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Discovery of a supernova explosion at half the age of the Universe

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The ultimate fate of the Universe, infinite expansion or a big crunch, can be determined by using the redshifts and distances of very distant supernovae to monitor changes in the expansion rate. We can now find[1] large numbers of these distant supernovae, and measure their redshifts and apparent brightnesses; moreover, recent studies of nearby type Ia supernovae have shown how to determine their intrinsic luminosities[2-4]—and therefore with their apparent brightnesses obtain their distances. The >50 distant supernovae discovered so far provide a record of changes in the expansion rate over the past several billion years[5-7]. However, it is necessary to extend this expansion history still farther away (hence further back in time) in order to begin to distinguish the causes of the expansion-rate changes—such as the slowing caused by the gravitational attraction of the Universe's mass density, and the possibly counteracting effect of the cosmological constant[8]. Here we report the most distant spectroscopically confirmed supernova. Spectra and photometry from the largest telescopes on the ground and in space show that this ancient supernova is strikingly similar to nearby, recent type Ia supernovae. When combined with previous measurements of nearer supernovae[2,5], these new measurements suggest that we may live in a low-mass-density universe.

SN1997ap was discovered by the Supernova Cosmology Project collaboration on 5 March 1997 UT, during a two-night search at the Cerro Tololo Interamerican Observatory (CTIO) 4-m telescope that yielded 16 new supernovae. The search technique finds such sets ofhigh-redshift supernovae on the rising part of their light curves and guarantees the date of discovery, thus allowing follow-up photometry and spectroscopy of the transient supernovae to bescheduled[1]. The supernova light curves were followed with scheduled R-, I- and some B-band photometry at the CTIO, WIYN, ESO 3.6-m, and INT telescopes, and with spectroscopy at the ESO 3.6-m and Keck II telescopes. (Here WIYN is the Wisconsin, Indiana, Yale, NOAO Telescope, ESO is the European Southern Observatory, and INT is the Isaac Newton Telescope.) In addition, SN1997ap was followed with scheduled photometry on the Hubble Space Telescope (HST).

Figure 1 shows the spectrum of SN1997ap, obtained on 14 March 1997 UTwith a 1.5-h integration on the Keck II 10-m telescope. There is negligible ($\lesssim$5%) host-galaxy light contaminating the supernova spectrum, as measured from the ground- and space-based images. When fitted to a time series of well-measured nearby type Ia supernova spectra[9], the spectrum of SN1997ap is most consistent with a 'normal' type Ia supernova at redshift $z = 0.83$ observed 2$\pm$ 2 supernova-restframe days ($\sim$4 observer's days) before the supernova's maximum light in the rest-frame B band. It is a poor match to the 'abnormal' type Ia supernovae, such as the brighter SN1991T or the fainter SN1986G. For comparison, the spectra of low-redshift, 'normal' type Ia supernovae are shown in Fig. 1 with wavelengths redshifted as they would appear at $z = 0.83$. These spectra show the time evolution from 7 days before, to 2 days after, maximum light.

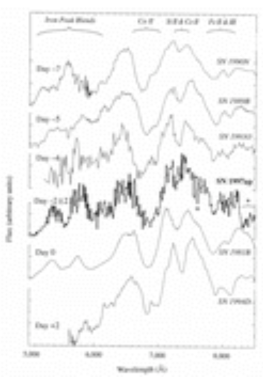

Figure 1 Spectrum of SN1997ap placed within a time sequence of five 'normal' type Ia supernovae. Full legend

High resolution image and legend (93k)

Figure 2 shows the photometry data for SN1997ap, with significantly smaller error bars for the HST observations (Fig. 2a) than for the ground-based observations (Fig. 2b and c). The width of the light curve of a type Ia supernova has been shown to be an excellent indicator of its intrinsic luminosity, both at low redshift[2-4] and at high redshift[5]: the broader and slower the light curve, the brighter the supernova is at maximum. We characterize this width by fitting the photometry data to a 'normal' type Ia supernova template light curve that has its time axis stretched or compressed by a linear factor, called the 'stretch factor'[1,5]; a 'normal' supernova such as SN1989B, SN1993O or SN1981B in Fig. 1 thus has a stretch factor of $s \approx 1$. To fit the photometry data for SN1997ap, we use template U- and B-band light curves that have first been $1+z$ time-dilated and wavelength-shifted (' K-corrected') to the R- and I-bands as they would appear at $z = 0.83$ (see ref. 5 and P.N. *et al.*, manuscript in preparation). The best-fit stretch factor for all the photometry of Fig. 2 indicates that SN1997ap is a 'normal' type Ia supernova: $s = 1.03 \pm 0.05$ when fitted for a date of maximum at 16.3 March 1997 UT(the error-weighted average of the best-fit dates from the light curve, 15.3 $\pm$ 1.6 March 1997 UT, and from the spectrum, 18 $\pm$ 3 March 1997 UT).

