Type Ia Supernovae, Cosmology and the VLT

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1. Type Ia Supernovae and Cosmology

Over the last decade, two international teams have used the magnitude-redshift relation of type Ia supernovae (SNe) to measure the mass density Ω_M and the cosmological constant Ω_Λ of the universe. Both teams, using largely independent data sets and independent analysis methods, reach the conclusion that the cosmological constant is non-zero and that the expansion of the universe is accelerating (Riess et al. 1998, Perlmutter et al. 1999).

These results were derived from observations of 56 distant type Ia SNe, spanning a redshift range from $z = 0.16$ to $z = 0.97$. The mean redshift of the combined sample is around z = 0.5. In what is an excellent example of international collaboration, the observations have been taken with 13 different telescopes spread over 7 different sites in both the Northern and Southern Hemispheres.

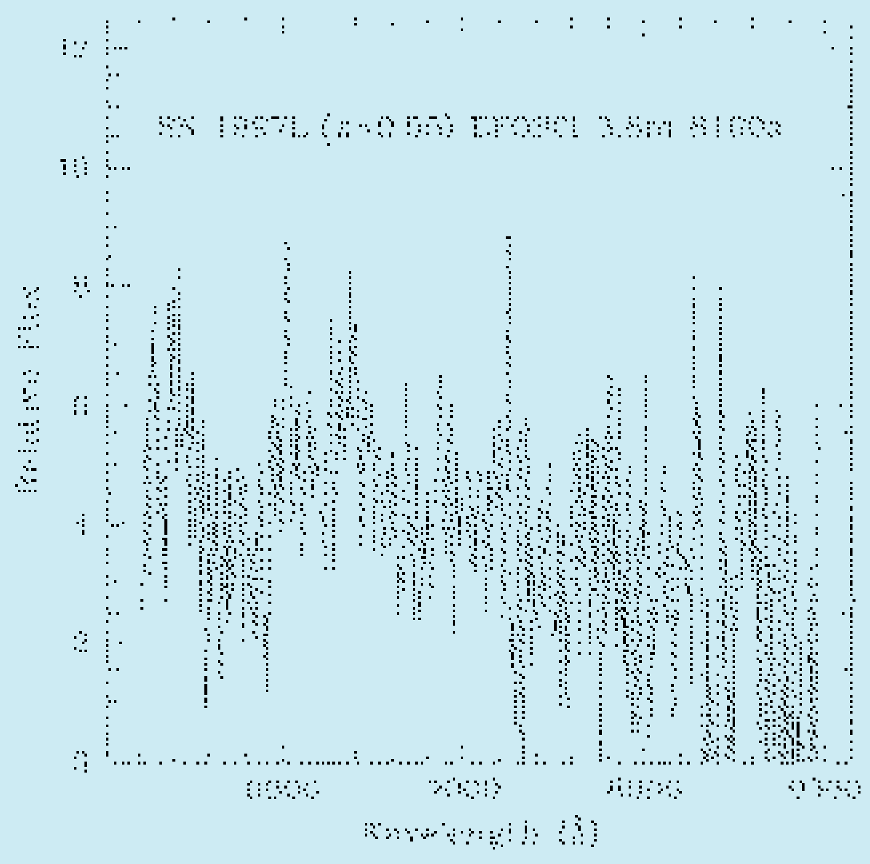

Figure 1: An unsmoothed spectrum of 1997L taken with EFOSC1 on the 3.6-m.

The SNe are discovered by observing blank fields over two epochs, which are separated by about three weeks. The fields are observed before and after full moon. In this way, the SNe are discovered while still brightening (Perlmutter et al. 1995), and follow-up observations can start during the following new moon. A final photometric point is taken after the SNe has faded, which is usually one year later.

The confirmation of the SN type has mostly been done by obtaining low-resolution spectra with the Keck 10-m telescope, but about 10 type Ia SNe have been confirmed from spectra taken with 4-m-class telescopes, such as the MMT and the ESO 3.6-m. As an example, the spectrum of SN 1997L (z = 0.55), which was observed with EFOSC1 on the ESO 3.6-m, is shown in Figure 1.

Up until 1998, the photometric monitoring was mostly done with 4-m-class telescopes, including the ESO 3.6-m telescope and the ESO NTT. The ESO 3.6-m has been used to follow over 60 high redshift type Ia SNe. Now, with both groups finding more distant SNe ($z \approx 1$), the photometry is done either from space with HST or with the largest ground-based telescopes, such as the VLT.

