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A Definitive Measurement of Time Dilation in the Spectral Evolution of the Moderate-Redshift Type Ia Supernova 1997ex

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ABSTRACT

We have obtained high-quality Keck optical spectra at three epochs of the Type Ia supernova 1997ex, whose redshift z is 0.361. The elapsed calendar time between the first two spectra was 24.88 d, and that between the first and third spectra was 30.95 d. In an expanding universe where $1 + z$ represents the factor by which space has expanded between the emission and detection of light, the amount of aging in the supernova rest frame should be a factor of $1/(1 + z)$ smaller than the observed-frame aging; thus, we expect SN 1997ex to have aged 18.28 d and 22.74 d between the first epoch and the second and third epochs, respectively. The quantitative method for determining the spectral-feature age of a SN Ia, developed by Riess et al. (1997), reveals that the corresponding elapsed times in the supernova rest frame were 16.97 ± 2.75 d and 18.01 ± 3.14 d, respectively. This result is inconsistent with no time dilation with a significance level of 99.0%, providing evidence against “tired light” and other hypotheses in which no time dilation is expected. Moreover, the observed timescale of spectral evolution is inconsistent with that expected in the “variable mass theory.” The result is within $\sim 1\sigma$ of the aging expected from a universe in which redshift is produced by cosmic expansion.

Subject headings: stars: supernovae: individual (SN 1997ex) — cosmology:
observations

1. Introduction

It has long been accepted that the redshifts of distant extragalactic objects are caused predominantly by a cosmological expansion. However, assertions that redshifts are not of cosmological origin are occasionally made (Arp 1987; Burbidge et al. 2004, and references therein), and alternative theories have been proposed that try to explain the redshifts through other means such as “tired light” (e.g., La Violette 1986; Crawford 1999) and variable mass (e.g., Narlikar & Arp 1997). Despite the predominance of the current redshift paradigm, little direct observational evidence exists in support of cosmological expansion (Sandage & Perlmutter 1991; Pahre et al. 1996).

One prediction of cosmological expansion is that time will be dilated by a factor of $1 + z$. Most astronomical phenomena evolve on very long time scales, making a time dilation measurement infeasible. However, supernovae (SNe), which rise and fall in brightness on a time scale of a few months and are visible at moderate to high redshifts, are ideal for this experiment. Indeed, decades ago Wilson (1939) and Rust (1974) suggested that the light curves of SNe Ia might be used to detect the expected time dilation.

Leibundgut et al. (1996) showed that the light curve of SN 1995K ($z = 0.479$) was abnormally wide for a SN Ia if time dilation was ignored. However, the light curve of SN 1995K compressed by a factor of $1/(1 + z)$ provided a good match to low- z SN Ia light curves. Since the intrinsic light curves of SNe Ia span a wide range (roughly 0.5–1.6 times the normal width; e.g., Goldhaber et al. 2001), the null hypothesis of no time dilation was not completely ruled out. Goldhaber et al. (2001) showed that a sample of SN Ia (which included 42 high- z objects) light curves is consistent ($\sim 18\sigma$) with time dilation. However, this result is statistical, relying on many objects which have already had their light-curve width modified by an intrinsic “stretch factor,” and Narlikar & Arp (1997) contend that the stretching is explained in the variable mass model. Because there may be

evolutionary factors that change a light curve’s shape, a positive time dilation result from the examination of *spectral features* provides more compelling evidence for time dilation. Moreover, for any individual SN Ia, the intrinsic width is unknown, so without assuming a $1 + z$ dilation, the intrinsic width and dilation can not be separated.

In addition to the predictable nature of the SN Ia light curve, the SN Ia spectrum also evolves in a very reliable way (e.g., Filippenko 1997). As shown by Riess et al. (1997), the method of spectral-feature aging, which compares a single-epoch spectrum to a catalog of comparison spectra with known ages to determine a spectral-feature age (SFA), can determine the age of a SN Ia using a single spectrum; no light-curve information is necessary. Using this method, Riess et al. (1997) demonstrated that the multi-epoch spectra of SN 1996bj are consistent with a $(1 + z)$ -stretched temporal evolution, and inconsistent with no time dilation at the 96.4% confidence level.

