Time Dilation in the Light Curve of the Distant Type Ia Supernova SN 1995K

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ABSTRACT

The light curve of a distant Type Ia supernova acts like a clock that can be used to test the expansion of the Universe. SN 1995K, at a spectroscopic redshift of $z = 0.479$, provides one of the first meaningful data sets for this test. We find that all aspects of SN 1995K resemble local supernova Ia events when the light curve is dilated by $(1 + z)$, as prescribed by cosmological expansion. In a static, non-expanding universe SN 1995K would represent a unique object with a spectrum identifying it as a regular Type Ia supernova but a light curve shape and luminosity which do not follow the well-established relations for local events. We conclude that SN 1995K provides strong evidence for an interpretation of cosmological redshifts as due to universal expansion. Theories in which photons dissipate their energy during travel are excluded as are age-redshift dependencies.

Subject headings: Cosmology: observations – galaxies: distances and redshifts – supernovae: general – supernovae: individual (SN 1995K)

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1. Introduction

The nature of galaxy redshifts has usually been interpreted as due to a general expansion of the universe. However widely accepted clear experimental proof of this fundamental assumption of most cosmological models has been lacking. The main argument in favor of expansion is the observed nearly perfect blackbody energy distribution of the cosmic background radiation (Mather et al. 1990, Peebles et al. 1991). The Tolman surface brightness test (Tolman 1930) fundamentally probes for expansion as well, but implementation of this test has proven difficult (Sandage & Perelmutter 1991, Pahre et al. 1996), as galaxy evolution has to be evaluated independently. The interpretation of redshifts as due to universal expansion has been questioned (e.g. Arp 1987, Arp et al. 1990). Observations of the apparent clustering of high-redshift quasars around low-redshift galaxies (Burbidge et al. 1971, Arp 1987) and the anomalous distribution of redshifts in groups (Arp 1994) have been used to argue against cosmological expansion. A theory linking observed redshifts to the ages of the objects has been developed to explain these findings (Narlikar & Arp 1993).

A direct test of the nature of cosmological redshifts is provided by the observable effects of time dilation on time variable phenomena at large redshifts. In an expanding universe these redshifts are directly related to the change in the scale parameter inducing a change of distant clock rates for a local observer. The light curve of a distant supernova is predicted to be stretched in the observer's frame by a factor $(1+z)$ compared to the rest frame of the object (Wilson 1939, Rust 1974, Colgate 1979, Tammann 1979, Leibundgut 1990, Hamuy et al. 1993). Although the light curves of nearby events display, in general, a fairly uniform shape (Barbon et al. 1973, Leibundgut 1988), recent high-precision photometry shows that SNe Ia exhibit differences in their light curves which are related to their luminosities (Phillips 1993, Hamuy et al. 1995, Riess et al. 1995a).

To observe the real effect one needs a well observed, spectroscopically classified SN Ia at a considerable redshift and a thorough understanding of the varieties of light curve shapes. Attempts to measure the cosmological time dilation with SNe Ia have been made before. A sample of nearby events ($z < 0.05$) was investigated by Rust (1974). For such low redshifts, errors in photometry and the real variations in light curve shape mask the effect of time dilation. The light curve of the distant SN 1988U was employed for a first test ($z = 0.31$; Nørgaard-Nielsen et al. 1989, Leibundgut 1991), but the observations do not cover the maximum and no definite answer could be found. Recently, the light curve data on other distant supernovae have been used for a similar analysis (Goldhaber et al. 1996). Here we describe the time dilation test with observations of SN 1995K, a spectroscopically confirmed SN Ia with a well-observed light curve.

2. The case of SN 1995K

We have observed a distant supernova superposed on the spiral arm of a galaxy at a redshift of 0.479 (Schmidt et al. 1995, 1996). The SN spectrum identifies the object as a genuine Type Ia supernova displaying the characteristic [Si II] absorption around $\lambda_{rest} \approx 6100$Å observed near 9000Åand matches that observed near maximum for local events like SN 1990N or SN 1989B, but shows distinct differences from the peculiar examples SN 1991T and SN 1991bg (Schmidt et al. 1996).

