Testing Cosmic Acceleration with Type Ia Supernovae

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Abstract. We discuss recent evidence for an accelerating Universe from measurements of type Ia supernovae at high redshift, and describe tests of various systematic effects such as extinction and evolution that could be biasing the cosmological result. Continued observations of these objects, both over a wider wavelength region and at higher redshift, should provide strong evidence in favor or against the accelerating Universe hypothesis.

1. Introduction

Recent observations of type Ia supernovae (SN Ia) at high redshift \( z \gtrsim 0.3 \) by two groups provide evidence that the Universe is accelerating at the current epoch (Riess et al. 1998, hereafter R98; Perlmutter et al. 1999, hereafter P99). This result implies the existence of a constituent of the Universe, either the cosmological constant, \( \Lambda \), or something else with similarly negative pressure capable of accelerating the expansion, generically dubbed “dark energy” (see Riess 2000 for a review).

Restricting ourselves to a cosmological-constant model, the current constraints on cosmological parameters from SN Ia and cosmic microwave background (CMB) observations are shown in Figure 1. The shaded SN Ia region corresponds to the 99.7% confidence region on the matter density and vacuum energy density \( (\Omega_M, \Omega_\Lambda) \) from a combination of both groups’ published data (R98; P99), ensuring the sets of supernovae used were independent. Similarly, the shaded CMB region corresponds to the same 99.7% confidence region on these parameters from the latest CMB results, including the published BOOMERANG-98 and MAXIMA-1 data sets (Jaffe et al. 2000). The combined confidence region is shown with the contours, representing 68.3, 95.4 and 99.7% confidence levels. The combined constraints rule out a flat, matter-dominated Universe \( (\Omega_M = 1, \Omega_\Lambda = 0) \), as well as an open Universe with no cosmological constant \( (e.g., \Omega_M = 0.3, \Omega_\Lambda = 0) \), at high statistical significance. In this framework, the data clearly favor a significant and even dominant fraction of the energy density of the Universe in the cosmological constant. Even allowing for more exotic possibilities such as quintessence, the SN Ia data still require a dark
energy component to cause acceleration of the Universe (Garnavich et al. 1998; P99).

How secure is this result? The SN Ia data support an accelerating Universe at a high level of statistical confidence, but as is always the case, systematic uncertainties then become the primary concern. The observational result is simple: SN Ia at $z \simeq 0.5$ appear approximately 50% fainter than expected for a flat, matter-dominated Universe, and about 25% fainter than expected for an open Universe with $\Omega_M = 0.3$. Both groups observing high-redshift SN have explored a number of systematic effects that could bias the measurements (R98; P99), including Malmquist bias, sample contamination and gravitational lensing. None of these particular effects reconcile the data with a decelerating (or even coasting) Universe.

There are two other potential sources of systematic uncertainty that are of obvious concern. First, a natural candidate to explain the observed faintness of the high-redshift supernovae is extinction by interstellar dust. Second, evolution of the intrinsic properties of SN Ia, or a change in the population of SN Ia observed at high-redshift relative to those nearby, could bias the results. In this paper we describe methods of testing these possibilities from measurements of SN Ia themselves. We are in the midst of carrying out these tests; the results will either bolster confidence in our current cosmological paradigm or present a serious challenge to the picture, by teaching us something new about cosmic dust or supernova evolution.

2. Extinction

Nearby SN Ia clearly show effects of dust extinction from the Milky Way and the SN host galaxy (Hamuy et al. 1996; Riess, Press, & Kirshner 1996; Phillips et al. 1999; Jha et al. 1999). Extinction by normal dust grains reveals itself as a color excess, preferentially extinguishing bluer light. Both groups observing high-redshift SN Ia now measure light curves in at least two passbands, typically rest-frame $B$ and $V$, allowing for a measurement of any color excess and a correction for extinction using a standard reddening law with $R_V = 3.1$ (Cardelli, Clayton, & Mathis 1989) performed either on an individual supernova by supernova basis or in the mean.

The results from both groups to date suggest that extinction by normal dust is not the reason for the apparent faintness of high-redshift SN Ia. The color excess $E(B - V)$ for the high-redshift objects is consistent with zero in both the R98 and P99 samples. Furthermore, systematic uncertainties are unlikely to change this result significantly, the “worst-case” plausible color excess is likely no more than 0.03 or 0.04 mag, which for normal dust grains ($R_V = 3.1$) implies an extinction of at most $\sim 0.1$ mag, not enough to disfavor an accelerating Universe.