Following the method of Riess et al. (1997), we examine the spectral evolution of SN 1997ex, a normal SN Ia with $z = 0.361$, to determine the SFA at the time the spectra were obtained. Comparing this result to the time between epochs will result in a measurement of the time dilation. We present the observations in Section 2, and in Section 3 we determine the rate at which SN 1997ex ages. Section 4 discusses the results and implications of our measurement.

2. Summary of Observations

SN 1997ex was discovered on 28 December 1997 (UT dates are used throughout this paper) by the Supernova Cosmology Project (Nugent et al. 1998). Spectra were obtained on 1998 January 1, 1998 January 26, 1998 February 1, and 1998 March 5 using the Keck II 10-m telescope with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995).

We were able to determine accurate SFAs for the first three epochs, but not for the fourth epoch.

The original spectra were contaminated by host-galaxy light. Removal of this light is important for creating accurate SFAs. We obtained a Keck/LRIS spectrum of the host galaxy on 1999 January 21, approximately a year after discovery of SN 1997ex, with the intention of using these data for galaxy light subtraction. During this time the SN had faded significantly; the SN component of this latest spectrum is below the noise level. First, we extracted the SN without any galaxy subtraction. Then, scaling to narrow lines present in both the SN spectra and the galaxy template spectrum, we were able to subtract the galaxy component of the original SN spectra.

The deredshifted, galaxy-subtracted spectra are shown in Figure 1. Figure 2 shows the rest-frame spectra of the three epochs of SN 1997ex along with low- z comparison spectra. All comparison spectra are of “Branch-normal SNe Ia” (Branch et al. 1993). Examining the earliest spectrum, we see strong absorption on the red side of the Ca II H & K lines and the lack of Ti II absorption at ~ 4200 Å, indicating that SN 1997ex is not similar to the subluminous SN 1991bg (e.g., Filippenko et al. 1992a) or the overluminous SN 1991T (e.g., Filippenko et al. 1992b). Although pre-maximum spectra are particularly useful for identifying the peculiar nature of a SN Ia, we note that the late-time spectra of SN 1997ex are consistent with a Branch-normal SN Ia as well.

3. Time Dilation Measurement from Spectral-Feature Aging

The observations of SN 1997ex were separated by 24.88 d (between the first and second epochs), 6.07 d (between the second and third epochs), and 31.92 d (between the third and fourth epochs). In an expanding universe, the spectra should have aged only 18.28 d,

4.46 d, and 23.45 d (respectively) between these epochs. Using the spectral-feature aging method of Riess et al. (1997), we have determined the SFA for three of our four spectra, as presented in Table 1. For this calculation, we have used the features listed in Table 2. These features were selected by a genetic algorithm designed to choose the best subset of features from a randomly generated set of 400 features. This method chooses different subsets of features, keeps the subsets with the best age determinations, redistributes the remaining features into new subsets and iterates. (see Charbonneau 1995 for a general description and Foley et al. 2005 for details).

The fourth spectrum has a lower signal-to-noise ratio (S/N) than the other spectra. Moreover, the age of the SN at the fourth epoch is larger than the age of any SN spectrum in the catalog invoked for the spectral-feature aging method (Riess et al. 1997). The spectrum was obtained 62.87 d after the first-epoch spectrum and 59.30 ± 1.66 d after the time of B maximum found from fitting the SFAs (the date corresponding to $t = 0$ in the fit). Even with the time dilation corresponding to $z = 0.361$, the fourth-epoch spectrum should have an SFA of 43.57 ± 1.22 d. Since the training set of Riess et al. (1997) has one spectrum at $t = 40$ d and none of older spectra and the S/N of the fourth-epoch spectrum is low, it is understandable that no reliable age for this spectrum was obtained.