CCD photometry of SN 1995K has been secured in special filters corresponding to B and V passbands shifted to a redshift of 0.45 and in Kron-Cousins R and I filters. Rest frame B and V light curves have been constructed from these observations. The close match of the regular B passband with the R filter at redshift 0.48 reduces the K-correction terms to a nearly constant value, independent of the exact color evolution (Kim et al. 1996, Schmidt et al. 1996). The available rest frame B light curve of SN 1995K covers the supernova peak for over 7 weeks. At least one pre-maximum point from pre-discovery search observations of the field has been recorded. Since the search was performed with the redshifted B filter we lack any pre-discovery observations in the rest-frame V passband.

Simple determination of the decline after maximum indicates a very slow apparent evolution compared to even the slowest local events (e.g. SN 1992bc; Maza et al. 1994, Hamuy et al. 1995). In fact, SN 1995K is the slowest SN Ia ever observed which we attribute not to intrinsic properties of SN 1995K but to time dilation. The photometric observations of SN 1995K provide the basis for this test of time dilation. The cases of an expanding and a static universe are discussed separately in the following sections. We compare the rest-frame photometry of SN 1995K with light curves of local supernovae of different decline speeds. As representatives of local SNe Ia we have taken SN 1990N (Leibundgut et al. 1991), SN 1991T (Phillips et al. 1992), SN 1992bc (Maza et al. 1994), and an average SN Ia template (Leibundgut 1988). SN 1991T and SN 1992bc are the slowest SNe Ia observed to date, while SN 1990N represents a fairly regular event. All three supernovae have well-observed light curves from which we constructed comparison templates. SN 1991T displayed spectral peculiarities near maximum (Filippenko et al. 1992, Ruiz-Lapuente et al. 1991, Phillips et al. 1992), which we would have detected, if they were present, in SN 1995K. The photometry of SN 1995K has been fitted to the light curves of the local events by means of χ^2 minimization. We find that the simplest possible hypothesis fits the facts best: SN 1995K has the spectrum and the light curve of a normal SN Ia, stretched in time by a factor (1+0.479).

We could hope to find a close relative of SN 1995K in the sample of nearby SNe Ia by determining the best fitting case, very similar to the procedure employed by Hamuy et al. (1995). The results of simultaneous fits to the rest frame B and V photometry are presented in Table 1. As can be seen, the best fit is achieved for the template light curve of SN 1991T. However, no clear trend emerges and all fits are quite acceptable. The dates and magnitudes at maximum found in the comparisons agree with each other to within the errors. This is an encouraging result as it means we are able to determine these values fairly accurately independently of the assumptions about the comparison light curve. Conversely, it indicates the small differences among the comparison templates near maximum. The variations in χ^2 of the best fits for the different templates are largely determined by the observations made well before and well after peak. The sigmas are the formal errors from the fit and only include the photometric uncertainties of the data. Systematic errors certainly increase the uncertainty on the peak magnitudes.

To demonstrate the robustness of the result, we can estimate the redshift of SN 1995K from the photometry through the redshift dependence of the light curve stretching. The results of this analysis is shown in the upper panel of Figure 1. The deduced redshift changes with the assumed light curve shape. Interestingly, the formally best fits appear to prefer a slow supernova at a somewhat smaller redshift than determined from the spectra, although the differences are small. A zero redshift is clearly excluded in all fits. The light curves of SN 1995K are certainly consistent with the ones of regular SNe Ia assuming

TABLE 1
FIT PARAMETERS FOR $z = 0.479$

Comparison template	t^B_{max} [a]	$\sigma(t^B_{max})$	B_{max}	$\sigma(B_{max})$	V_{max}	$\sigma(V_{max})$	χ^2 [b]
average template	802.7	1.0	22.93	0.06	22.98	0.05	12.6
SN 1990N	801.5	1.0	22.92	0.06	22.93	0.05	12.4
SN 1991T	802.5	1.1	22.94	0.06	22.96	0.05	11.1
SN 1992bc	799.8	1.1	22.89	0.06	22.85	0.06	12.1

[a] JD – 2449000

[b] Degrees of freedom: 21

a time dilation as expected from universal expansion.

