# Supernovae Observations of the Accelerating Universe

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Over the past three decades, supernovae observations have been the primary tool used in measuring both the current expansion rate and the expansion history of the universe. Supernovae are preferred because they are the best known standard candle and they can be observed in the early and recent universe. But because they are rare and unpredictable, they are difficult to measure. In the late 1990's, two independent groups developed wide-filed imaging methods to systematically discover supernovae type 1a, and measure their magnitude and redshift. Their results showed that the expansion of the universe is accelerating. This discovery has many implications on cosmological theory, and requires the existence of some form of dark energy or cosmological constant to supply the repulsive force that leads to acceleration.

## I. Introduction

Since Edwin Hubble's discovery of expansion in 1929, scientists have struggled to obtain an accurate measure of the Hubble constant, $H_0$, which gives the current rate of expansion of the universe, an important cosmological parameter. With the rise of Alan Guth's inflation theory in the 1980's, there was an increased desire to measure not only the current rate of expansion, but also how the expansion rate has changed throughout the universe's history. In the simplest models of inflation, the expansion is determined solely by the mass density $\rho_m$. The greater the mass density, the more the expansion is slowed by gravity – so a decrease in expansion rate is expected as gravity pulls the universe back together. But, other models that include more energy density terms, or assume a specific spatial curvature predict different expansion rates.

Measuring the current rate ($H_0$) requires accurate distance and redshift measurements to distant objects, but measuring the derivative of that rate requires observations of much more distant objects. In the 1980's and 90's, supernovae observations emerged as a promising tool, and would ultimately be used to obtain one of the best measurements of $H_0$, and the first quality measurements of the acceleration/deceleration of expansion.

The task of measuring the history of cosmic expansion is easy in principle. Accurate distance measurements are needed and are made using an astronomical standard candle. A standard candle can be any class of astronomical objects that all have the same, well-known intrinsic brightness and spectrum, and can be found in the universe over a wide range of distances. The uniformity of standard candles allows us to determine the distance to distant candles by comparing their apparent brightness in the sky to the intrinsic brightness it is known to have. This distance measurement then gives the amount of time that has passed since the light left its source ($t$ = distance to Earth / $c$).

Because the expansion of the universe stretches the wavelength of light, the light from distant stars will always be redshifted. The redshift of the light from a standard candle is measured by comparing to the well-known standard spectrum. The redshift gives a direct measure of the amount that space has been expanded during the time that the light has traveled to Earth. The amount of expansion per unit length is equal to $z = \Delta\lambda/\lambda$. So, determining a measure of apparent magnitude (time) and redshift (expansion distance) for a number of standard candles over a wide range of distances allows for the construction of an expansion history for the universe.

## II. Supernovae Observations

The experimental task of measuring expansion now involves finding a class of objects uniform enough to be used as reliable standard candles, and obtaining accurate distance measurements to a number of these objects. Early luminosity distance investigations by Hubble and others used galaxies because they were the brightest objects available. This failed because of the inhomogeneity of galaxies and changes in galaxy properties as a function of look-back time. The use of Supernovae was first proposed in the 1930's, and in the late 1960's supernovae (type 1) emerged as a promising candidate[1]. Large, violently exploding stars may not seem like a good standard, but their radiative properties are relatively simple, they are intrinsically bright, and they are found everywhere in the early and recent universe[2], all of which are important features of any standard candle. Further sub-classification of supernovae 1 into groups 1a and 1b/c revealed a surprising uniformity in the spectra of supernovae 1a. Type 1a are generally thermonuclear explosions of white dwarfs, while type 1b/c are massive stars that undergo a core collapse. The subclass 1a (1b/c) are defined by the presence (absence) of a silicon absorption feature at 6150 angstroms in the supernovae spectra[1].

By the late 1980s/early 1990s, a strong case was being made that the vast majority of the type Ia SNe had strikingly similar light curve shapes, spectral time series, and absolute magnitudes. A 1992 review[3] of a variety of studies concluded that the uniformity in SNe 1a spectrum make them "the best standard candles known so far."

In 1990, the Calan/Tololo Supernova Search (CTSS) obtained a crucial set of 38 high quality SNe light curves and spectra of nearby ($z \sim 0.1$, where $z$ defines the amount of redshift) supernovae. The CTSS data allowed people to classify outliers and thus determine the most standard subset of supernovae 1a[4].

