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DISCOVERY OF THE MOST DISTANT SUPERNOVAE AND THE QUEST FOR Ω*

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ABSTRACT

A search for cosmological supernovae has discovered a number of a type Ia supernovae. In particular, one at $z = 0.458$ is the most distant supernova yet observed. There is strong evidence from measurements of nearby type Ia supernovae that they can be considered as "standard candles". We plan to use these supernovae to measure the deceleration in the general expansion of the universe. The aim of our experiment is to try and observe and measure about 30 such distant supernovae in order to obtain a measurement of the deceleration parameter q_o which is related to Ω. Here Ω is the ratio of the density of the universe to the critical density, and we expect a measurement with an accuracy of about 30%.

One of the fundamental problems in particle astrophysics is the question, how to determine the density of the Universe? As a lower limit we have the density in

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visible baryonic matter, which stands at about 0.01 of the critical density, ρ_c. If the current density, ρ, is greater than ρ_c, gravitational attraction will eventually cause the expansion of the universe to cease, and contraction to begin. If $\rho \leq \rho_c$ the expansion of the universe would continue forever. The ratio ρ/ρ_c is denoted by Ω. At present, estimates of Ω, based on a variety of experiments, range from 0.1 to 1.5. Since the light emitting matter contributes roughly 0.01 to Ω, a measurement of Ω would determine the amount of dark matter in the universe.

Our work is based on the study of type Ia SNe in that they represent "standard candles" which, because of their brightness can be observed out to very large distances. One SN we discovered, SN1992bi, is the most distant SN ever observed with a red shift $z = 0.458$ or a distance of about 5 billion light years. This implies that the light we observed in April '92 corresponds to an explosion which occured at the time of the creation of our solar system.

There is good evidence that type Ia Supernovae (SNe), the brightest of all the different types of SNe, have a fixed brightness. A plausible explanation for this behavior is that type Ia SNe are the consequence of the explosion of a white dwarf star as it reaches a critical mass, of 1.4 solar masses, the Chandrasekhar limit.

A white dwarf is a star that has burned all of its hydrogen and helium to carbon nitrogen and oxygen and as a result has collapsed under the gravitational force to a degenerate electron gas in which the C, N and O nuclei are embedded. The white dwarf thus has the mass of the order of the mass of the sun but a radius comparable to that of the earth. If this white dwarf is in a binary system with another star, a very common occurrence, it can accrete matter from the companion star and will then collapse when the gravitational force exceeds the degeneracy pressure. In this collapse the temperature rises to the point at which the C, N and O nuclei fuse and produce higher mass nuclei, within seconds. Since the original nuclei all have equal number of protons and neutrons the fusion products will also. The fusion process stops at ^{56}Ni, a radioactive isotope with equal number of protons and neutrons. In fact an enormous amount of ^{56}Ni is produced, 0.6 of a solar mass. In the implosion under gravity the star collapses and then rebounds within seconds. On rebound the newly produced material is ejected with velocities of about 10,000 km/sec. At first, light is unable to penetrate the very dense material. Over a period of about 15 days light begins to penetrate and reaches a maximum value. It is during this period that we first discover the SN as we will describe below. The light observed is produced by ionization from the ^{56}Ni decay products. This isotope has a half life of 6 days which then decays to ^{56}Co which has a half life of 77 days which then decays to stable ^{56}Fe.

The light curve, one observes from type Ia SNe (in blue filter), has the characteristic exponential decay features corresponding to these two lifetimes as modified by absorption in the expanding ejecta. Fig. 1 shows this light curve for a compilation of 22 SNe by Branch and Tammann.(1) It also illustrates the degree of uniformity of the SN Ia light curves. The scale shown is in magnitudes, a logarithmic scale, with all individual SN data aligned with the curve. Fig. 2 illustrates the degree of uniformity of the type Ia SNe. What is plotted is the absolute magnitude for 30 SNe Ia. We note a large peak at absolute magnitude $M_B \simeq -19$, where M_B is the magnitude

