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Measurement of q_0 with Type Ia Supernovae

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Measurement of q_0 with Type Ia Supernovae

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Abstract : Our search for high-redshift Type Ia supernovae discovered, in its first years, a sample of seven supernovae. The spectra and light curves indicate that almost all were Type Ia supernovae at redshifts $z = 0.35$ to 0.5 . These high-redshift supernovae can provide a distance indicator to measure the cosmological parameter q_0 . In this paper, observation strategies, analysis and preliminary results on q_0 , are presented.

Résumé : Dans une première étape de notre programme de recherche de supernovae à grand décalage vers le rouge, nous avons découvert 7 supernovae. Les spectres et courbes de lumière indiquent que pratiquement toutes sont de type Ia avec des décalages vers le rouge variant entre $z=0.3$ et $z=0.5$. Ces supernovae peuvent être utilisées comme indicateurs de distance pour mesurer le paramètre cosmologique q_0 . Dans ce papier, les stratégies d'observation, l'analyse ainsi que les résultats préliminaires concernant la mesure de q_0 sont présentés.

1. Introduction

Since the mid 1980's, Type Ia supernovae (SNe Ia) have appeared likely to be homogeneous enough that they could be used for cosmological measurements. At the time, it appeared that they could be used to determine H_0 , if their absolute magnitude at peak could be measured, i.e., if some SN Ia's distance could be calibrated. They could also be used to determine q_0 from the *apparent* magnitudes and redshifts of nearby and high redshift supernovae, if high redshift SNe Ia could be found. We will here discuss the search for high redshift supernovae and the measurement of q_0 .

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2. High Redshift Supernovae Search Strategy

Type Ia Supernovae at high redshift are difficult to work with for at least three reasons: they are rare, they are rapid, and they are random. The estimates of SN Ia rates—a few per millennium per galaxy—are daunting, if one wants a statistically useful sample of supernovae. Much of the interesting data must be obtained rapidly, since the supernova rises to maximum light within a few weeks and, at high redshifts, fades below the largest telescopes’ limits within a month or two. Furthermore, it is not possible to guarantee photometry and particularly spectroscopy of randomly occurring high-redshift supernovae, since the largest, most over-scheduled telescopes are needed to observe them.

To solve these problems, we developed a new search technique. Just after a new moon, we observe many tens of high-galactic-latitude fields (including known high-redshift clusters when possible) on a 2.5- to 4-meter telescope. With a wide-field camera, each image contains hundreds of galaxies at redshifts $0.3 - 0.6$. Just before the following new moon, we observe the same fields again. We compare the images, thus checking tens of thousands of high redshift galaxies (including those below our detection limit) to find the ten or so showing the new light of a supernova that was not there on the previous observation. The supernovae generally do not have time to reach maximum light, with only 2.5 to 3 weeks (or approximately 11 to 14 days in the supernova rest frame) between our after- and before-new-moon comparison images. In order to begin the follow-up photometry and spectroscopy immediately, we have developed extensive software to make it possible to complete the analysis of all the images within hours of the observations.

We report here results concerning the first 9 supernovae found during 1994. Seven of these were found within the standard 2.5 – 3 week search interval and were followed with photometry and spectroscopy (Perlmutter *et al.* 1994, 1995a). (Since these were the demonstration runs of the project, not all of the follow up was scheduled.) We observed light curves for all of the supernovae in at least one filter (usually R band), and spectra for all of the host galaxies and three of the supernovae.

The results of the batch search strategy can be seen in Figure 1, which shows a preliminary analysis of the *R*-band light curves as of Dec 1995. For each of the supernovae, there is the 2.5 – 3 week gap in the observations leading up to the discovery just before maximum light. (There is also a gap during the following full moon.)

Fig. 1.— Preliminary *R*-band light curves for the first seven high-redshift supernovae. Shading behind the solid curves represent the $1\text{-}\sigma$ bounds on the best fit Leibundgut template light curve. An *I*-band light curve is also shown for SN 1994G; other photometry points in *I* and *B* for these supernovae are not shown on this plot. The lower of a “spontaneous generation” event, a transient point-source of light on a region of an image where no host galaxy is visible; the follow-up photometry was not as extensive for this event.