What about sources of opacity along the line of sight other than normal dust grains? For instance, dust which reddens less than normal (i.e., a distribution of

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1Falco et al. (1999) point out that the mean color excess of the R98 sample is negative at the 1 to $2\sigma$ level of significance, meaning the SN Ia at high redshift may be bluer than the nearby sample. The more precise observations described here will confirm or modify this result.
Figure 1. Cosmological constraints from SN Ia and CMB data. The SN Ia shaded region marks the 99.7% confidence region from an independent combination of SN Ia data from the High-Z SN Search Team (R98) and the Supernova Cosmology Project (P99). The shaded CMB region marks the same confidence region from the latest CMB results (Jaffe et al. 2000). The combination of the two constraints results in the 68.3, 95.4 and 99.7% solid contours shown.
dust grains with high $R_V$) could extinguish enough light to reconcile the SN Ia data with a non-accelerating Universe without measurable reddening. Nonetheless, the current SN data can still constrain such “grey” dust. The scatter of the SN Ia measurements at high redshift does not show any increase relative to the nearby sample beyond that caused by measurement uncertainties (R98; P99). This rules out the existence of grey dust that is patchy like normal dust; if some of the SN were extinguished by grey dust more or less than the others, the scatter at high redshift would increase. Thus, any grey dust dimming the light of high redshift SN must be relatively uniform, similarly extinguishing the light from every SN. Even with such strong constraints, there are still models for dust which could behave this way; Aguirre (1999) and Aguirre & Haiman (2000) have proposed that intergalactic grey dust could exist in sufficient quantities to dim the light from distant SN Ia by 0.25 mag, without violating other astrophysical constraints.

How do we detect such grey dust? Fortunately, any realistic model of such grains leads to dust that is not completely grey; by observing distant SN Ia over a wide wavelength range we can detect reddening by such “grey” dust. Riess et al. (2000) showed that observations of a high-redshift SN in the rest-frame $B$, $V$, and $I$ bands could begin to detect the effects of grey dust. However, the data in that paper were not sufficient to provide a strong constraint, and it was clear that additional, precise measurements were required. We in the High-Z SN Search Team are in the process of making such measurements, by extensively observing a sample of seven SN Ia at $z \simeq 0.5$ from the ground and with $HST$, covering rest-frame $UBVRI$ (which approximately corresponds to observer-frame $VRIZJ$).

Figure 2 shows how these observations constrain extinction. The curves show the expected color excess as a function of wavelength (i.e., $E(U - B)$, $E(U - V)$, etc.) for different extinction models, normalized to produce an extinction $A_V = 0.25$ mag necessary to explain the R98 and P99 data in a non-accelerating Universe. The normal dust curves correspond to dust grains with $R_V = 3.1$, while the grey dust curves correspond to two models presented by Aguirre (1999). We also show the expectation of zero color excess if there were no dust present. The error bars in the figure indicate the precision with which we can determine the color excesses for each supernova based on the details of our observing strategy and measurement errors. With seven SN Ia these observations should definitively show whether the apparent faintness of high-redshift SN is due to extinction by dust, grey or otherwise.

Our campaign to discover and followup these $z \simeq 0.5$ SN Ia is well underway. We discovered a large number of candidates during our searches at the Canada-France-Hawaii 3.6m telescope and at the Cerro Tololo Inter-American Observatory 4m telescope, with template runs in late September 2000 and search runs in late October 2000 (Schmidt et al. 2000). With subsequent spectroscopy of these candidates from the European Southern Observatory 8.2m ANU Large Telescope, we were able to choose seven SN Ia for the intensive followup with $HST$ and ground-based telescopes. We list these supernovae in Table 1. Figure 3 shows one of these objects as imaged by $HST$.

In addition to settling the question of extinction, the full $UBVRI$ light curves for these high-redshift SN Ia will allow us to address other questions. For
Figure 2. Color excess curves for various dust models, including normal and “grey” dust. The curves are normalized to produce $A_V = 0.25$ mag, necessary to reconcile the SN Ia results with a non-accelerating Universe. Also shown are the uncertainties expected from measurements of one SN Ia at $z \simeq 0.5$ from rest-frame $UBVRI$ ground-based and $HST$ observations currently underway. See text for details.