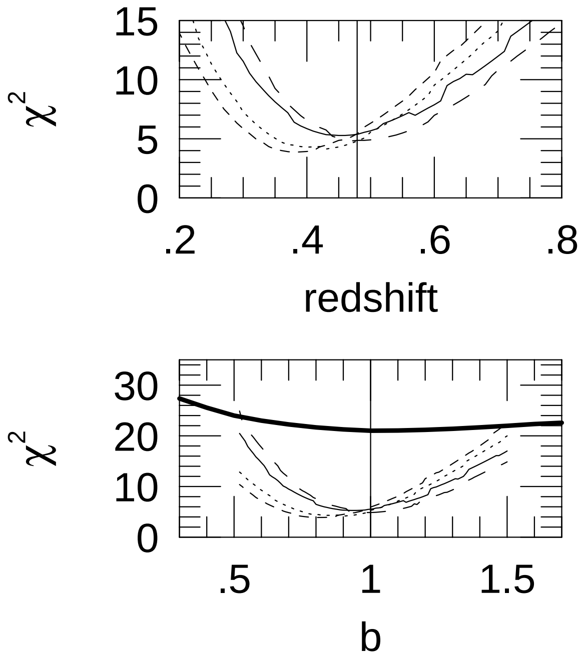

Fig. 1.— χ^2 distributions for different values of the fitting parameters. For each calculation the other parameter have been set to the canonical values, i.e. z = 0.479 and b = 1. The curves are for SN 1990N (full lines), SN 1991T (dotted), SN 1992bc (short dashes), and the average template (long dashes). The thick line is the result from the LCS fitting.

To investigate time dilation in a more general manner, we have performed fits with a parameterized dilation factor of the form $(1+z)^b$. However, the data do not constrain the problem enough to fit both parameters simultaneously. The analysis was performed in such a way that we determined the global χ^2 of the fit by varying one parameter while keeping the other at the expected value (0.479 for z and 1 for b). The lower panel in Figure 1 display the results of this analysis. Values of $b > 1$ introduce additional light curve stretching and a compression for $b < 1$. We find that for comparisons with slower local supernovae, the SN 1995K light curve is too fast for the regular dilation factor. The faster light curves reach values closer to 1 as they need a larger stretching factor to match the SN 1995K photometry. Independent fits employing the light curve shape fitting method developed by Riess et al. (1995a,b) confirm this result. This method is based on a set of known light curve shapes and interpolates between them. It further uses a weighing scheme for the model points which gives more importance to brighter peak magnitudes and larger uncertainties to the fainter parts of the light curve. This is the reason for the higher χ^2 of this fit and the much shallower minimum in the χ^2 distribution. This method also indicates a solution for $b = 1.0^{+0.5}_{-0.25}$ and also clearly excludes small values of b.

In a static universe time dilation is not expected to act on the light curve. Redshift in this case is caused by tired light or an equivalent theory (e.g. the variable mass hypothesis; Narlikar & Arp 1993) and is linked to distance through analyses such as the expanding photospheres in Type II supernovae (Schmidt et al. 1994) and gravitational lenses (Dar 1991). Another manifestation is the redshift-apparent magnitude diagram of brightest cluster galaxies (e.g. Postman & Lauer 1995) and SNe Ia. The small scatter in the Hubble diagram of Hamuy et al. (1995) supports this redshift-distance relation. Table 2 lists the fit parameters for the non-dilated light curve shapes. The global χ^2 values clearly exclude these fits. None of the known light curves of local SNe Ia is slow enough to match the photometry of SN 1995K (Figure 2). In particular the maximum magnitude is far from the observed one due to the attempt of the fits to match the pre-maximum point. The formal errors of the fit parameters are not valid, as can be judged from large χ^2.

If we take a static universe literally, then SN 1995K was observed at an earlier phase (16 days before maximum) than any nearby supernova. In that case we are depending on extrapolated pre-maximum points in the template light curves, which may not be correct. Therefore we have removed the pre-maximum point from the SN 1995K photometry and compared it again with light curves of local SNe Ia. The quality of the fits improves dramatically (Figure 2). The maximum date and magnitude agree much better with the observations. Slower light curves are clearly favored in this picture. Nevertheless, even the slowest local templates are qualitatively worse than dilated light curves; the evolution of SN 1995K was considerably slower than any of the comparison curves.