Between the first two epochs (an observed time of 24.88 d), the SFA changed by 16.96 ± 2.75 d. Between the second and third epochs (an observed time of 6.07 d), the SFA changed by only 1.04 ± 3.03 d.

Shifting the data in Table 1 so that the SFAs have a weighted mean of zero, we were able to use a least-squares method to fit the data with no covariance between the age factor and the date of B maximum, resulting in an age factor of 1.602 ± 0.234 . Since the no time dilation model predicts an age factor of 1.000, this age factor corresponds to a 2.57σ result if there were no time dilation; thus, the measured aging for SN 1997ex is inconsistent with

the null hypothesis at the 99.0% confidence level.

The observed age factor is larger than the expected factor of $1 + z = 1.361$. The difference between the observed age factor and the expected value corresponds to a 1.03σ event, which should be observed 30.3% of the time by chance.

4. Discussion

We have shown that the spectral evolution of SN 1997ex has likely been dilated by a factor of $1 + z$, as expected in an expanding universe. This result also shows that the null hypothesis of no cosmic expansion is ruled out at the 97.9% level. Thus, “tired light” and other hypotheses that predict no time dilation are essentially eliminated. To be consistent with the observations, alternatives such as the “variable mass theory” (e.g., Narlikar & Arp 1997) would require a highly unlikely series of coincidences, culminating with SN Ia spectral evolution that mimics the result expected with simple time dilation. Narlikar & Arp (1997) discount the results of Leibundgut et al. (1996) since the variable mass theory changes the decay rate of ^{56}Ni (which dictates the shape of a SN Ia light curve) with redshift. However, the evolution of spectral features depends on the composition of the ejecta and opacities, and therefore on temperature and density. Although the redshift of a given spectral feature will depend on the mass of subatomic particles, the evolution of that line does not depend on the mass of these particles. Since spectral evolution should not change with redshift, we therefore can rule out the variable mass theory with our current data.

With the current large-scale searches for high-redshift SNe, such as ESSENCE (<http://www.ctio.noao.edu/wproject>; Smith et al. 2002) and the CFHT Legacy Survey (<http://www.cfht.hawaii.edu/Science/CFHLS>; Pain & SNLS Collaboration 2002), there are many more multi-epoch high-redshift SN Ia

spectra. A similar analysis should be performed on this larger data set to confirm and improve upon these results. Knowing the time of rest-frame B maximum is helpful in two ways: (1) this time is independent of any intrinsic width of the SN light curve, avoiding many of the photometric issues found in Leibundgut et al. (1996); and (2) this time is well-constrained and avoids any evolutionary effects of SNe Ia. The time of B maximum is another point that can be used to determine time dilation.

Given a large sample of SNe Ia, well-sampled light curves, and at least one spectrum of each SN, the effect of time dilation across this sample could be easily determined. One can place all of the SFAs and spectral epochs on the same axes by matching the time of B maximum and scaling by redshift. With a single multi-epoch SN, we were able to exclude the null hypothesis at the 97.9% level; with a hundred data points, one should be able to easily rule out the null hypothesis at a much higher significance level.

An improvement in the SN Ia time dilation measurement can be obtained through higher S/N spectra (reducing the errors on an individual SFA), more epochs per SN, an expanded training set for spectral-feature aging (to reduce the inherent SFA errors and to match earlier-time and later-time spectra), higher-redshift SNe (which should show even more time dilation), and more objects. The increase in the number of objects is certain to occur as the major high-redshift SN Ia searches are finding ~ 100 SNe Ia per year. The higher S/N spectra and multiple-epoch data sets are difficult to obtain because of the constraints on spectroscopic follow-up time of SNe Ia on large-aperture telescopes. Likewise, much time must be spent to obtain even a single spectrum of a faint SN Ia at $z \approx 1$. However, a better training set will be available soon, after more light curves are published (CfA sample, Jha et al. 2005; LOSS sample, Li et al. 2005).