With the VLT now in operation and with other large 8-m telescopes coming on line, it is perhaps timely to review how these telescopes can contribute to the study of type Ia SNe, not only in terms of measuring the cosmological parameters but also measuring the evolution of type Ia properties as a function of redshift.

2. VLT Observations of a Type Ia SN at *z* = 0.54

Discovering type Ia SNe beyond z = 0.3 is now routine and both groups combined have now observed over 100 such SNe. The SNe are discovered by using the largest wide field imagers available on 4-m-class telescopes. Both the BTC camera on the 4-m Blanco Telescope in Chile and the CFH12k on the CFHT in Hawaii have been used to discover distant type Ia SNe.

During our most recent run on the CFHT, we discovered a type Ia SNe well before maximum light. This SNe, which we nicknamed Beethoven[1], has a redshift of z = 0.54, which is similar to the mean redshift of all the SNe that have been used to conclude that the universe is accelerating. A preliminary analysis of our data on SN Beethoven suggests that the CFHT discovery image was taken 14 days (in the rest frame of Beethoven) before maximum, and that the spectrum subsequently taken with FORS1 was taken 12 days before maximum. The early discovery of Beethoven enabled us to plan and execute relatively high signal-to-noise ratio target of opportunity observations with FORS1 and ISAAC with the aim of testing whether SN Beethoven is a normal type Ia SNe or not.

The observations with FORS1 on ANTU (UT1) were done on May 12, 2000. The observing conditions were very good, with a mean seeing of 0.55″ and a clear sky. We used FORS1

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[1] We give a temporary name, for use within the team, to every candidate we find during a campaign. This time the names were composers. Once a SN candidate has been confirmed, we write an IAU circular and an official name is given to the SN following the IAU nomenclature.

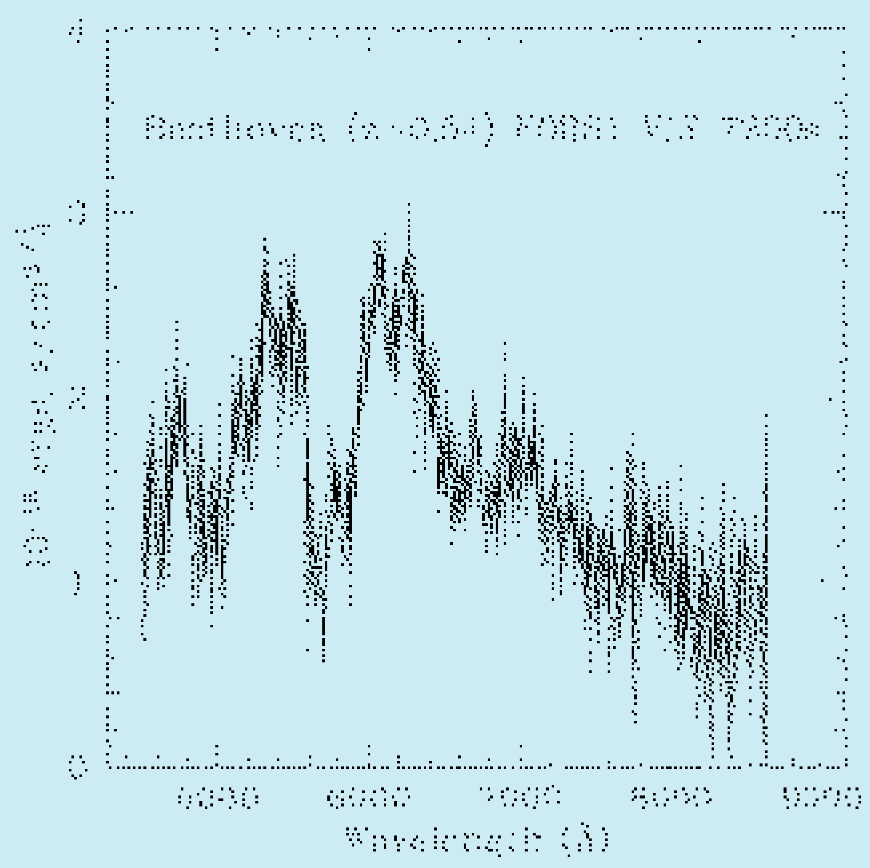

Figure 2: An unsmoothed spectrum of SN Beethoven (z = 0.54) taken with FORS1 on ANTU UT1. The signal-to-noise ratio of the SN Beethoven spectrum is six times larger than the signal-to-noise ratio of the spectrum of 1997L.

in long-slit mode and with the 300 V grism. The total integration time was two hours.