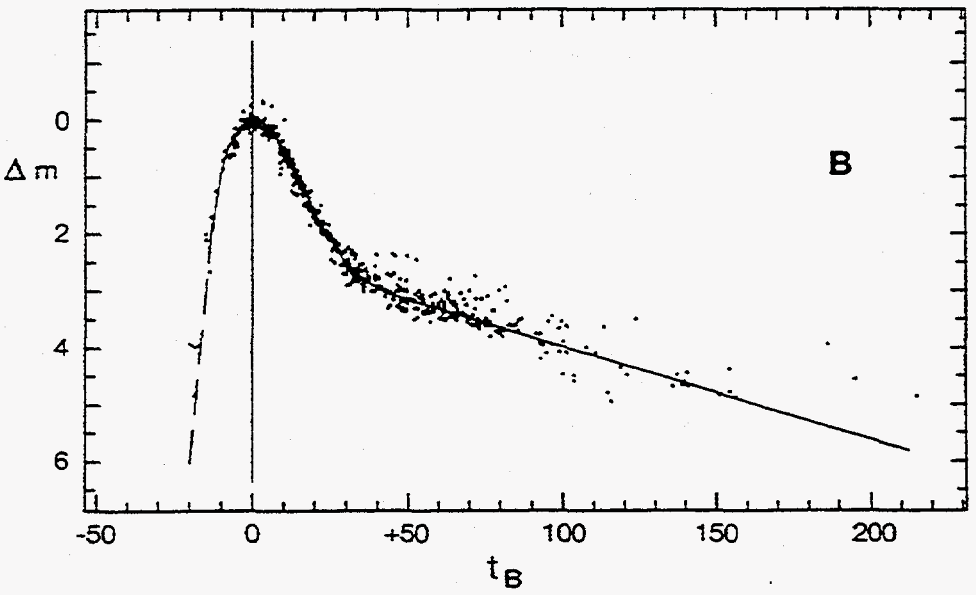

Fig. 1. The standard Blue light curve$^{(1)}$ based on observations of 22 SN Ia.

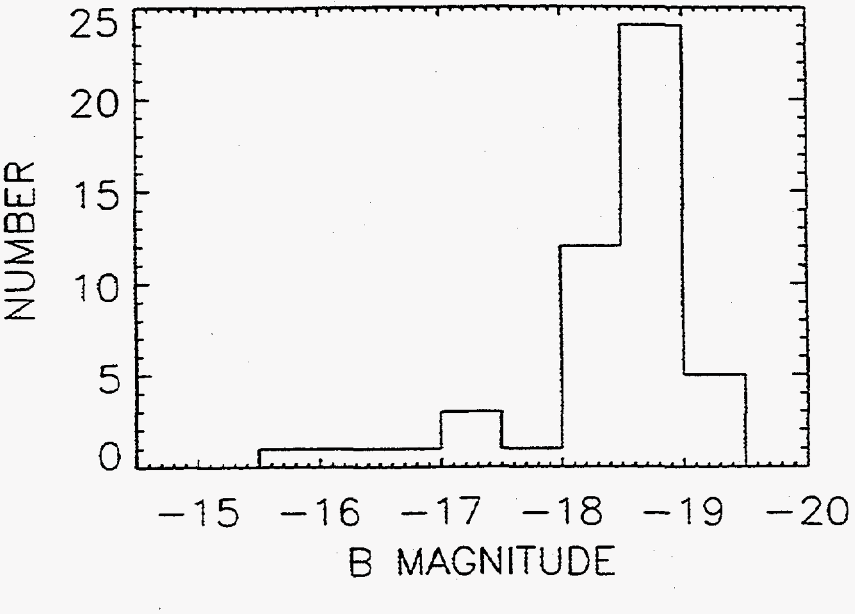

Fig. 2. *B* magnitude distribution for type Ia SNe. Adapted from compilation by Vaughan ref. 2.

observed with a blue filter. Brightness increases to the right in this figure. The width of this peak indicates the degree of uniformity of these SNe. Actually the true width must be smaller since this compilation made from over 50 years of SN observations includes the individual measurement errors as well as the true intrinsic width.(2) The tail on the left hand side comes from SNe which occurred in galaxies with considerable inclination towards us, so that the SN light passed through a large thickness of the galaxy and thus suffered "extinction" (partial absorption).

1. The Observation of the Most Distant Supernova, SN1992bi

In April 1992 we discovered a SN which on a later acquisition of the spectrum of the host galaxy, turned out to be at $z = 0.458$, the most distant SN ever observed.(3) See Fig. 3. The discovery was based on the analysis of images taken with the 2.5 m Isaac Newton Telescope (INT) at La Palma. In particular images taken 4 weeks earlier March 25 and 27 were compared with the discovery images taken on April 28. In each case two 10 min. images were taken with the INT 1024 × 1024 pixel CCD camera. Since we are looking for objects that vary over the 4 week period it is important to take two images in succession rather than one longer image because this allows us to eliminate asteroids and cosmic rays. The asteroids move between the two images and the cosmic rays will only occur in one of the two images. A number of further images taken during the following weeks indicated that we had observed the SN at its peak luminosity. The filter used was a red filter and from the photometry curve we conclude that we have observed a type Ia SN, to about 90% probability.

