Distant Type Ia Supernovae and Cosmology

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Distant Type Ia Supernovae have provided stunning evidence for an accelerated expansion of the universe. This unexpected and exciting result is based on scant knowledge of these explosions and some assumptions on their values as distance indicators.

The broad picture of thermonuclear explosions of white dwarfs seems generally accepted, but the detailed explosion physics still escape us. Nickel masses determined from observations and, in the foreseeable future, ejecta masses of these explosions will provide more stringent constraints for the variety of models discussed currently. The light curve corrections required for a reliable distance measurement are still not fully understood and the proposed implementations can deviate for even nearby supernovae.

1. Introduction

Surprises are still in store for astronomers and cosmologists. The latest one has come from the use of Type Ia Supernovae (SNe Ia) as distance indicators and has provided evidence for an accelerated expansion over the last several 10^9 years (Riess et al. 1998, Perlmutter et al. 1999a). There has been a keen interest in changing the favored world model to one including a cosmological constant or some other agent which could drive the universal expansion (e.g. Turner & Tyson 1999, Bahcall et al. 1999). Other, astrophysical interpretations of the data should, however, be investigated as well. The most prominent proposals have been evolution (Höflich et al. 1998, Drell et al. 2000) and absorption by dust (Aguirre 1999a, b).

Astrophysical distance indicators are either based on a physical model, like the CMB fluctuations, or calibrated with nearby objects. The calibration in itself can be rather difficult and in the case of SNe Ia is mostly based on the Calán/Tololo (Hamuy et al. 1996) and CfA (Riess et al. 1999) samples. To determine cosmological parameters large distances have to be measured. For SNe Ia this is currently possible to about $z \leq 1$, which covers roughly 60% of the age of the universe for all reasonable world models. After the calibration has been established, it has to be shown that the distant objects have the same properties as the nearby ones to confidently use them as distance indicators. Even after this has been established one has to worry that there are no other astrophysical effects which can influence the measurements. The most obvious ones are intervening

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dust, evolution, and (de-)amplification by gravitational lensing. All these issues have to be addressed in a serious attempt to determine the cosmology we live in.

The following section will describe the current observational status of SNe Ia, before we move on to the cosmological measurements. The implications by the supernova results are presented in §3. Several alternative explanations could at least still influence the cosmological conclusions and are explained in §4. We end with a summary and a brief outlook of what can still be expected from this type of research.

2. Observations of Type Ia Supernovae

This section concentrates mostly on the peak luminosity, light curve shape and the correlations between them (a more complete overview can be found in Leibundgut (2000)). The calibration of the peak luminosity of SNe Ia has a checkered history. They have often been called standard candles, but it is really the fact that they can be normalized to a uniform luminosity by virtue of their light curve shape (Phillips 1993) which makes them useful distance indicators. The normalization has changed over the years and also depends on the exact implementation. The light curve shape *vs.* luminosity correlations are all based on the Calán/Tololo and CfA samples with the addition of a few well-observed nearby SNe Ia. It should be noted that significant discrepancies for the corrections are present even for well-sampled light curves of very close SNe Ia (Leibundgut 2000).

There are now about 40 nearby ($z < 0.1$) SNe Ia with good, published light curves (cf. Phillips et al. 1999, Riess et al. 1998). Pre-requisites are coverage of the peak phase for about one month and sufficient spectral coverage to detect anomalies. The fraction of "peculiar" SNe Ia based on a volume-limited sample seems to be larger than assumed so far (Li et al. 2000). Also, any corrections for dust in the host galaxies have to be determined carefully. These are mostly based on assumptions on intrinsic colors, but there may be a dependence of the color at peak luminosity and the light curve shape (Tripp 1998, Phillips et al. 1999, Parodi et al. 2000).

The importance of the luminosity normalization is illustrated in Figure 1. These light curves are sampling the total $UBVRI$ ("bolometric") luminosity of the SNe Ia. The large intrinsic range is obvious even when the most extreme cases are excluded (Contardo et al. 2000).