Now that a suitable standard candle had been found, it could be used to obtain data about the expansion history. There was first interest in using supernovae to measure $H_0$. This could be done by measuring nearby stars that exploded ~100 million years ago. The ability to measure much more distant stars – ones that exploded several billion years ago - would allow for measurements of the acceleration/deceleration rate of the expansion over time.

There are, however, some difficulties in finding and measuring these supernovae. They are rare (only 1 or 2 per galaxy per millennium), unpredictable, and need to be measured immediately after they are found, as they will pass their peak of brightness within a period of a few weeks[1]. These difficulties are compounded by the fact that telescope time at the world's leading telescopes is assigned several months in advance, which is at odds with the unpredictability and short life of supernovae. In fact, much of the CTSS data had to be taken on other people's telescope time[2].

In the 1990's, astronomers led by two groups, the Supernovae Cosmology Project (SCP) of LBL and the High-Z Supernovae Search of Australia's Mount Stromlo observatory put together a systematic solution for obtaining supernovae data. The telescope time was reserved in advance on the promise of having supernovae to observe when the time came. Large field imagers were used to search a large section of sky (at short exposure) in one night, increasing the chances of supernovae discovery[1]. With meter-class telescopes, the teams could search up to a million galaxies a night for supernovae at a redshift of $z < 0.5$ (higher redshifts require longer exposures to find). Using this wide-field imaging technique, the groups could guarantee the discovery of several (as many as 50 in two nights) supernovae and use the prescheduled time at the major telescopes (including the Hubble Space Telescope) to make the follow-up observations. The large advance in computing power in the 80's and 90's was crucial in

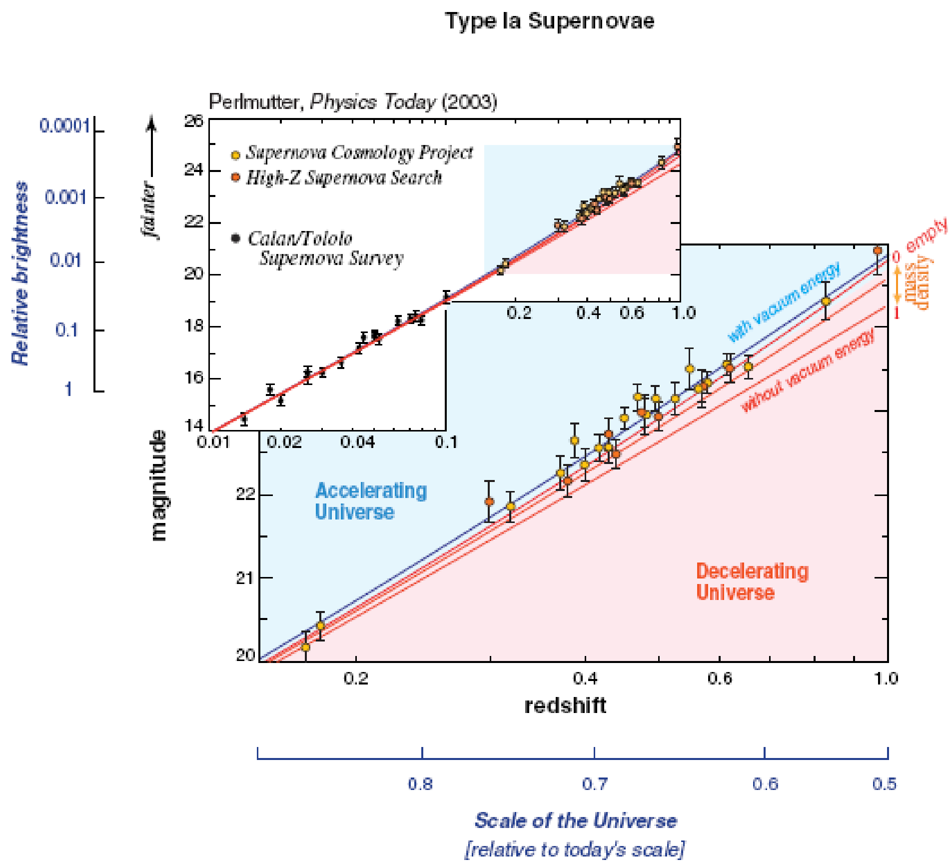


Figure 1: Results of the CTSS[4] (upper left insert), SCP[5], and HZSNS[6] studies of nearby and distant supernovae show evidence of an accelerating expansion.

allowing the teams the ability to process the data from the wide-field imaging and find potential targets in a timely fashion.

