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Cosmology from High Redshift Supernovae

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Abstract. The discovery of a correlation between the light curve shape and intrinsic brightness has made Type Ia supernovae exceptionally accurate distance indicators out to cosmologically interesting redshifts. Ground-based searches and follow-up as well as Hubble Space Telescope observations of Type Ia supernovae have produced a significant number of objects with redshifts between 0.3 and 1.0. The distant SNe, when combined with a local sample analyzed in the same way, provide reliable constraints on the deceleration and age of the Universe. Early this year, an analysis of a handful of Type Ia events indicated that the deceleration was too small for gravitating matter alone to make a flat Universe. A larger sample of supernovae gives the surprising result that the Universe is accelerating, implying the existence of a cosmological constant or some other exotic form of energy.

The success of this research has depended on the development of algorithms and software to register, scale and subtract CCD images taken weeks apart and to search for variable objects. A good fraction of the point-sources identified are asteroids, variable stars, or AGN, so spectra are needed to confirm the identification as a Type Ia supernova and obtain a redshift. The best candidates are followed photometrically to construct light curves. The steps to transform the observed light curves into cosmologically interesting results will also be described.

1. Introduction

Supernovae are the ultimate variable stars. Type Ia explosions are thermonuclear detonations of lowly white dwarfs. Over two weeks their brightness can rise by more than 20 magnitudes, a factor of 100 million. These exploding stars are easily seen in in small telescopes as far out as the Virgo cluster of galaxies and if we were lucky enough to have one go off in our Milky Way, the supernova would be easily visible during the day.

But supernovae are relatively rare events. On average, a Type Ia supernova explodes in a galaxy the size of ours once every 500 years. To be guaranteed a discovery on any given night requires searching tens of thousands of galaxies. Such wholesale searching has been made possible by the development of large area charge-coupled device (CCD) detectors and mosaics of CCDs used at the focus of 4-meter aperture telescopes.

Two groups, the High-Z Supernova Search Team led by Brian Schmidt (Schmidt et al. 1998) and the Supernova Cosmology Project led by Saul Perlmutter (Perlmutter et al. 1999) have begun very successful searches for distant supernovae using the 4-m telescope at the Cerro-Tololo Inter-American Observatory. Between them, the two teams have nearly tripled the supernova discovery rate (Fig. 1). The purpose of these searches is to find supernovae at cosmologically interesting distances. Type Ia supernovae make excellent distance indicators, so these events at high redshift can be used to map out the history of the expanding Universe.

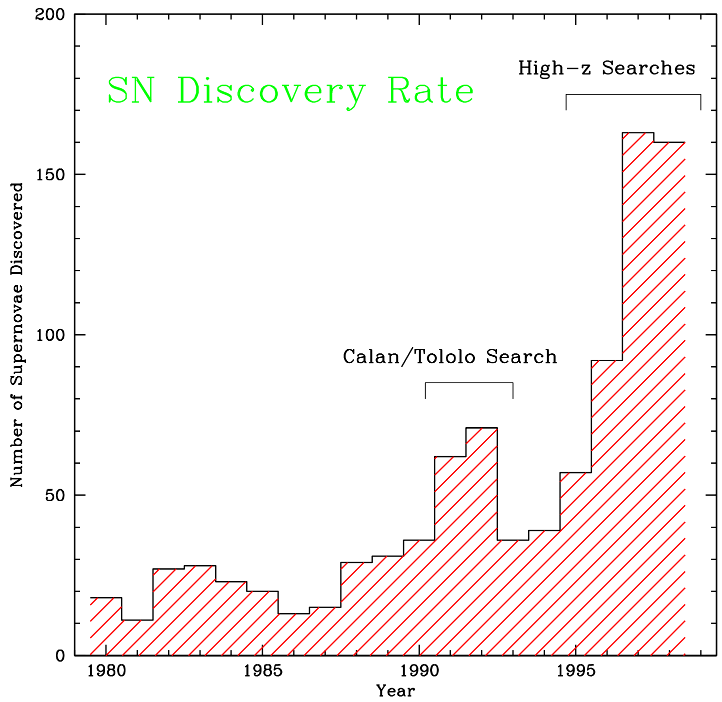

Figure 1. The discovery rate of all supernovae between 1980 and 1998. The Calan/Tololo Survey (Hamuy et al. 1996) was a collaboration of Chilean astronomers that was very successful in finding supernovae in the early 1990's. The sharp rise in the number of discovered supernovae beginning in 1996 is due to the success of two groups searching for supernovae at high redshift.