Two groups have published samples of distant (z>0.3) SNe Ia. A careful balance between data quality, especially the light curve coverage, and the number of objects to evade small number statistics has to be found. This is the main difference between the two collaborations who are pursuing this project. The Supernova Cosmology Project (SCP) has analyzed 42 distant objects (Perlmutter et al. 1999a), some without spectral classification or color information, which could create uncertainties due to sample contamination and assumptions about dust evolution (Totani 1999). The High-z Supernova Search Team has published a much smaller set of 10 distant SNe Ia (Riess et al. 1998). In this case, light curves in two filters and a spectrum are available for all objects. The spectral classification of some objects can not be established convincingly (e.g. SN 1996E and SN 1997ck; Riess et al. 1998), but a better control of the sample is exercised. Spectroscopy of these distant supernovae will be a vital tool to investigate any evolutionary changes. An appreciation of the quality of the SN spectroscopy can be found in Coil et al. (2000).

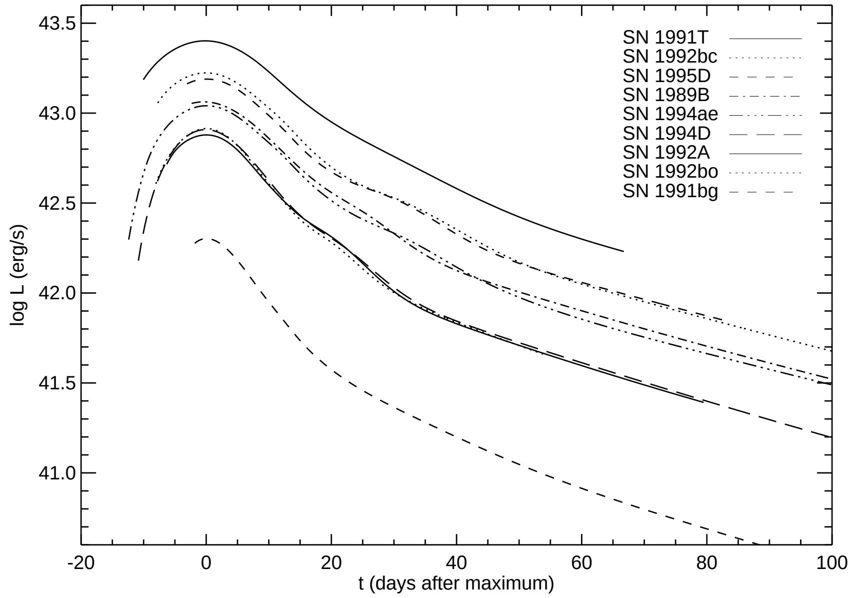

Figure 1. Bolometric light curves of Type Ia Supernovae. These light curves have been corrected for absorption and placed at the most accurate available distances (Contardo et al. 2000).

All SNe Ia have been normalized to the same light curve shape. The philosophy on how to derive the normalization has been slightly different between the two groups. While the High-z SN Team has used the best available local definition of the relations (in two different implementations, the template (Δm_{15}) method by Phillips et al. (1999) and the Multi Light Curve Shape method by Riess et al. (1996, 1998)) to correct the distant objects, the SCP has chosen to derive the corrections from the whole sample, including the distant supernovae. Both methods make the fundamental assumption that the local and the distant supernovae follow the same relations. A simple check is that the light curve shapes do not deviate significantly from one sample to the other and first investigations in this direction have started (Riess et al. 2000).

The High-z SN Team further corrects all objects for absorption in the host galaxies according to the observed colors assuming an intrinsic color derived from objects free of absorption, e.g. in elliptical galaxies. The assumption here is that the Galactic absorption law can be applied to galaxies at about half the universal age as well.

More data are becoming available in the near future as both groups are analyzing additional observing runs. The photometry of these faint objects is not easy and has to take into account complications, like the uneven background from the host galaxies or seeing effects. However, an improved control of the corrections must be targeted. This can only be achieved by a better understanding of the nearby supernovae.