The spectrum of SN Beethoven is shown in Figure 2. The signal-to-noise ratio is around 10 per pixel (2.6Å) or 20 per resolution element (which is 5 pixels and corresponds to the width of the slit). This is an exceptionally high signal-to-noise ratio for a SN at $z = 0.54$ and it allows us to clearly see that SN Beethoven is a type Ia that was observed about a week (rest frame) before maximum light.

A comparison with spectrum SN 1997L in Figure 1 shows the dramatic improvement in the signal-to-noise ratio. Both SNe have similar redshifts and both have been observed about one week before maximum light. The VLT clearly allows us to make the transition from qualitative statements, such as “It looks like a SN Ia”, to quantitative measurements of line strengths and comparisons with nearby SNe.

SN Beethoven was also observed with ISAAC on three separate occasions, which approximately correspond to the epoch of maximum light, and to 16 and 32 rest frame days after maximum light. SN Beethoven was observed with the Js filter, which, in SN Beethoven’s rest frame, corresponds to the I-band. The conditions at the time of the observations were again very good, with a median seeing of 0.6″ and clear skies.

There are two reasons for observing moderately distant type Ia SNe with near-IR instruments such as ISAAC. As discussed by Riess et al. (2000), near-IR observations provide a longer wavelength baseline to test for the presence of near-grey dust. They also provide a test which is not accessible at optical wavelengths. In the I-band, nearby SNe exhibit a second maximum approximately one month after the first. For SNe at $z \approx 0.5$, this second maximum occurs in the near-IR and has been observed in SN 1999Q (Riess et al. 2000).

The images from individual epochs and an image that combines all three epochs, which totals almost 10,000 seconds of integration time, are shown in Figure 3. SN Beethoven, which is marked by the arrows, is visible, with moderate signal-to-noise, about 1 arcsec away from the host galaxy. The FWHM of the star images in the final frame is 0.55″.

From a visual inspection of the images, it can be seen that at 32 days after the first maximum SN Beethoven is still visible with approximately the same intensity as it had at 16 days after maximum. However, at this preliminary stage of the analysis it is not clear if this is consistent with a second maximum or if a plateau better describes the observations.

3. The Near Future: the Role of the VLT

The use of type Ia SNe as standard candles has led to the proposition that the universe is dominated by an unknown form of dark energy, which is most commonly interpreted as a non-zero cosmological constant and that, at the present epoch, the expansion of the universe is accelerating. This is revolutionary and it is important

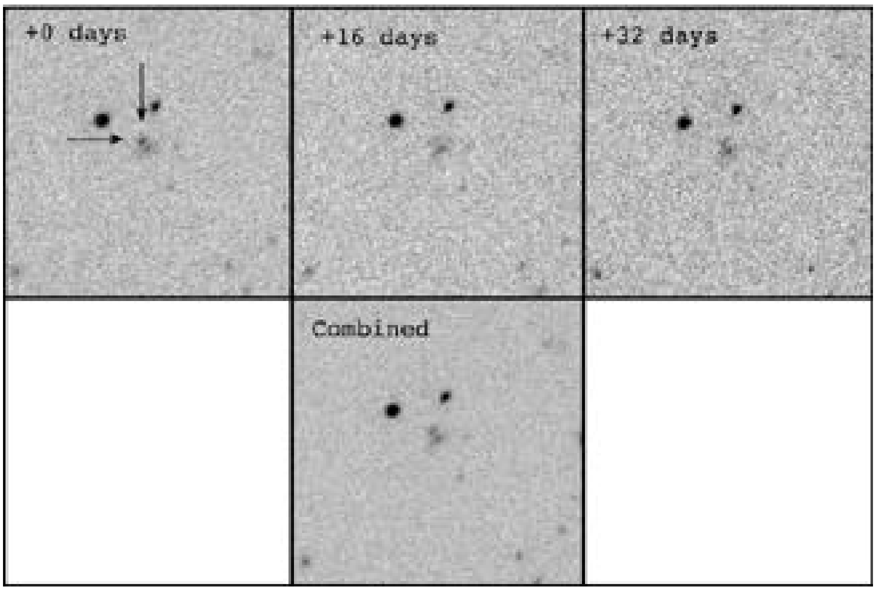

Figure 3: In the top row, a series of ISAAC images taken at different epochs. SN Beethoven is indicated by the arrows. In these images, North is down and East is to the right. FWHM of star images, 0.55 arcsec. The combined image is shown in the bottom row. To get an accurate measure of the underlying flux of the galaxy, a fourth and final image will be taken one year from now.

to make sure that the observed dimming of type Ia SNe with z is not caused by evolution, which has been the downfall of all standard candles to date, nor by grey dust.

