w_a) = (-1, 0)\).

For the static equation of state, they find values of \( w \) which are consistent with a cosmological constant. For the data on its own, assuming \( \Omega_m = 0.27 \pm 0.04 \), they find \( w = -1.02 \pm 0.13 \), and including extra constraints from WMAP and 2dFGRS, they find \( w = -1.08 \pm 0.18 \). The results from the simple parametrization which varies with \( z \) is shown in figure 7, where they have estimated the results using a few subsets of data. From this parametrization, a cosmological constant cannot be ruled out, and more data will be needed. In figure 8, are the results from the additional parametrization removing the divergence at high \( z \). To set constraints, they have presented confidence intervals in \( w_o - w_a \) space subject to 3 different priors, including the additional cosmological datasets indicated. Again they cannot rule out a cosmological constant, however they can say that from these results if there is evolution in dark energy, it is not rapid.

Does it worry you that the results change depending on your choice of parametrization? It
Figure 8: Average SEDs for high-z SNIa (gray) and low-z SNIa (black), there is no evidence of any evolution in SNIa. Riess et al., 2007.

should! See figure 9, for an example of how these results are affected. Here they’ve compared the non-diverging evolution model (pink) with the same model expanded to 4th order in powers of $\ln(1 + z)$ (blue). The $1 - \sigma$ uncertainty region changes dramatically. They conclude, that choosing a simple dark energy parametrization is equivalent to imposing a strong and unjustified prior.

5 Summary

They have presented the sample of highest-z SNIa, including 23 SNIa above $z > 1$, discovered with HST. It exends our knowledge of the hubble diagram to over 10 Gyr. They have estimated the hubble parameter $H(z)$, and observe the current epoch of acceleration, and see that it was preceded by an epoch of deceleration. They also estimate that the ’cosmic jerk’ occurred around $z = 0.43.$
From these results, there is no direct evidence of simple SN evolution and the gray dust model is ruled out. (Note: this excludes the unattractively tuned 'replenishing dust model'.) Additionally, the cosmological constant cannot be ruled out as a description of dark energy. But, the authors caution that an assumed parametrization form for \( w(z) \) can act like an unjustified prior. We need to start probing how the dark energy component of the universe behaves between \( 1.8 < z < 1089 \)... as soon as we figure out how!

Figure 10: Constraints on the equation of state using the non-diverging evolution model. Black dot indicates position of cosmological constant. Riess et al., 2004.
Figure 11: An example of how the region of uncertainty given a chosen parametrization changes. Pink is the non-diverging parametrization, and blue is the same model but expanded to 4th order in powers of $\ln(1 + z)$. Riess et al., 2007.