In 1997, the SCP published some preliminary results of its first seven high-redshift supernovae. The results suggested a slowing expansion (which would have fit with the idea that gravity was pulling the universe back together), but there were not enough results to be conclusive. In 1998, both teams released larger data sets[5,6] – a total of nearly 70 high-$z$ supernovae – and the results were very different (figure 1). The distance to the highest-redshift supernovae was much larger than expected. If the mass density-only models are true, then the universe would have been expanding faster in the past – so we should not have to look too far back in time to see a high redshift. But, the results of 1998 showed that "the high-redshift supernovae are fainter than would be expected even for an empty cosmos[1]." The immediate implication is that the expansion is actually accelerating, and the mass-density only cosmological models are too simple. The acceleration discovery opened the door to theories involving some kind of cosmological constant/dark energy, which had already become popular on the basis of CMB and galaxy cluster studies (Section IV).

## III. Measurement Uncertainties

Because of the suggested theoretical implications, the accuracy of the high-redshift measurements is placed under great scrutiny. There are several difficulties in measuring the luminosity of high-$z$ supernovae that could introduce systematic errors into the data. One common difficulty relevant to high-redshifted spectra is the calculation of the K-correction. The spectra and brightness of nearby supernovae ($z < 0.1$) are well-known, but comparing these observations to those at much greater redshifts is difficult. When astronomical observations are made on Earth, they are made in fixed band-passes. Thus, the spectra of the near SNe and the high-$z$ SNe cannot be compared using the same filters. To relate the apparent (observed) magnitude in a given band-pass to the absolute magnitude in the corresponding rest-frame (standard) bandpass requires the calculation of the K-correction. An accurate K-correction calculation requires knowledge of the flux densities of the observed source and the standard source (compiled from nearby sources), and the amplitude-frequency dependence in the filters[7]. The uncertainty in the calculation comes from the standard spectra, and is a reflection of the standardness of the SNe1a class. To help eliminate the dependence of their measurements on this correction, the two groups used a detector "whose spectral acceptance band was shifted by 1 + *z* at all wavelengths[7]."

Dust extinction is currently the largest source of uncertainty in the SNe measurements. As the light from distant SNe travels to the Earth, its magnitude can be dimmed by interaction with dust (usually within its own galaxy). First-order effects can be removed from the data simply by observing light at multiple frequencies and looking for frequency-dependent effects. But systematic errors can come from second-order effects such as a changing in the average amount of dust, or changes in the properties of the dust as a function of reshift[2]. There is also dust in our own galaxy that can dim the light. There is a systematic error associated with this due to the lack of knowledge of the effect this dust has on high-*z* (near infrared) light[2].

A selection problem known as Malmquist Bias introduces uncertainty based on the fact that there is often a bias toward the brighter SNe, since they are more readily observed[2]. Unknown effects from gravitational lensing of the SNe light also introduce errors. This is more of a problem for greater *z*, and can be reduced somewhat by obtaining larger data sets. The following table summarizes the current systematic error budget of the combined data.

Table: Summary of main systematic errors in luminosity magnitude measurements[2].

| | |
|---|---|
| K-correction | ~0.01 mag |
| Host galaxy dust extinction | <0.06 mag |
| Milky Way dust extinction | <0.06 mag |
| Selection effects | ~0.04 mag |
| Gravitational Lensing (for $z \sim 0.5$) | <0.02 mag |

The good agreement between the two independent teams (SCP and HZSNS) results helps to displace questions of replicability, but the small size of the data sets certainly introduces a large statistical error. At present, the statistical errors are greater than the expected systematic errors, so the results will be improved as more and more data is collected.