3. Discussion

Figure 2 shows the rest-frame B light curve of SN 1995K compared to the best fits of light curves stretched by the ex-

TABLE 2
FIT PARAMETERS FOR NON-DILATED LIGHT CURVES ($z = 0$)

Comparison template	t^B_{max} [a]	$\sigma(t^B_{max})$	B_{max}	$\sigma(B_{max})$	V_{max}	$\sigma(V_{max})$	χ^2 [b]
average template	799.1	0.5	22.27	0.06	22.54	0.05	137.7
SN 1990N	798.9	0.5	22.32	0.06	22.54	0.05	129.0
SN 1991T	799.4	0.6	22.38	0.06	22.58	0.05	90.1
SN 1992bc	797.5	0.5	22.36	0.05	22.39	0.05	74.7

[a] JD – 2449000

[b] Degrees of freedom: 21

pected factor $(1+z)$ for universal expansion and for non-dilated templates. Two fits for the non-dilated case are shown which emphasize the importance of the pre-maximum observation. The figure demonstrates that without time dilation effects, SN 1995K must be a unique event unrelated to the observational data of local SNe Ia. When we assume universal expansion, SN 1995K appears as a rather normal SN Ia. The spectrum shows great similarities to local events which are regarded as non-peculiar, the color at maximum ($0.0 < B - V < 0.1$) is similar to unreddened nearby SNe Ia, indicating little if any absorption, and the luminosity is in the range expected from expanding cosmologies (Schmidt et al. 1996). The light curve in itself indicates a redshift which is close to the spectroscopic redshift. Complicating the analysis is the variety of light curve shapes observed for nearby SNe Ia. This effect has been interpreted as an apparent stretching of an underlying basic template (Perlmutter et al. 1996). However, we know from detailed analysis that the light curve behavior is more complicated (Riess et al. 1995a). The data of SN 1995K, unfortunately, can not distinguish which local supernova provides the best match. We find the formally best fits to indicate a slightly lower redshift or, equivalently, a slightly retarded cosmological expansion. All fits are determined very strongly by the pre-maximum observation and the latest data points. This highlights the importance for extended coverage of SN Ia events to perform this time dilation test. In addition, the photometric accuracy of the data critically determines the goodness of the fits.

In a static universe the Hubble constant is time-independent and just measures the redshift-distance proportionality. For a conventional Hubble constant of $H_0 = 50$ km s^{-1} Mpc^{-1} one unit in redshift corresponds to 6000 Mpc. The same number for $H_0 = 80$ km s^{-1} Mpc^{-1} is 3750 Mpc. The luminosity of SN 1995K in such a static universe is $M_B = -19.3 + 5\log(H/50)$. Our best estimate for the absolute magnitude SN 1995K should have when we use the decline rate relation of Hamuy et al. (1995), however, is $M_B = -20.4 \pm 0.2 + 5\log(H/50)$, with $\Delta m_{15} \approx 0.5$ and the most conservative estimate of the decline-luminosity relation (eq. 11 of Hamuy et al. 1995). This means SN 1995K should be about 1 magnitude more luminous than what would be observed in a static universe model. Note that the extrapolation goes well beyond the set of objects on which the method is based ($0.8 < \Delta m_{15} < 1.5$). Even compared to the average absolute magnitude of local supernovae ($M_B = -19.7 \pm 0.25 + 5\log(H/50)$) SN 1995K appears underluminous. In a static universe, SN 1995K would have been a truly unique SN Ia - exhibiting the slowest known photometric evolution, yet displaying a normal spectrum, and being substantially less luminous than its nearby counterparts.