3. The cosmological implications

It is often not appreciated that the cosmological results are inferred from distant *and* local supernovae. It is the difference between these two data sets which makes up the signal. In this respect the two groups are not too different. The Supernova Cosmology Project has a larger sample at higher redshifts, but their nearby sample is limited to 18 SNe Ia and entirely based on data from the Calán/Tololo survey. The High-z Team based its analysis on a larger nearby set (27 SNe Ia), which allowed them a much tighter definition of the local expansion rate relative to the distant objects. This is the main reason, why the results of the two groups are comparable, even though the statistics for the distant SNe are rather different.

The result is displayed in Figure 2. It shows the Hubble diagram of Type Ia Supernovae with the data from both teams. For this figure we had to adjust the relative distance zero-point and have used the template fitting (Δm_{15}) method for the distances. The offset of the distant supernovae from the predictions of simple world models is obvious. In effect, the distant objects are fainter than their nearby counterparts. This is the clear signature of accelerated expansion.

An accelerated expansion in Friedman world models is only possible with a cosmological constant (e.g. Carroll et al. 1992). A repulsive force has to counteract gravity to push the distant objects away from us. Other proposals include the release of energy due to the decay of a particle field, in modern terms referred to as 'quintessence' (Caldwell et al. 1998). In any case, the equation of state of such a field is very strange indeed as it has negative pressure for a positive energy density.

To explain the supernova result in a cosmological context the unavoidable conclusion is that an extra component in the universal model is required.

4. Alternatives

The conclusion of the previous section assumes that the distant supernovae are identical to the nearby ones and that there are no other astrophysical effects which dim them by about 0.2 magnitudes relative to an empty ($\Omega_M = 0, \Omega_\Lambda = 0$) universe at $z \sim 0.5$. Of course, these assumptions ideally should be tested.

Evolution of the supernova peak luminosity could be an alternative. Since we are measuring luminosity distances, the direct check of intrinsic luminosity evolution is degenerate with the cosmological implications. To check for evolutionary changes one has to resort to indirect methods which try to establish that the distant supernovae are indeed the same as the nearby ones. The observational checks performed so far are to search for the characteristic light curve shape of the rest-frame I light curve, distribution of light curve forms, and spectroscopy. For nearby supernovae the I light curves display a very strong secondary peak in their light curves about 30 days after maximum light (Ford et al. 1993). This peak is also observed at near-IR wavelengths (Elias et al. 1981) and is mostly not understood. The bolometric light curves also show an inflection at about the same epoch (Contardo et al. 2000). A first check with SN 1999Q (z=0.46) has shown that this distant event indeed also displays a similar rest-frame I light curve (Riess et al. 2000).

The available spectroscopy of the distant supernovae is also in most cases consistent