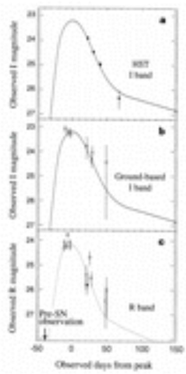

Figure 2 Photometry points for SN1997ap. Full legend

High resolution image and legend (109k)

It is interesting to note that we could alternatively fit the 1+ z time dilation of the event while holding the stretch factor constant at $s = 1.0_{-0.14}^{+0.05}$ (the best fit value from the spectral features obtained in ref. 10). We find that the event lasted $1+z = 1.86_{-0.09}^{+0.31}$ times longer than a nearby $s = 1$ supernova, providing the strongest confirmation yet of the cosmological nature of redshift[9,11,12].

The best-fit peak magnitudes for SN1997ap are $I = 23.20 \pm 0.07$ and $R = 24.10 \pm 0.09$. (All magnitudes quoted or plotted here are transformed to the standard Cousins[13] R and I bands.) These peak magnitudes are relatively insensitive to the details of the fit: if the date of maximum is left unconstrained or set to the date indicated by the best-match spectrum, or if the ground- and space-based data are fitted alone, the peak magnitudes still agree well within errors.

The ground-based data show no evidence of host-galaxy light, but the higher-resolution HST imaging shows a marginal detection (after co-adding all four dates of observation) of a possible $I = 25.2 \pm 0.3$ host galaxy 1 arcsec from the supernova. This light does not contaminate the supernova photometry from the HST and it contributes negligibly to the ground-based photometry. The projected separation is ~6 kpc (for $\Omega_M = 1$, $\Omega_\Lambda = 0$ and $h_0 = 0.65$, the dimensionless cosmological parameters describing the mass density, vacuum energy density and Hubble constant, respectively) and the corresponding B-band rest-frame magnitude is $M_B \approx -17$ and its surface brightness is $\mu_B \approx 21$ mag arcsec^{-2}, consistent with properties of local spiral galaxies. We note that the analysis will need a final measurement of any host-galaxy light after the supernova has faded, in the unlikely event that there is a very small knot of host-galaxy light directly under the HST image of SN1997ap.

We compare the K-corrected R–I observed difference of peak magnitudes (measured at the peak of each band, not the same day)to the U–B colour found for 'normal' low-redshift type Ia supernovae. We find that the rest-frame colour of SN1997ap [$(U - B)_{SN1997ap} = -0.28 \pm 0.11$] is consistent with an unreddened 'normal' type Ia supernova colour, $(U - B)_{normal} = -0.32 \pm 0.12$ (see ref. 14 and also P.N. *et al.*, manuscript in preparation). In this region of the sky, there is also no evidence for Galactic reddening[15]. Given the considerable projected distance from the putative host galaxy, the supernova colour, and the lack of galaxy contamination in the supernova spectra, we proceed with an analysis under the hypothesis that the supernova suffers negligible host-galaxy extinction, but with the following caveat.

Although correcting for $E(U - B) \approx 0.04$ of reddening would shift the magnitude by only one standard deviation, $A_B = 4.8E(U - B) = 0.19 \pm 0.78$, the uncertainty in this correction would then be the most significant source of uncertainty for this one supernova. This is because of the large uncertainty in the (U -

$B)_{SN1997ap}$ measurement, and the sparse low-redshift U-band reference data. HST J-band observations are currently planned for future $z > 0.8$ supernovae, to allow a comparison with the restframe $B - V$ colour, a much better indicator of reddening for type Ia supernovae. Such data will thus provide an important improvement in extinction correction uncertainties for future supernovae and eliminate the need for assumptions regarding host-galaxy extinction. In the following analysis, we also do not correct the lower-redshift supernovae for possible host-galaxy extinction, so any similar distribution of extinction would partly compensate for this possible bias in the cosmological measurements.

The significance of type Ia supernovae at $z = 0.83$ for measurements of the cosmological parameters is illustrated on the Hubble diagram of Fig. 3. To compare with low-redshift magnitudes, we plot SN1997ap at an effective rest-frame B-band magnitude of $B = 24.50 \pm 0.15$, derived, as in ref. 5, by adding a K-correction and increasing the error bar by the uncertainty due to the (small) width-luminosity correction and by the intrinsic dispersion remaining after this correction. By studying type Ia supernovae at twice the redshift of our first previous sample at $z \approx 0.4$, we can look for a correspondingly larger magnitude difference between the cosmologies considered. At the redshift of SN1997ap, a flat $\Omega_M = 1$ universe is separated from a flat $\Omega_M = 0.1$ universe by almost one magnitude, as opposed to half a magnitude at $z \approx 0.4$. For comparison, the uncertainty in the peak magnitude of SN1997ap is only 0.15 mag, while the intrinsic dispersion amongst stretch-calibrated type Ia supernovae is ~0.17 mag (ref. 5). Thus, at such redshifts even individual type Ia supernovae become powerful tools for discriminating amongst various world models, provided observations are obtained, such as those presented here, where the photometric errors are below the intrinsic dispersion of type Ia supernova.