2. The Observation of 6 Additional SN Candidates

In December 1993 and in January 1994 we have again repeated the earlier images at the INT. This time we observed 1 SN candidate in December 1993 by comparison with the March and April 1992 images. Three additional candidates were observed, in the comparison of January 94 and December 93 images. All three of these SN candidates were observed while still rising in intensity. Two additional SN were observed in early February on images taken earlier(4) at the Kitt Peak National Observatory (KPNO) 4 meter telescope. All these SNe are consisten with type Ia. Because type Ia are the brightest SNe, they are observed preferrentially at these large distances. Definitive identification will have to await complete photometry curves and in two cases galaxy spectral measurements to obtain the red shifts. The preliminary Photometry curves for the 5 new SNe which were discovered before maximal light are shown in Fig. 4.

Spectra have been obtained on two of these SNe at the Multiple Mirror Telescope in Arizona(5) SN1994G and at the Keck 10 m telescope in Hawaii(6) SN1994F respectively.

Our procedure is to take about 80 different CCD images of fields which, whenever possible, contain a cluster of distant galaxies. Each image covers about 12 × 12 square minutes of arc on the sky. The total area covered is thus about 3 square degrees. The

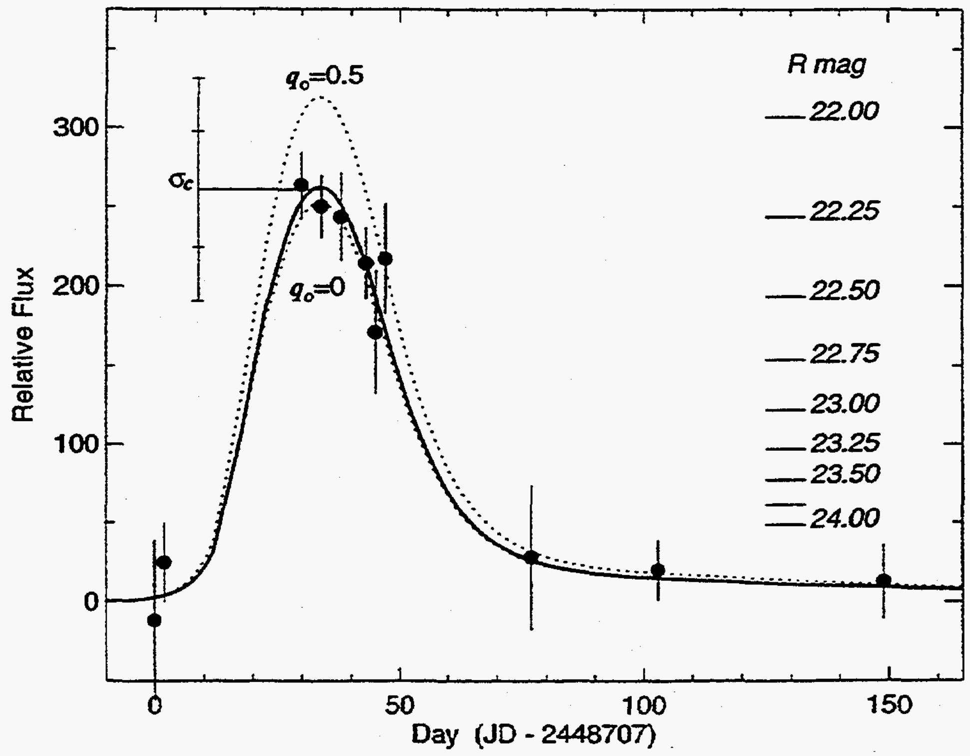

Fig. 3. Photometry curve for SN 1992bi. Solid curve shows the calculated light curve, relative flux $f_R(t)$, for the best fit $q_0 = 0.1$, based on the template B light curve for nearby supernovae. The dotted curves are $f_R(t)$ for $q_0 = 0.5$ (upper curve) and for $q_0 = 0$ (lower curve). The data points are the reference subtracted SN signal. The inner error bar, σ_c, shows the combined uncertainty at maximum light in $f_R(t)$ and in the reference image's photometry and magnitude calibration; the outer error bar includes the intrinsic dispersion of the nearby SNe. The inset scale shows R magnitudes. For the best fit q_0, the peak magnitude is $m_R = 22.2$ on Day 34.