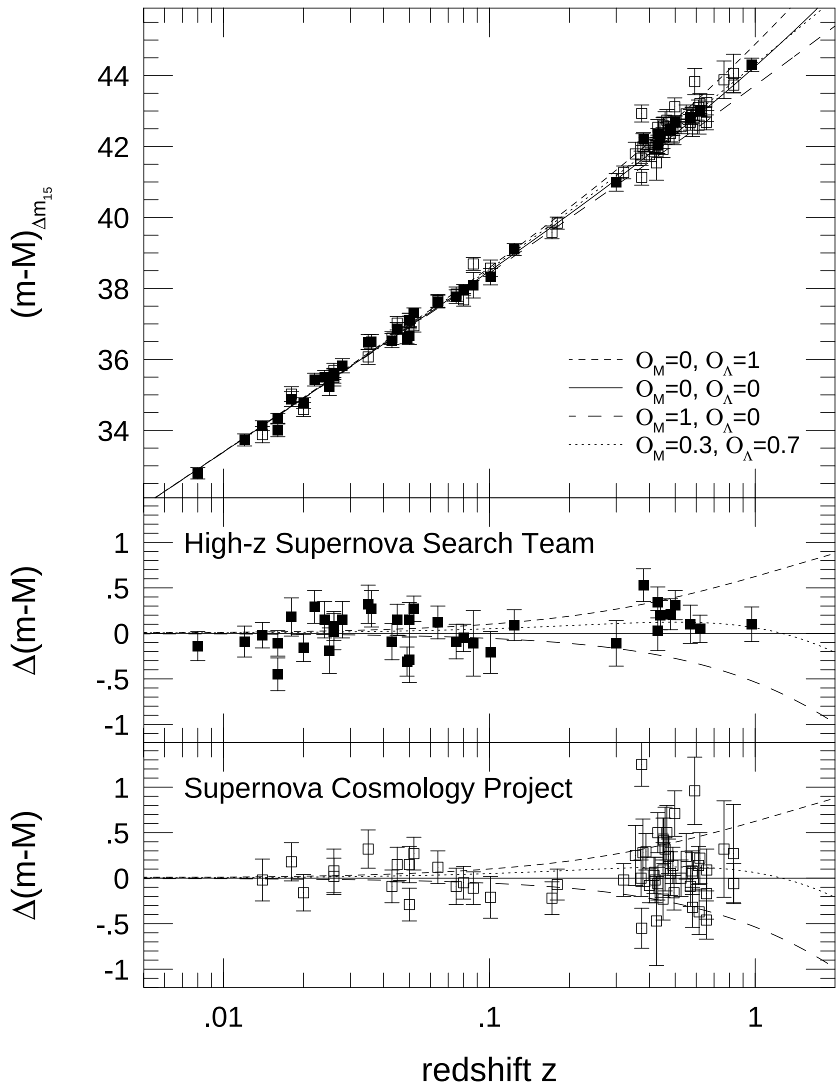

Figure 2. Hubble diagram of SNe Ia

with the observations of nearby objects (Schmidt et al. 1998, Riess et al. 1997, 1998, Perlmutter et al. 1998, Coil et al. 2000). However, in no case is the signal high enough for a detailed comparison and investigation with models. In fact, the spectral changes predicted by models are rather subtle (Höflich et al. 1998) and can not be checked with the current data. The next observational campaigns of the High-z SN Team will address the spectral evolution and the multi-filter light curve shapes in quite some detail.

Theoretical predictions for evolutionary changes are rather difficult as there is no generally accepted explosion model nor do we know which progenitors turn into Type Ia Supernovae (Hillebrandt & Niemeyer 2000, Livio 2000, Nomoto 2000, Leibundgut 2000). Of importance in this respect is the recent evidence for clear differences in the nickel mass synthesized in the explosions. Contardo et al. (2000) find that there is a wide range of nickel produced in Type Ia Supernovae. Using Arnett's rule (Arnett 1982) they convert the peak bolometric luminosity of nearby SNe Ia (cf. Fig. 1) into nickel masses and find that some SNe Ia produced nearly ten times as much nickel than others.

Another possible source of dimming is unrecognized dust. Although the High-z SN Team made every effort to obtain colors to be able to correct for absorption, it can not detect dust which does not redden. Dust with significantly larger grain size has a much smaller reddening effect and if such dust prevailed at the time the SN light was emitted, then we would not have detected the predicted small color changes (Aguirre 1999a, 1999b). This dust scenario can only be excluded with careful observations over a wide wavelength range. These data are available for many nearby supernovae, and no such effect has been detected so far (Phillips et al. 1999), but they are largely missing for the distant events (see Riess et al. 2000 for an exception). It is interesting to note that such dust would also have an impact on other cosmological areas and should eventually be observable in the far-infrared background. Should this background be resolved into individual objects, then the inter-galactic dust component can not be important (Aguirre & Haiman 2000).

A last source of uncertainty is gravitational lensing of the distant supernovae. Luckily, the distances are not yet large enough that this is hampering the global conclusions (e.g. Wambsganss et al. 1997, Holz 1998, Holz & Wald 1998). Even if all matter would be clumped in dense objects would this effect not account for a sufficient systematic shift to reconcile the supernova result with an Einstein-de Sitter world model.