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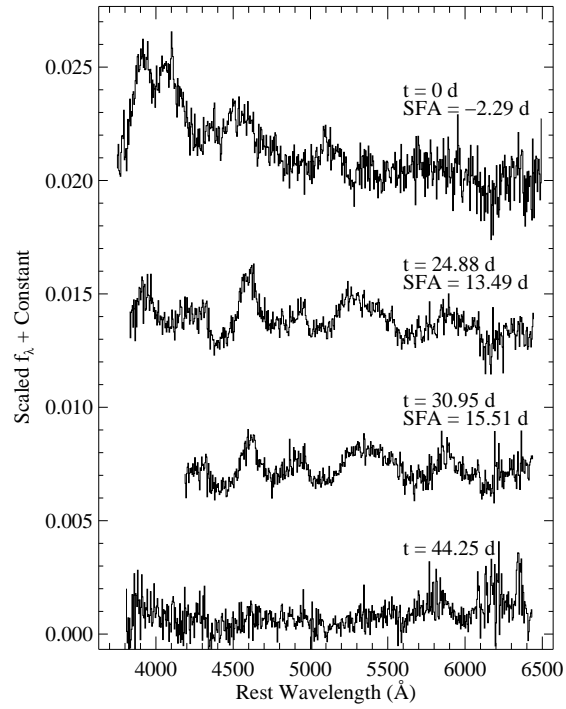


Fig. 1.— Spectra of SN 1997ex. The spectra have been deredshifted to the rest frame, and host-galaxy light has been subtracted.

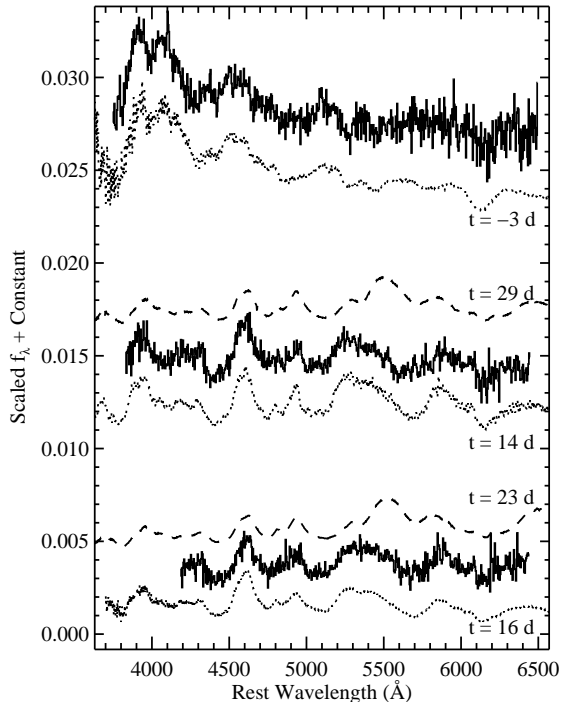


Fig. 2.— Spectra of SN 1997ex with low- z SN comparison spectra. The spectra have been deredshifted to the rest frame. The dotted lines are spectra at the SFA for each SN 1997ex spectrum (SN 1995E (Riess et al. 1998), SN 1990N (Filippenko, private communication), and SN 1994D (Filippenko 1997) are at photometric ages of -3 d, 14 d, and 16 d relative to B maximum, respectively). The dashed lines are spectra of SN 1994D at the epoch corresponding to the time elapsed in the observed frame, assuming that the first-epoch SFA is equivalent to its true age ($t = -2.28$ d). Clearly, the latter spectra are a poor match to the observed spectra of SN 1997ex.