2. High-Redshift Searches

At very faint magnitude limits, $m \sim 22$, supernova searches become efficient because so many galaxies can be seen in a single deep CCD exposure on a large telescope. Five to ten supernovae per night can be found using a 4-m aperture telescope and a large area detector with a $0\overset{\circ}{.}5$ field of view.

The high-z searches require observing the same fields more than 3 weeks apart and subtracting the images using sophisticated software that matches seeing, background, and flux levels between the epochs. What should remain after this process are the objects that have changed in some way, asteroids, variable

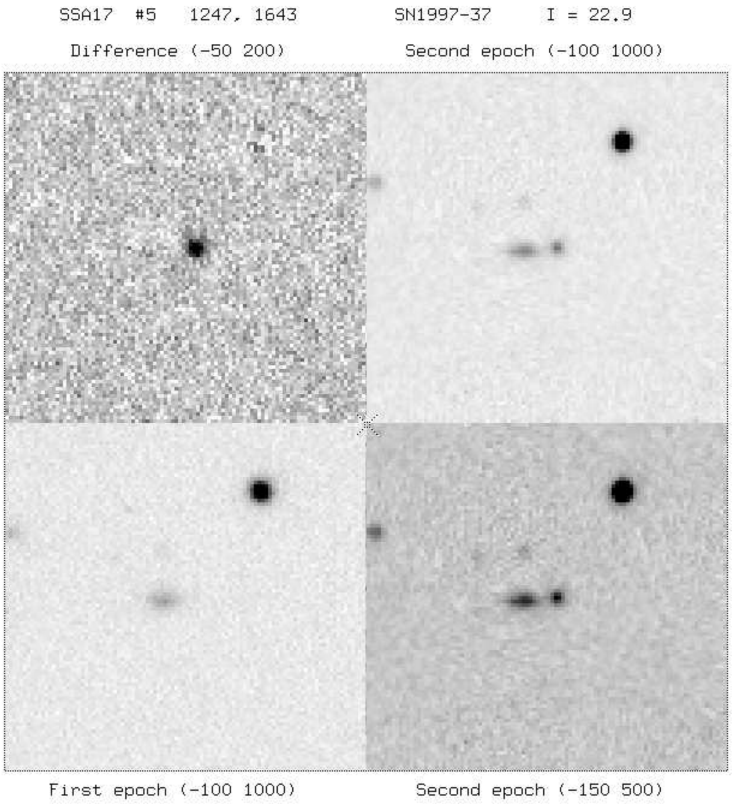

Figure 2. The discovery images of SN 1997cd at a redshift of 0.51. The lower-left panel shows the 'template' image taken three weeks before discovery. The two panels on the right show the discovery image at two contrast levels. The upper-left panel displays the difference between the two epochs and clearly shows the galaxy and foreground stars subtracted away and the presence of the supernova.

stars, active galactic nuclei (AGN) and supernovae (Fig. 2). Asteroids are very numerous at these magnitude limits but can be identified by their motion if multiple images of each field are taken on the same night. Distinguishing supernovae from AGNs and other variables is more difficult. Spectra are generally taken to confirm the identification as well as measure a redshift and attempt to determine the supernova type.

The High-Z Search Team currently uses a Perl script to combine existing programs, such as IRAF, DoPHOT and DAOPHOT, to manipulate the images and extract the photometric information. This approach has the advantage of reducing the amount of new code that had to be created. But it does complicate the process of transporting the search, as many of the versions of the existing programs differ from machine to machine.