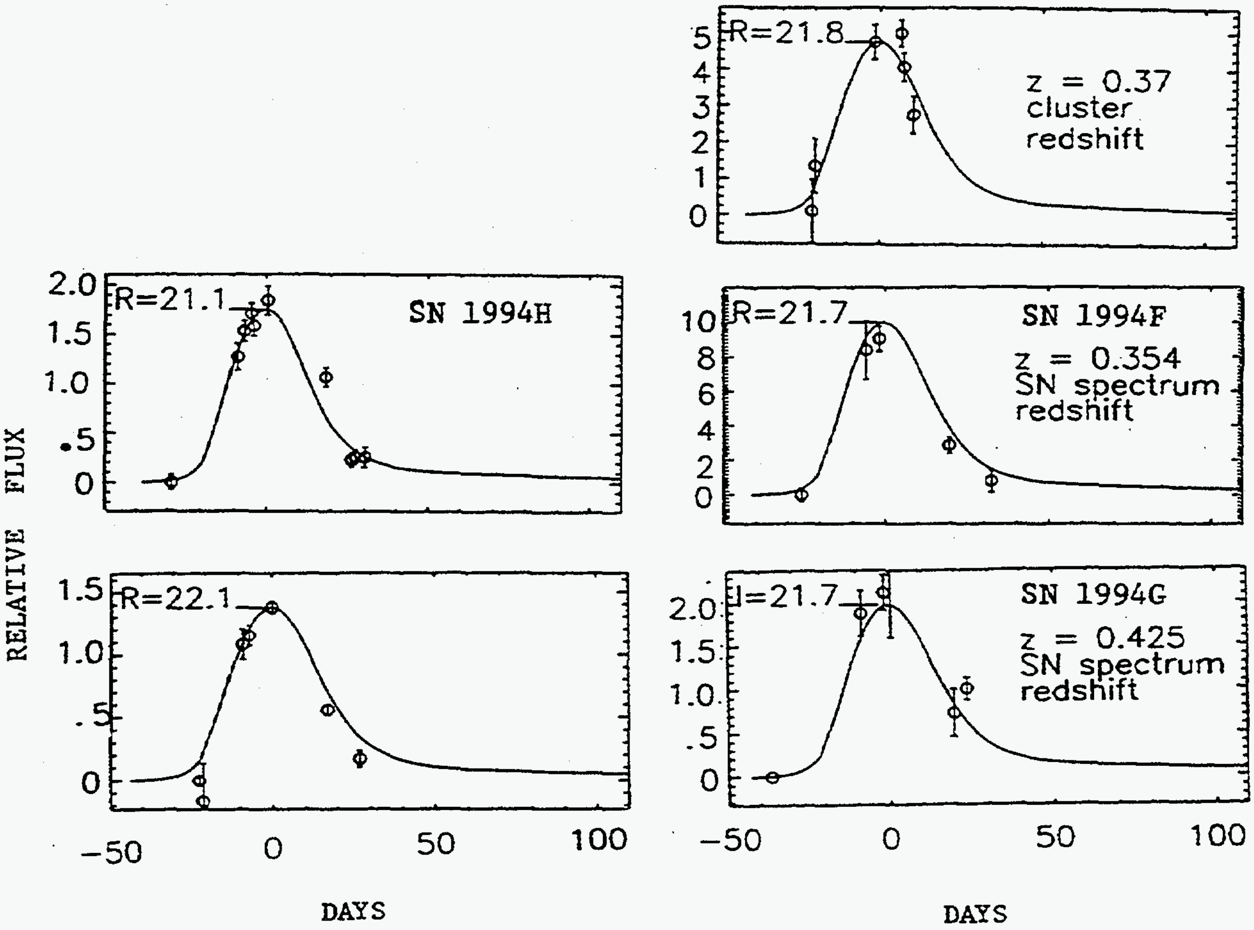

Fig. 4. Preliminary light curves for the 5 1994 SNe observed before maximum light.

first set of images are considered as "reference" images. The second set observed about 3 weeks later, are the "search" images in which we hunt for the new light due to a supernova. Three of our new set of supernovae have already been named SN 1994F, SN 1994G, and SN 1994H.