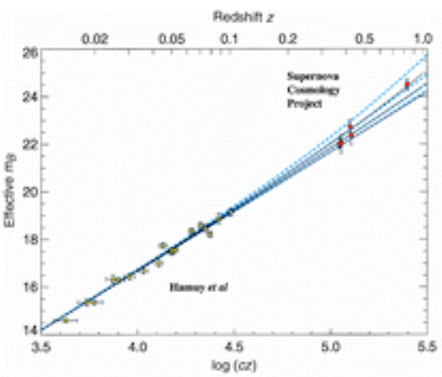

Figure 3 SN1997ap at z = 083 Full legend

High resolution image and legend (84k)

By combining such data spanning a large range of redshift, it is also possible to distinguish between the effects of mass density Ω_M and cosmological constant Λ on the Hubble diagram[8]. The blue contours of Fig. 4 show the allowed confidence region on the Ω_Λ $(\equiv \Lambda /(3 H^2_0))$ versus Ω_M plane for the $z \approx 0.4$ supernovae[5]. The yellow contours show the confidence region from SN1997ap by itself, demonstrating the change in slope of the confidence region at higher redshift. The red contours show the result of the combined fit, which yields a closed confidence region in the Ω_M–Ω_Λ plane. This fit corresponds to a value of $\Omega_M = 0.6 \pm 0.2$ if we constrain the result to a flat universe ($\Omega_\Lambda + \Omega_M = 1$), or $\Omega_M = 0.2 \pm 0.4$ if we constrain the result to a $\Lambda = 0$ universe. These results are preliminary evidence for a relatively low-mass-density universe. The addition of SN1997ap to the previous sample of lower-redshift supernovae decreases the best-fit Ω_M by approximately 1 standard deviation compared to the earlier results[5].

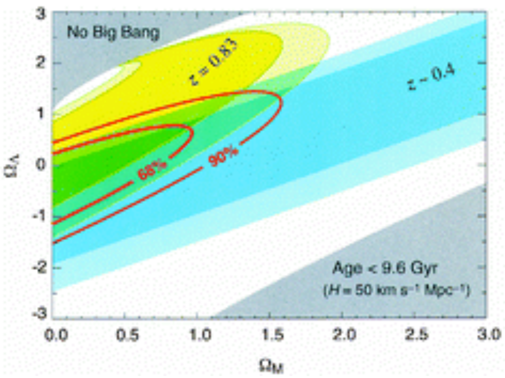

Figure 4 Contour plot of the best fit confidence regions in the Ω_Λ versus Ω_M plane for. Full legend

High resolution image and legend (146k)

Our data for SN1997ap demonstrate: (1) that type Ia supernovae at $z > 0.8$ exist; (2) that they can be compared spectroscopically with nearby supernovae to determine supernova ages and luminosities and check for indications of supernova evolution; and (3) that calibrated peak magnitudes with precision better than the intrinsic dispersion of type Ia supernovae can be obtained at these high redshifts. The width of the confidence regions in Fig. 4 and the size of the corresponding projected measurement uncertainties show that with additional type Ia supernovae having data of quality comparable to that of SN1997ap, a simultaneous measurement of Ω_Λ and Ω_M is now possible. It is important to note that this measurement is based on only one supernova at the highest ($z > 0.8$) redshifts, and that a larger sample size is required to find a statistical peak and identify any 'outliers'. In particular, SN1997ap was discovered near the search detection threshold and thus may be drawn from the brighter tail of a distribution ('Malmquist bias'). There is similar potential bias in the lower-redshift supernovae of the Calán/Tololo Survey[2], making it unclear which direction such a bias would change Ω_M.

Several more supernovae at comparably high redshift have already been discovered by the Supernova Cosmology Project collaboration, including SN1996cl, also at $z = 0.83$. SN1996cl can be identified as a very probable type Ia supernova, as a serendipitous HST observation (M. Donahue *et al*., personal communication) shows its host galaxy to be an elliptical or S0. Its magnitude and colour, although much more poorly constrained by photometry data, agree within uncertainty with those of SN1997ap. The next most distant spectroscopically confirmed type Ia supernovae are at $z = 0.75$ and $z = 0.73$ (ref. 16; these supernovae are awaiting final calibration data). In the redshift range $z = 0.3$–0.7, we have discovered over 30 additional spectroscopically confirmed type Ia supernovae, and followed them with two-filter photometry. (The first sample of supernovae with $z \approx 0.4$ were not all spectroscopically confirmed and observed with two-filter photometry[5].) These new supernovae will improve both the statistical and systematic uncertainties in our measurement of Ω_M and Ω_Λ in combination. A matching sample of $\geqslant 6$ type Ia supernovae at $z > 0.7$ is to be observed in two filters in Hubble Space Telescope observations due to start on 5 January 1998. SN1997ap demonstrates the efficacy of these complementary higher-redshift measurements in separating the contribution of Ω_M and Ω_Λ to the total mass-energy density of the Universe.

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