Table 1. SN Ia currently being studied by the High-Z SN Search Team

| SN Ia                  | R.A. (2000) | Dec. (2000) | Discovery | $R$ Mag | $z$  |
|------------------------|-------------|-------------|-----------|---------|-----|
| SN 2000dy (Elmo)       | 23:25:35.93 | −00:22:34.0 | 22.7      | 0.61    |
| SN 2000dz (PlasticMan) | 23:30:41.36 | +00:18:42.7 | 23.1      | 0.50    |
| SN 2000ea (RubberDucky)| 02:09:54.02 | −05:28:17.8 | 23.3      | 0.42    |
| SN 2000ec (Submariner) | 02:11:32.03 | −04:13:56.1 | 22.7      | 0.47    |
| SN 2000ee (InvisibleW oman) | 02:27:34.53 | +01:11:49.4 | 22.6      | 0.47    |
| SN 2000eg (WonderW oman) | 02:30:21.05 | +01:03:48.5 | 22.5      | 0.54    |
| SN 2000eh (Penguin)    | 04:15:02.44 | +04:23:18.1 | 22.4      | 0.49    |
instance, precise measurements of the SN color evolution will allow us to check that our adopted K-corrections are valid (a potential systematic uncertainty that affects both teams in common, as the K-corrections are based on the same, small sample of nearby SN spectrophotometry). Additionally, the $U$-band observations are particularly interesting; they provide great leverage on measuring variations in the extinction law. However, in order to make sense of the rest-frame $U$-band data at high redshift, we also need a comparison sample of $U$-band light curves of nearby SN Ia. Such a sample is becoming available only now, with $UBVRI$ light curves of about 40 SN Ia observed as part of a monitoring campaign at the CfA (Jha et al. 2001, in preparation).

3. Evolution

If the observed faintness of high-redshift SN Ia cannot be explained by intervening material along the line of sight, intrinsic variations in the luminosities of the supernovae themselves may be the culprit. Without a detailed understanding of SN Ia and their progenitors, predicting the expected evolutionary effects to $z \approx 0.5$ is difficult. So far there is no indication that the SN Ia observed at high-redshift are intrinsically different from those nearby, with the light curves and spectra showing a strong similarity (R98; P99; Coil et al. 2000). More observations may strengthen this case; for instance the rest-frame $U$-band data from the current $HST$ campaign may be useful in this regard, as variations in SN Ia progenitors are predicted to lead to observable effects in the near ultraviolet (Höflich et al. 2000). However, it is unclear whether the data will be precise enough to detect subtle indications of evolution. Beyond this, we do not have
clear knowledge of how potential evolution of SN Ia would affect their luminosities (and more importantly, the luminosity/decline-rate relationship), which are the basis for the cosmological inferences (see Leibundgut 2000 for a recent review).

Because of the difficulty of definitively ruling out evolution or other systematic uncertainties, it would be desirable to test directly that the SN Ia are faint because of cosmology. Fortunately, the best-fit cosmologies in Figure 1 provide an avenue for such a test. In a flat $\Omega_M = 0.3, \Omega_\Lambda = 0.7$ Universe there was a transition from decelerated expansion (where the energy density was dominated by matter) to accelerated expansion that occurred at $z \simeq 0.7$. This effect is shown in Figure 4, where we display the luminosity-distance/redshift relation for various cosmologies, relative to an empty Universe. The heavy dashed line shows the expectation for an $\Omega_M = 0.2, \Omega_\Lambda = 0.8$ model, and it shows that at higher redshifts $z \simeq 1$, the SN become less faint relative to an empty Universe, i.e. the prediction turns over. If the current SN data were explained by other effects, for instance a systematic uncertainty which grows linearly with redshift illustrated as by the heavy solid line, we would expect the SN Ia results at
Higher redshift to diverge significantly from the cosmological prediction. Thus, observations of SN Ia at $z \simeq 1$ provide an excellent test to confirm or refute the current cosmological paradigm.

The downside is that finding and following up SN Ia at $z \simeq 1$ with the necessary precision is quite a bit more difficult than measuring SN Ia at $z \simeq 0.5$. Both groups have undertaken efforts to observe such SN Ia (e.g., Fabbro et al. 1999; Tonry et al. 1999), and the reduction and analysis of these objects are underway. More objects are necessary, and we in the High-Z Team will make these higher-redshift SN Ia a priority in the upcoming year. With these data, we expect to measure the luminosity-distance/redshift relation at $z \simeq 0.8$ and $z \simeq 1.2$ with the uncertainties shown by the heavy open and filled points in Figure 4. This should allow us to discriminate the cosmological signal from systematic effects.

Other lines of astrophysical evidence suggest that we live in a flat Universe with low matter density ($\Omega_M \simeq 0.3$), with a dominant contribution from “dark energy” such as the cosmological constant. But only the data from SN Ia provide clear and direct evidence for the qualitative prediction of dark energy: acceleration of the expansion. It is imperative, then, that the SN Ia results be checked against systematic error, which is the purpose of the observations discussed here. If the SN Ia results indeed arise from some systematic uncertainty, resolving the current cosmological constraints will be an exciting challenge. On the other hand, confirming the SN Ia results will open up even more exciting questions as to the nature and evolution of the mysterious dark energy. It is quite likely that continued precise observations of SN Ia will provide an important tool for these further investigations.

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