We can test this proposition by conducting an intense optical and IR study of a dozen type Ia SNe at $z = 0.5$, the redshift at which the acceleration of the universe was derived. As we have demonstrated with SN Beethoven, the VLT, with ISAAC and the two FORS instruments, is well suited to contribute significantly to this necessary work.

Both groups of observers are now regularly finding SNe at redshifts of order one, and with instruments like VIMOS on UT3 becoming available soon, the number of such SNe will increase. With VIMOS, it will also be possible to detect lensed (highly magnified) SNe at even higher redshifts.

At $z \approx 0.5$, type Ia SNe can only be used to place joint limits on Ω_M and Ω_Λ. They cannot be used to test whether or not the universe is flat. However, with a relatively small sample of SNe at $z \approx 1$, one can very significantly improve the determination of Ω_M and Ω_Λ separately and of the equation of state of the dark energy.

However, follow-up observations of type Ia SNe at $z \approx 1$ are both difficult and time consuming. At these redshifts, the restframe B-band, where the lightcurve of type Ia SNe are best understood, is shifted into the near-IR, where the sky background from the ground is relatively high. The R-band, where the background is more favourable, corresponds to restframe U. But observations of nearby type Ia SNe in the restframe U-band are scarce and their properties in that band are not yet accurately known. It is not clear, at present, whether from U band observations alone type Ia SNe can be used as distance indicators.

SN Beethoven, at a redshift of $z = 0.54$ and SN 1999Q at a redshift of $z = 0.46$ (Riess et al. 2000) have both been successfully observed with state-of-the-art infrared instrumentation on the largest telescopes. Near-IR follow-up observations of type Ia SNe at $z \approx 1$ and beyond will probably have to wait for the next generation of IR instruments that use adaptive optics, like NAOS and CONICA, which will be installed on the VLT next year.

In the meantime, the VLT will continue to be used to confirm and follow up type Ia SNe at more moderate redshifts, $z \approx 0.8$. Its performance will be strengthened further if the planned upgrade of FORS2 with red sensitive CCDs goes ahead.

4. Acknowledgements

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Lensed Quasars: A Matter of Resolution

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1. Lensed Quasars

The interest in studying lensed quasars amongst the astronomical community has always been somewhat fluctuating. Periods of great enthusiasm and of profound disappointment have regularly followed one another.

Precisely described in the context of Einstein's Theory of General Relativity, the phenomenon of light deflection was first seen as a pure theoretical curiosity. It was however observed by Dyson et al. (1920), who measured, during a total solar eclipse, the angular displacement of a star by the sun's gravitational field. Gravitational lensing was thus established as an observed phenomenon, but the next important observational step was not made until 1979, with the discovery by Walsh et al. of the first lensed quasar, which had an angular separation of 6 arcsec between the two components. On the theoretical side, Refsdal (1964) proposed, well before Walsh's discovery, to use multiply imaged quasars to constrain cosmological parameters. As the travel times of photons along the light path to each quasar image are different, an intrinsic intensity variation of the quasar is seen at different moments in each lensed image. The so-called time delay between the detection of the intensity variation in each image is directly related to the cosmological parameter, H_0 and to the position and shape of the deflecting mass. One can therefore infer an estimate of H_0 by measuring the time delay, provided the gravitational potential responsible for light splitting is known. Conversely, one might as well want to assume a "preferred" value for H_0 and use the time delay to constrain a lens model, i.e., to study the mass distribution in distant lens galaxies. Both issues are undoubtedly of capital importance. They both require high spatial resolution observations. With the Hubble Space Telescope (HST) or, better, with large ground-based telescopes located in privileged sites, it is now possible to perform in a routine manner observations which were impossible only 10 years ago. As an illustration of this, we present in this report recent VLT FORS2 observations of HE 1104-1805, a doubly imaged quasar at z = 2.319 discovered in the framework of the Hamburg-ESO survey for bright quasars (Wisotzki et al. 1993). The choice of HE 1104-1805 is not intended to be representative of the importance of this particular object, but rather reflects how old observationally intractable problems can be tackled in a new way. We also present more recent results, obtained at the 1.54-m Danish telescope for another Hamburg-ESO quasar: HE 2149-2745.

2. The First Step: The Lens Geometry and the Time Delay

Resolving the blended images of multiply imaged quasars is one way to confirm or rule out their lensed nature.