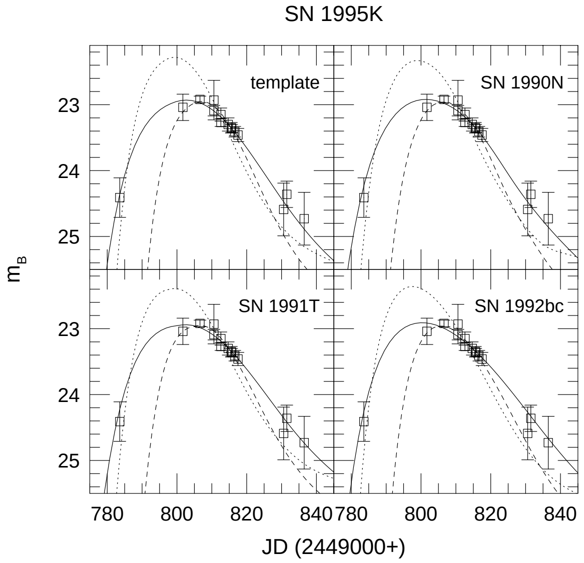

Fig. 2.— Comparison of the SN 1995K photometry with B light curves of local supernovae. The lines correspond to the best fits assuming a $(1 + z)$ stretching as expected from universal expansion. Short dashes represent the best fit of non-dilated light curves to the data and long dashes are the best fits excluding the pre-maximum observation of SN 1995K.

The apparent peak magnitude of SN 1995K can also be compared to the expectation of a steady-state model. Since the universe is expanding in this model, time dilation cannot distinguish it from the standard Big Bang. However, the steady-state model predicts a luminosity-redshift relation. With the sample of nearby SNe Ia compiled by Hamuy et al. (1995) we can predict the expected apparent magnitude of a distant supernova given its redshift. With equation (9) from Hamuy et al., i.e. excluding any luminosity corrections from the light curve shape, we predict a peak magnitude of SN 1995K of B=23.4 ± 0.1 where the error is composed from the uncertainty in the determination of the zero-point (cf. difference between eqs. (3) and (9) in Hamuy et al.). The scatter of the local supernovae around the relation is $\sigma = 0.25$. SN 1995K was observed about 0.4 magnitude brighter than this prediction. With this single measurement we are thus not able to exclude the steady-state model due to the intrinsic scatter in the luminosity of SNe Ia.

4. Conclusions

The photometry of SN 1995K extending over about 50 days provides sufficient data to probe the effect of time dilation on a clock running at a cosmological distance. We find that including the time dilation expected from universal expansion makes SN 1995K comparable to local SNe Ia and a fair representative of its class. The spectrum, color, luminosity at maximum, and the light curve shape are all very similar to what is observed in local Type Ia supernova. Together with more SNe Ia at cosmological distances it can be used to determine the deceleration parameter and contributions of non-baryonic mass to the cosmic mass density.

On the other hand, assuming a static universe, SN 1995K had the slowest photometric evolution of all known SNe Ia despite appearing spectroscopically indistinguishable from local events. The photometry of SN 1995K cannot be approximated by any light curve shape of nearby events and, in a non-expanding universe, does also not follow the decline-luminosity relation established for nearby events. It is even less luminous than the mean of local supernovae and would constitute a unique and peculiar SN Ia.

We take this as a clear vindication of an expanding universe. Further supernovae at redshifts beyond 0.1 provide additional checks (cf. Goldhaber et al. 1996). Such distant objects are currently discovered at a regular rate (Perlmutter et al. 1995a,b, 1996, Kirshner et al. 1995, Garnavich et al. 1996a,b) and will provide additional tests for consistency. The importance of extensive light curve coverage as early and as long as possible must be stressed. It is only these observations which provide enough leverage to perform this test. The early and late phase photometry is also of paramount importance for an accurate determination of the deceleration parameter q_0 in order to identify the best local counterpart and find the most appropriate luminosity. Direct observation of the detailed spectral evolution of a distant supernova provides a further test. Here the changes in line shifts and relative strengths would reveal the apparently retarded evolution of the supernova.