5. Conclusions

The real strength of the supernova result is its combination with measurements of the fluctuation scale of the cosmic microwave background (White 1998, Garnavich et al. 1998, Lineweaver 1998, Eisenstein et al. 1998). The distance measurements are each degenerate in the $\Omega_\Lambda vs. \Omega_M$ diagram. While the angular size distances as measured by the CMB trace out regions along $\Omega_\Lambda + \Omega_M$, probability regions from supernovae lie mostly along $\Omega_\Lambda - \Omega_M$. The third constraint comes from mass determinations in clusters or from the measurements on large scale flows (e.g. Carlberg et al. 1996, Evrard 1997, Willick & Strauss 1998). They are independent of the cosmological constant. These orthogonal measures can be successfully combined to narrow the probability regions considerably. There have been many papers describing this. The most recent combinations are from the new CMB publications (de Bernardis et al. 2000, Jaffe et al. 2000). The combination of all available measurements (e.g. Turner & Tyson 1999, Bahcall et al. 1999) exclude an Einstein-de Sitter model ($\Omega_\Lambda = 0, \Omega_M = 1$) as a viable world model. Instead a contribution from the cosmological constant, or one of its modern cousins, is required. The best current estimates are that the universe is flat, which is determined entirely from the CMB observations, with a currently dominating contribution from the cosmological constant. Matter in the universe accounts for about 1/3 of the overall energy density.

This combination of cosmological parameters has the nice feature that it solves the problem of the dynamical age of the universe. With an accelerated expansion, i.e. a cosmological constant favored by the measurements, the universe with the most recent estimates of the current expansion rate, the Hubble constant, is older than predicted by the Einstein-de Sitter model. An age of about 12 to 14 Gyr comfortably accommodates the oldest known stellar components.

For a flat geometry the SNe Ia can also measure the equation of state parameter of the universe (Garnavich et al. 1998, Perlmutter et al. 1999b). The current measurements are consistent with a cosmological constant and are already excluding topological defects, like textures and domain walls as the dominant form of energy in the universe, but they can not exclude other forms of decaying particle fields, like 'quintessence.'

However, not all problems are solved. The size of the cosmological constant is a big puzzle. Although $\Omega_\Lambda = 0$ is not explainable with the current theories (e.g. Weinberg 1989), it has been favored for many years. If the cosmological constant is explained by the vacuum density in particle physics, its small value is just as puzzling. The only energy scale with which the vacuum energy can be associated is the Planck scale which predicts a cosmological constant many orders of magnitudes larger than observed. These are the often quoted 120 orders of magnitude (e.g. Carroll et al. 1992).

Another problem is the fact that we seem to be privileged to be able to observe both the matter and the vacuum energy density. Matter density decreases with $(1+z)^3$, i.e. the increase of the volume by the expansion, while the cosmological constant remains unchanged. Hence the value of Ω_M relative to Ω_Λ changes 8-fold for one unit in redshift.

Critical tests to assure the cosmological results from supernovae are under way. Any grey dust, if present, should be detectable with accurate colors for distant SNe Ia, which can be measured by accurate multi-filter photometry. The evolution of supernovae can also be assessed by improved spectroscopy and more detailed sampling of the light curves to find subtle differences, if they exist. Major progress can be expected from an improved understanding of nearby supernovae. Finding the progenitor systems and converging on an explosion model will mean real progress.

Fairly soon distant supernovae will also be used to find the star formation history of the universe. The core-collapse supernovae are the final fireworks of massive stars and hence trace the star formation. They are bright enough to be observed to redshifts of about 3 with the next generation of telescopes (Dahlén & Fransson 1999), but already with the existing large facilities will we be able to outline the supernova rates over the second half of the age of the universe. The enrichment history of the universe will remain a main research topic of the coming decade.

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