3. Results

Why work so hard to find and study these distant events? The Hubble constant describes the current expansion rate of the Universe, but by comparing the brightnesses and redshifts of nearby and distant Type Ia supernovae, it is possible to see if the rate of expansion has changed over cosmic time. At $z \sim 1$, the Universe was half its current age and between then and now the deceleration of the expansion should be detectable from accurate measurements of the distances and redshifts of supernovae. The deceleration rate is a direct measure of the total matter density of the Universe since it is the gravitational pull of the matter which is slowing the expansion (Fig. 3).

The initial results suggested very little deceleration over the past 7 billion years and therefore, insufficient matter in the Universe to reverse the expansion (Garnavich et al. 1998a). Now, with a total of more than fifty supernovae analyzed by the two groups, it is clear that the Universe is currently accelerating. This surprising result suggests that the vacuum may have a non-zero energy density which currently dominates over the matter density. Of course, there are other, even more exotic, forms of energy which would cause the observed acceleration (Garnavich et al. 1998b).

There is some danger involved. If dust or properties of Type Ia supernovae have evolved between $z = 1$ and the present, then the distances measured from the supernovae may be systematically affected. Currently there is no evidence for evolution in the supernovae or in the dust extinction. But more work on understanding both the high$-z$ supernovae and nearby events are needed to place the cosmological observations on firm ground.

4. Conclusions

It is currently possible to discover and study supernovae out to redshifts of ≈ 1. These searches require two epochs of imaging more than one square degree of sky to $R > 22$ in order to be assured of finding supernovae. Two groups have now discovered over 100 supernovae and have analyzed the light curves of more than half of these events. The results are surprising. The Universe appears to be accelerating at the current epoch, suggesting that the Universe is dominated by an unknown energy component with a large negative pressure.

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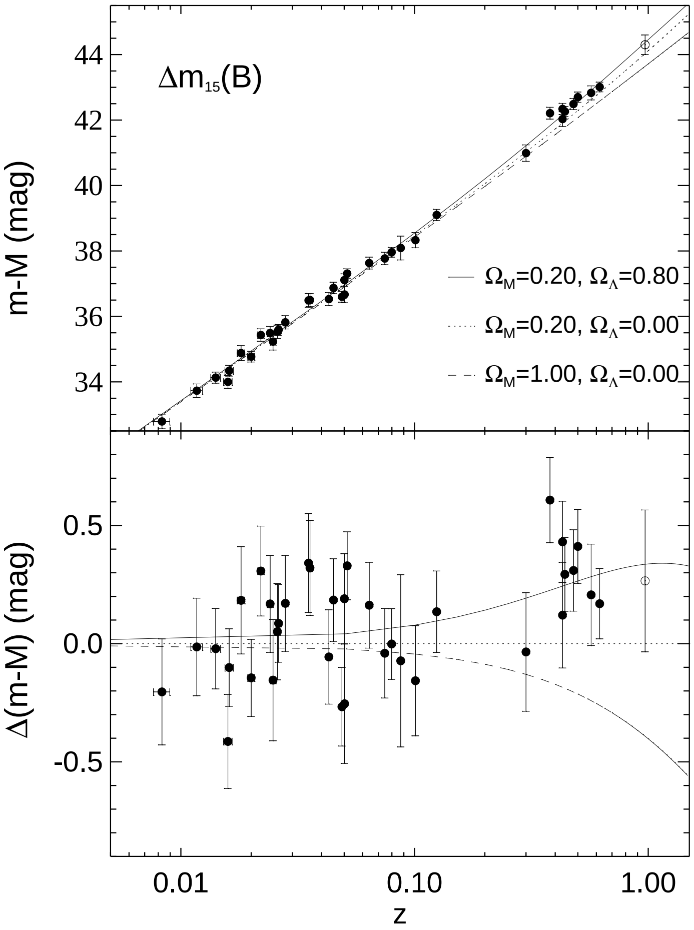

Figure 3. The supernova Ia Hubble diagram (distance as $m - M$ versus redshift z) extending to nearly $z = 1.0$ from Riess et al. (1998). The many low-redshift supernovae define the zeropoint (Hubble constant and Type Ia absolute magnitude), so that measuring the brightness of the high-z events provides a direct estimate of how the expansion rate has changed. The lower panel shows the deviation of the supernovae magnitudes from a model Universe with a low matter density (Ω_m) and no vacuum energy (Ω_Λ).