IV. Theoretical Implications

The discovery of an accelerating expansion rate means that gravity is not pulling the universe together, and there must be some other form of energy (other than mass) that is causing the acceleration. But this result had already been predicted by some inflation-based models. Inflationary theory, which has dominated cosmology since the 1980's, predicts a flat universe for which $\Omega_o$ (the ratio of the mean energy density to the critical energy density) = 1. The idea of a flat universe was eventually confirmed by the measurements of the CMB, but the measurements of $\Omega_o$ were coming up short. In 1980, the best estimates of the mass density had $\Omega_M = 0.1$. By the 1990's, the addition of dark matter to the theories gave estimates at $\Omega_M = 1/3$. If $\Omega_o = \Omega_M$, then the estimates are still short.

To fix the problem, some theorists proposed the addition of Einstein's cosmological constant so that $\Omega_o = \Omega_M + \Omega_\Lambda$. This theory ($\Lambda$CDM – Cold Dark Matter plus a cosmological constant) met the requirement of a flat universe, but it also predicted an accelerated expansion. Although the 1998 result was unexpected from the standpoint of the results of previous experiments, it fit very well with the ΛCDM theory.

The problem that is left is to determine the origin of the cosmological-constant contribution to the energy density. One consideration is the virtual pairs that fill the vacuum – a result of quantum field theory. This vacuum energy density has large negative pressure creating repulsive gravity, and is thus mathematically equivalent to the cosmological constant. Unfortunately, the predicted value of the vacuum energy density is many orders of magnitude greater than the needed value of $\Omega_\Lambda$. When a 100 GeV cutoff is imposed (with no cutoff the sum of zero-point energies diverges), the best estimate of supersymmetric models predicts $\Omega_\Lambda = 10^{55}$ instead of $\Omega_\Lambda = 0.7$.[8]

The mysterious energy density $\Omega_\Lambda$ has come to be referred to as dark energy. Regardless of its physical origins, the dark energy must be very evenly distributed, since no effects of energy clumping have been observed. An even distribution must mean that the dark energy has extremely low density everywhere. Combine that with little to no interactions with ordinary matter, and laboratory detection of dark energy gets ruled out.

Better cosmological measurements, however, can tell us something about the source of dark energy. The quantum vacuum zero-point energy is only one of many theories to explain dark energy. Different dark energy theories produce different values of $w = p/\rho$, the ratio of pressure to energy density. This equation of state determines how the dark energy density changes as the universe expands[8], $\rho \sim 1/R^{3(1+w)}$, where $R$ is a cosmic scale factor. Thus, different values of $w$ would give different expansion rates. More accurate measurements of the expansion history can help shed light on which of these dark energy models are acceptable. For the vacuum energy, $w = -1$, and $w = 0$ for ordinary matter. Current supernovae data places the restriction[2] $w < -0.5$.

## V. Current and Future Work

The differences in the dark energy theories are small. To properly distinguish between them would require SNe observations of about an order of magnitude better precision and about twice as far back in time as has so far been observed[1]. Future research must focus on collecting more data to reduce the statistical errors, and developing more accurate observation techniques to eliminate the dominating sources of systematic error.

In 2001, Adam Reiss and other members of both SCP and HZSNS discovered[9] the most distant supernovae found to date, at a redshift of $z = 1.7 \pm 0.1$. The star was found at a redshift and apparent magnitude that would fit with the idea of a deceleration epoch that preceded the current acceleration. Because the dark energy density depends on the scale of the universe, there should have been a time when the mass density dominated and the expansion was decelerating. More SNe at similar redshift will show the existence or absence of this phase of expansion.

Currently, the SCP team is focusing on SNe found in galaxy clusters. These clusters are known to be dominated by early-type galaxies that are nearly dust-free, which would reduce the main source of uncertainty in determining the SNe distances[10].

There is also a proposed satellite - the SuperNovae/Acceleration Probe (SNAP) currently being designed at LBL and NASA. SNAP would use large arrays of Charge-coupled Detectors (CCD's) to increase the SNe discovery rate to 2000 per year[11]. It would also be able to measure SNe at higher redshift than have previously been observed because of the enhanced sensitivity to infrared light above the atmosphere. The SNAP results combined with more research to reduce dust and selection effects should be able to produce a detailed expansion history of the universe going back as far as 10 billion years, and greatly increase the precision in the value of the dark energy equation of state.

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