3. Photometry and Light Curve Analysis

The data analysis involves several stages, first to reduce the observed image data to individual photometry points and then to compare these points with nearby SN Ia light curves to determine the luminosity distance and hence q_0 . The supernova light in each image must be measured and the underlying host galaxy light subtracted off.

To compare these high-redshift supernova photometry points to nearby SN Ia light curves, it is necessary to calculate the K correction that accounts for the redshifting of the light observed in a given filter. The standard K corrections give the magnitude difference between the light emitted in a given filter band and the light observed after redshifting in that same band. Since at redshifts of order $z = 0.45$ the light received in the R band corresponds approximately to the light emitted in the B band, we calculate a generalization of the K correction, K_{RB} , that gives the magnitude difference between the rest frame B magnitude and the observed R magnitude.

In the past year, the case has become quite strong that SNe Ia are a family of very similar events, not all identical. Hamuy *et al.* (1995) and Riess, Press, and Kirshner (1995) present evidence indicating that this family can be described by a single parameter, essentially representing the shape or width of the light curve, and that this parameter is tightly correlated with the absolute magnitude at maximum. The broad, slow-light-curve supernovae appear somewhat brighter, while the narrow, fast-light-curve supernovae are somewhat fainter.

Hamuy *et al.* used Phillips’ (1993) characterizations of this light curve width, Δm_{15} , the magnitude drop in the first 15 days past maximum, and fit their data to template light curves from supernovae representing various Δm_{15} values. Riess *et al.* added and subtracted different amounts of a “correction template” to a Leibundgut “normal” template (Leibundgut *et al.* 1991 and references therein) to represent this same light curve variation.

For our preliminary analysis, we have chosen a third alternative approach, to stretch or compress the time axis of the Leibundgut template by a “stretch factor” s . We find that this simple parameterization gives variations on the light curve that fit the variety of SNe Ia and can be translated to Phillips’ Δm_{15} via the formula $\Delta m_{15} = 1.7/s - 0.6$. Calibrating nearby supernovae with this s -factor, we find the width-brightness relation can be characterized by a magnitude correction of $\Delta \text{mag} = 2.35(1 - s^{-1})$, which closely matches Hamuy *et al.*’s Δm_{15} correction.

4. Preliminary Scientific Results

To use high-redshift SNe Ia as distance indicators, we must first ask if the width-brightness relation holds at $z \sim 0.4$. We plotted the stretch factor—or equivalently Δm_{15} —versus the K -corrected and Galactic-extinction-corrected absolute magnitude (for a given q_0 and H_0), and we found a correlation that is consistent with that found for nearby supernovae. Using the width-brightness relation as a magnitude “correction,” established using only nearby SNe Ia, tightens the dispersion of the high redshift supernova K -corrected peak magnitudes from $\sigma_{\text{raw}} = 0.32$ mag to $\sigma_{\text{corrected}} = 0.21$ mag. These dispersions are quite comparable to those found for nearby SNe Ia before and after correcting for the width-brightness relation. For our preliminary estimate of q_0 , we have applied the width-brightness correction to all seven of the high-redshift supernovae, on the assumption that they are all SNe Ia with negligible extinction and that the zero point of the width-brightness relation has not evolved in the ~ 4 billion years back to $z \sim 0.4$. Given the range of host galaxy ages for the nearby supernovae used to derive this relation, it is unlikely that it would have been very different at $z \sim 0.4$.

Figure 2 shows the results of this analysis plotted on a Hubble diagram, together with the relatively nearby SNe Ia of Hamuy *et al.* (1995). Comparing the upper and lower panels, it is clear that the scatter about the Hubble line decreases for both near and high-redshift supernovae after correcting for the width-brightness relation, although the error bars increase in the cases for which the light-curve width (s -factor or Δm_{15}) is poorly constrained by the photometry data. The three supernovae with the smallest error bars, after correction for the width-brightness relation, are all near the redshift $z = 0.37$ and their data points in Figure 2, lower panel, lie on top of each other. They favor a relatively high value for q_0 . Note that before the width-brightness correction (Figure 2, upper panel) their data points spread from $q_0 \approx -0.5$ (upper dotted line) to $q_0 > 1$ (lower dotted line); generally, the correction has brightened as many points as it has dimmed.