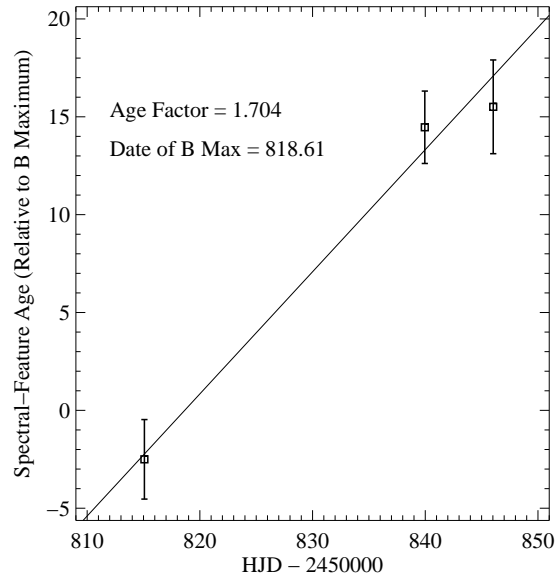


Fig. 3.— Age-factor fit to spectral-feature ages. The slope of the fit corresponds to an age factor of 1.704 ± 0.320 . *B*-band maximum is fit to be HJD 2450818.61 \pm 2.09.

Table 1. Spectral Feature Ages

UT Date	HJD- 2450000	SFA (days)
1998-01-01	815.08	–2.50 (2.03)
1998-01-26	839.96	14.46 (1.85)
1998-02-01	846.03	15.51 (2.39)

Note. — Spectral-feature age (SFA) is relative to *B*-band maximum. Uncertainties are indicated in parentheses.

Table 2. Spectral Features

Feature	Wavelength Range (\AA)
1	4397.72–5871.53
2	4682.52–5122.65
3	4725.47–4999.27
4	5593.93–5910.65
5	5642.64–6249.96
6	5716.59–6193.18
7	5719.52–5845.31
8	6015.48–6131.82

Table 3. Journal of Spectroscopic Observations of SN 1997ex

UT Date yymmdd	HJD –2450000	Tel. ^a	Range ^b (Å)	Res. ^c (Å)	P.A. ^d (deg)	O.P.A. ^e (deg)	Air. ^f	F. Std. ^g	See. ^h (")	Slit (")	Exp. (s)	Observers ⁱ
980101	815.08	KII	4900-9860	10	124	58	1.17	HD84	1.0	1	600	P,H,K,D
980126	839.96	KII	5184-8958	7	40	34	1.05	BD26	1.1	1	3x1200	F,L,R
980201	846.03	KII	5696-9486	7	60	66	1.36	HD19	1.5	1	2x1200,1300	F,L,R
980305	877.95	KII	5180-8946	7	63	66	1.36	BD26	1.1	1	2x1800	F,M
990121	1199.90	KII	5100-8840	7	63	129	1.10	HD19	0.8	1	2x1200	F,L

Note. — Additional observation details: 980101: 300/5000 grating. Extracted ± 5 pixels, background ± 7 –20. 980126: 400/8500 grating. Extracted ± 5 pixels, background ± 8 –18. Dithered between exposures. 980201: 400/8500 grating. Extracted ± 5 pixels, background ± 10 –25. 980305: 400/8500 grating. Extracted ± 5 pixels, background ± 10 –25. 990121: Extracted ± 5 pixels, background ± 10 –25. In all cases the CCD pixel scale was $0.42'' \text{ pixel}^{-1}$, and an optimal extraction (Horne 1986) was performed.

^aKII = Keck-II 10-m/Low Resolution Imaging Spectrometer (Oke et al. 1995).

^bObserved wavelength range of spectrum. In some cases, the ends are very noisy, and are not shown in the figures.

^cApproximate spectral resolution derived from night-sky lines.

^dPosition angle of the spectrograph slit.

^eOptimal parallactic angle (Filippenko 1982) near the midpoint of the exposures.

^fAverage airmass of observations.

^gThe standard stars are as follows: HD19 = HD 19445, HD84 = HD 84937, BD26 = BD+26°2606 (Oke & Gunn 1983).

^hSeeing is estimated from the FWHM of point sources on the CCD chip.

ⁱD = Susana Deustua; F = Alex Filippenko; H = Isobel Hook; K = Robert Knop; L = Douglas Leonard; M = Ed Moran; P = Saul Perlmutter; R = Adam Riess.