5. References

Arp, H. C. 1987, Quasars, Redshifts and Controversies, Interstellar Media, Berkeley

Arp, H. C. 1994, ApJ, 430, 74

Arp, H. C., Burbidge, G. R., Hoyle, F., Narlikar, J. V., & Wickramasinghe, N. C. 1990, Nature, 346, 807

Barbon, R., Ciatti, F., & Rosino, L. 1973, A&A, 25, 241

Burbidge, E. M., Burbidge, G. R., Solomon, P. M., & Strittmatter, P. A. 1971, ApJ, 170, 233

Colgate, S. A. 1979, ApJ, 232, 404

Dar, A. 1991, ApJ, 382, L1

Filippenko, A. V., et al. 1992, ApJ, 384, L15

Garnavich,, P., et al. 1996a, IAU Circ. 6332

Garnavich,, P., et al. 1996b, IAU Circ. 6358

Goldhaber, G., et al. 1996, Thermonuclear Supernovae, eds. R. Canal, P. Ruiz-Lapuente, & J. Isern, (Dordrecht: Kluwer), in press

Hamuy, M., Phillips, M. M., Wells, L. A., & Maza, J. 1993, PASP, 105, 787

Hamuy, M., Phillips, M. M., Maza, J., Suntzeff, N. B., Schommer, R. A., & Avilés, R. 1995, AJ, 109, 1

Kim, A., Goobar, A., & Perlmutter, S. 1996, PASP, in press

Kirshner, R. P., et al. 1995, IAU Circ. 6267

Leibundgut, B. 1988, Ph.D. Thesis, University of Basel

Leibundgut, B. 1990, A&A, 229, 1

Leibundgut, B. 1991, Supernovae, ed. S. E. Woosley, (New York: Springer), 751

Leibundgut, B., et al. 1991, ApJ, 371, L23

Mather, J., et al. 1990, ApJ, 354, L37

Maza, J., Hamuy, M., Phillips, M. M., Suntzeff, N. B., Avilés, R. 1994, ApJ, 424, L107

Narlikar, J. & Arp, H. 1993, ApJ, 405, 51

Nørgaard-Nielsen, H. U., Hansen, L., Jørgensen, H. E., Salamanca, A. A., Ellis, R. S., & Couch, W. J. 1989, Nature, 339, 523

Pahre, M. A., Djorgovski, S. G., & de Carvalho., R. R. 1996, ApJ, 456, L79

Peebles, P. J. E., Schramm, D. N., Turner, E. L., & Kron, R. G. 1991, Nature, 352, 769

Perlmutter, S., et al. 1995a, ApJ, 440, L41

Perlmutter, S., et al. 1995b, IAU Circ. 6270

Perlmutter, S., et al. 1996, Thermonuclear Supernovae, eds. R. Canal, P. Ruiz-Lapuente, & J. Isern, (Dordrecht: Kluwer), in press

Phillips, M. M. 1993, ApJ, 413, L105

Phillips, M. M., et al. 1992, AJ, 103, 1632

Postman, M. & Lauer, T. R. 1995, ApJ, 440, 28

Riess, A. G., Press, W. M., & Kirshner, R. P. 1995a, ApJ, 438, L17

Riess, A. G., Press, W. M., & Kirshner, R. P. 1995b, ApJ, 445, L91

Ruiz-Lapuente, P., Cappellaro, E., Turatto, M., Gouiffes, C. Danziger, I. J., Della Valle, M., & Lucy, L. B. 1992, ApJ, 387, L33

Rust, B. W. 1974, Ph.D. Thesis, Oak Ridge National Laboratory (ORNL-4953)

Sandage, A. & Perelmutter, J.-M. 1991, ApJ, 370, 455

Schmidt, B. P., Kirshner, R. P., Eastman, R. G., Phillips, M. M., Suntzeff, N. B., Hamuy, M., Maza, J., & Avilés, R. 1994, ApJ, 432, 42

Schmidt, B. P., et al. 1995, IAU Circ. 6160

Schmidt, B. P., et al. 1996, in preparation

Tammann, G. A. 1978, Astronomical Uses of the Space Telescope, eds. F. Macchetto, F. Pacini & M. Tarenghi (Garching: ESO Proceedings), 329

Tolman, R. C. 1930, Proc. Nat. Acad. Sci., 16, 511

Wilson, O. C. 1939, ApJ, 90, 634