5. Discussion and Conclusion

Given the error bars, our current measurements of q_0 do not yet clearly distinguish between an empty $q_0 = 0$ and closed $q_0 > 0.5$ universe. The data do, however, indicate that a decelerating $q_0 \geq 0$ is a better fit than an accelerating $q_0 < 0$ universe. This is an important conclusion since it limits the possibility that $q_0 = \Omega_0/2 - \Omega_\Lambda$ is dominated by the cosmological constant Λ (where Ω_Λ is the normalized cosmological constant $\Lambda(3H_0)^{-2}$). In an accelerating universe, high values for the Hubble constant do not conflict with the ages of the oldest stars, because the universe was expanding more slowly in the past. However,

Fig. 2.— Hubble diagrams for first seven supernovae (preliminary analysis). Upper panel: “raw” apparent magnitude measurements, after K correction from R -band (observed) to B -band (supernova rest frame), versus redshift. The upper dotted curve is calculated for $q_0 = -0.5$, the two solid curves are for $q_0 = 0$ and $q_0 = 0.5$, and the lower dotted curve is for $q_0 = 1$. Lower panel: apparent magnitude measurements after “correction” for width-brightness relation. Note that the three points with the smallest error bars lie on top of each other, in this plot. Inset: Points represent redshifts for the most recent 11 supernova discoveries that are still being followed.

in a “flat” universe, in which $\Omega_0 + \Omega_\Lambda = 1$, a cosmological constant $\Omega_\Lambda \geq 0.5$ would give an acceleration $q_0 \leq -0.25$, a poor fit to our data.

Note that extinction of the distant supernovae would make this evidence of deceleration even stronger, as would the possibility of inhomogeneous matter distribution in the universe as described by Kantowski, Vaughan, & Branch (1995), since both of these would lead to underestimates of q_0 if not taken into account.

It will be important to compare the q_0 value from our most distant supernovae to the value from our closest high-redshift supernovae to look for Malmquist bias. An estimate of the size of this bias using our studies of our detection efficiency as a function of magnitude suggests that a 0.2 mag intrinsic dispersion in calibrated SN Ia magnitudes would lead to an overestimate of 0.1 in q_0 , if not accounted for.

We have shown here that the scheduled discovery and follow up of batches of pre-maximum high-redshift supernovae can be accomplished routinely, that the comparison with nearby supernovae can be accomplished with a generalized K-correction, and that a width-brightness calibration can be applied to standardize the magnitudes. Ideally this will now become a standard method in the field, and SNe Ia beyond $z = 0.35$ will become a well-studied distance indicator—as they already are for $z < 0.1$ —useful for measuring the cosmological parameters. The prospects for this look good: already several other supernova groups have now started high-redshift searches.

The observations described in this paper were primarily obtained as visiting/guest astronomers at the Isaac Newton and William Herschel Telescopes, operated by the Royal Greenwich Observatory at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias; the Kitt Peak National Observatory 4-meter and 2.1-meter telescopes and Cerro Tololo Interamerican Observatory 4-meter telescope, both operated by the National Optical Astronomy Observatory under contract to the National Science Foundation; the Keck Ten-meter Telescope; and the Siding Springs 2.3-meter Telescope of the Australian National University. We thank the staff of these observatories for their excellent support. Other observers contributed to this data as well; in particular, we thank Marc Postman, Tod Lauer, William Oegerle, and John Hoessel for their more extended participation in the observing. This work was supported in part by the Physics Division, E. O. Lawrence Berkeley National Laboratory of the U. S. Department of Energy under Contract No. DE-AC03-76SF000098, and by the National Science Foundation’s Center for Particle Astrophysics, University of California, Berkeley under grant No. ADT-88909616. The author would like to thank Gerard Fontaine of CNRS-IN2P3 and Bernard Sadoulet of CfPA, Berkeley for encouraging his participation to the project.

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