3. The Photometry Curve

As the nearby SN photometry curves are measured with a blue filter while our measurements are made with a red filter we must first translate our measurements into the blue. As it turned out this correction was particularly straightforward for our most distant SN because $1 + z = 1.458$ gives the ratio of the redshifted wavelength to the wavelength at emission. This value turned out to be the ratio of the central wavelength transmitted by our red filter to that of the blue filter, used for the nearby standard light curve. The acceptance width of the two filters were also in this same ratio. From the shape of the photometry curve we were able to identify our SN as a type Ia with ~90% confidence. We found a peak apparent magnitude $m_R = 22.2 \pm 0.1$.

4. Our Plan for Obtaining q_o and Ω

To obtain q_o we make use of three measurements.

- The red shift of the supernova or parent galaxy, z is related to the wavelength change $\lambda - \lambda_o$ of the receeding object. Here z is defined as $z = (\lambda - \lambda_o)/\lambda_o$ and λ_o is the wavelength in the rest system while λ is the measured wavelength. This requires taking a spectrum of the SN whenever possible as well as of the galaxy.
- The apparent magnitude m of the SN at the peak of its photometry curve. This is based on measurment of the SN light intensity.
- The absolute magnitued M_B obtained from the group of well measured nearby Type Ia SN and quoted in the literature.

We have carried out Monte Carlo simulations to find out how many SN we need to measure Ω to an uncertainty of 30%. This turns out to be about 30 SN. To accomplish the detection of that many distant SN we plan a new detector, in collaboration with the Royal Greenwich Observatory (RGO). This will consist of 4 2048 × 2048 pixel CCD's. The plan is to place this new camera in the 2.5 m INT at La Palma. With this much larger camera we estimate that the proposed measurement will be possible in about two years.

5. Evaluation of q_o and Ω

The relation between the measured apparent magnitude m_R and the absolute magnitude M_B for type Ia SN, is given by

$$m_R = 5\ log D_L + M_B + 25 + \Delta m_{RB} \tag{1}$$

where D_L is the luminosity distance given here in Mpc. ($\approx$ 3 million light years)

$$D_L = \frac{c}{H_o q_0^2}\{1 - q_0 + q_0 z + (q_0 - 1)(2q_0 z + 1)^{1/2}\}. \tag{2}$$

Here H$_o$ is the Hubble constant c the velocity of light, z is the measured red shift $\Delta\lambda/\lambda$ obtained from the spectrum of the host galaxy and q_o is the deceleration parameter of the Universe. This expression can be solved for q_o which is related to the cosmological constant and Ω. If we assume that the cosmological constant = 0 then $\Omega = 2q_o$.

At first sight it appears that D_L depends on the Hubble constant H_o as well. However it turns out that the Hubble constant cancels because H_o also appears in the determination of M_B obtained from type Ia SN measurements in nearby galaxies. Our measurements have to be carried out at cosmological distances i.e., large values of z since for small z values $z < 0.1$, the dependence on q_o is negligible and the luminosity distance becomes $D_L = $ cz/H$_o$.

Furthermore, the shape of the light curve is red shifted by a factor $1 + z$ on the time axis.

Finally, Δm_{RB} is a correction factor between red and blue SNe magnitudes. For SN 1992bi, $\Delta m_{RB} = -0.7$.

6. References

1. D. Branch and G.A. Tammann *Ann. Rev. Astron. Astrophys.* 1992. 359–89.
2. D.E. Vaughan, D. Branch, D.C. Miller and S. Perlmutter *Astrophysical Journal*, (in press).
3. A Supernova at $z = 0.458$ and Implications for the Cosmological Deceleration. S. Perlmutter, C.R. Pennypacker, G. Goldhaber, A. Goobar, R.A. Muller, H.J.M. Newberg, J. Desai, A.G. Kim, M.Y. Kim, I.A. Small, B.J. Boyle, C.S. Crawford, R.G. McMahon, P.S. Bunclark, D. Carter, M.J. Irwin, R.J. Terlevich, R.S. Ellis, K. Glazebrook, W.J. Couch, J.R. Mould, T.A. Small, and R.G. Abraham *Astrophysical Journal Letters* in press.
4. The reference images at Kitt Peak were taken by M. Postman, W. Oegerle, T. Lauer and J. Hoessel.
5. Spectrum taken by P. Challis, R. Kirshner and R. Riess.
6. Spectrum taken by T. Bida, J. Cohen and J.B. Oke.