The Lick Observatory Supernova Search: Type Ia Supernovae, Cosmology, and the Accelerating Universe

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December 10, 2001

ABSTRACT

In this presentation I discuss my research in Astrophysics as a member of the Lick Observatory Supernova Search (LOSS) team conducted with Professor Alex Filippenko at the University of California, Berkeley from January 1999 to the present.[3] The LOSS group uses the multi-purpose 76 cm Katzman Automatic Imaging Telescope (KAIT), to scan a sample of as many as 1200 galaxies per night, in search of nearby, low redshift (low z) supernovae. My role in the group has involved both the supernova search itself and the photometric analysis of follow-up observations. As part of the supernova search, I have discovered 7 supernovae to date (1999bh, 1999bx, 1999ej, 1999gb, 2000fa, 2001L, and 2001ae). Regarding photometry, I have generated B, V, R, and I-band light curves for supernova 2000cx [4], and am in the process of generating the light curves for supernova 1998dh. As a member of the supernova search group, I was a coauthor of a conference proceedings paper (Cosmic Explosions 2000), and I am working on a paper in progress with tentative title, *"Photometric Observations of 30 Nearby Type Ia Supernovae,"* along with my direct superior, Dr. Weidong Li and Professor Alex Filippenko. I plan to generate the light curves for many Type Ia supernovae and work exclusively on this project during the Spring 2002 semester after I graduate.

This particular report will discuss the basics of the supernova search and photometry with KAIT [5], and detail how we use light curves of Type Ia supernovae in particular to test various cosmological models and measure the expansion rate of the universe. The emphasis of this report will ultimately be to explain how my research fits into the big picture of the recent accelerating universe results.

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[2]Research Advisor: Professor Alex Filippenko and direct superior Dr. Weidong Li. Physics Advisor: Professor Richard Muller (For the Physics H195AB Honors Thesis).

[3]I spent the Spring 2000 semester studying abroad at the University of New South Wales in Sydney, Australia, and this past semester (Fall 2001) largely away from research, teaching Astronomy 10, taking the Infrared Astronomy 122 Laboratory, taking Astronomy 160A, and applying to graduate schools and fellowships. I graduate this semester and will continue the research next semester until I enter graduate school in Astronomy for the Fall of 2002.

[4]This was a "practice" supernova whose results I compared to the light curves generated by my direct superior in the group, Dr. Weidong Li.

[5]I am in the process of writing up a training primer, "Photometry with KAIT," which I will use to help train the undergraduates in the group to do photometry beginning next semester.

1. Introduction

As a member of the LOSS group, I work under the larger auspices of the High-Z (i.e., high redshift) Supernova Search Team, headed by Dr. Brian Schmidt at the Australian National University in Canberra, Australia. The "big picture" goal of the group is to discover large numbers of Type Ia supernovae in distant galaxies, determine their spectra and light curves from follow-up observations, and use them to do cosmology. My research has focused on both searching for supernovae and performing photometry on the follow-up observations to obtain the supernova's light curves, which plot its apparent brightness as a function of time in several different filters (U, B, V, R and I-bands). These light curves are then used to test various cosmological models, and specifically, to measure the acceleration rate of the universe. Since Edwin Hubble's 1929 discovery that almost all galaxies are redshifted, and are thus receding from us, we have known that the universe is expanding. The major result of the High-Z Team, which was announced first in 1998, is that the high z supernovae we observed are consistently 10-15% dimmer than what we would expect from a coasting expanding universe, implying that they are actually farther away than expected, and thus that the expansion of the universe may actually be accelerating.

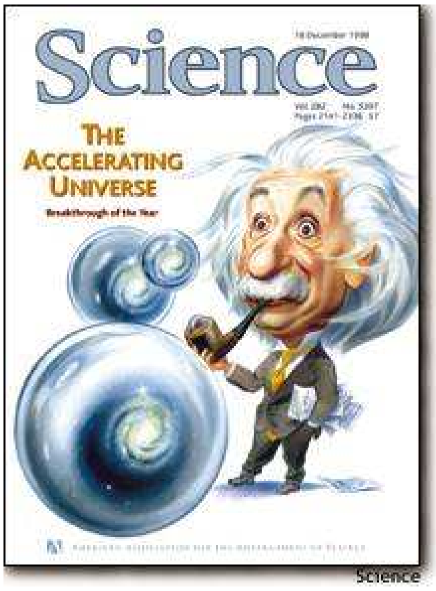

Fig. 1.— Science Magazine named the discovery of the Accelerating Universe the top science breakthrough of 1998. The results resurrected the idea of Einstein's cosmological constant Λ, first proposed as an ad hoc anti-gravitational term in the field equations of General Relativity to keep the universe static. Einstein later discarded Λ, when Hubble discovered that the universe was expanding, and is said to have called its introduction the "biggest blunder" of his career. Thus we see why his caricature above is pleasantly surprised at the possibility that Λ might not have been a blunder after all, and may actually be causing the universe to accelerate. The sheer excitement of this result was undoubtedly one of the reasons I joined the Filippenko group in early 1999.

2. The Supernova Search

If we want to ultimately use supernovae to do cosmology, the first thing one must do in such a project is to find them! Our team, which includes several undergraduates, searches for supernovae aided by IRAF (Image Reduction and Analysis Facility) image processing software specifically designed to find possible supernova candidates. Our data consists of optical CCD images that come from the Katzman Automatic Imaging Telescope (KAIT) located at Lick Observatory. The state of the art program we work with, which was designed by my direct superior, Assistant Research Astronomer Weidong Li, sifts through images of as many as 1200 galaxies per night, which statistically guarantees that we will discover a substantial number of supernovae before maximum brightness. In fact, with over 150 discoveries in the past four years and over 60 to date in 2001, KAIT is undisputedly the world's most successful search engine for nearby supernovae.

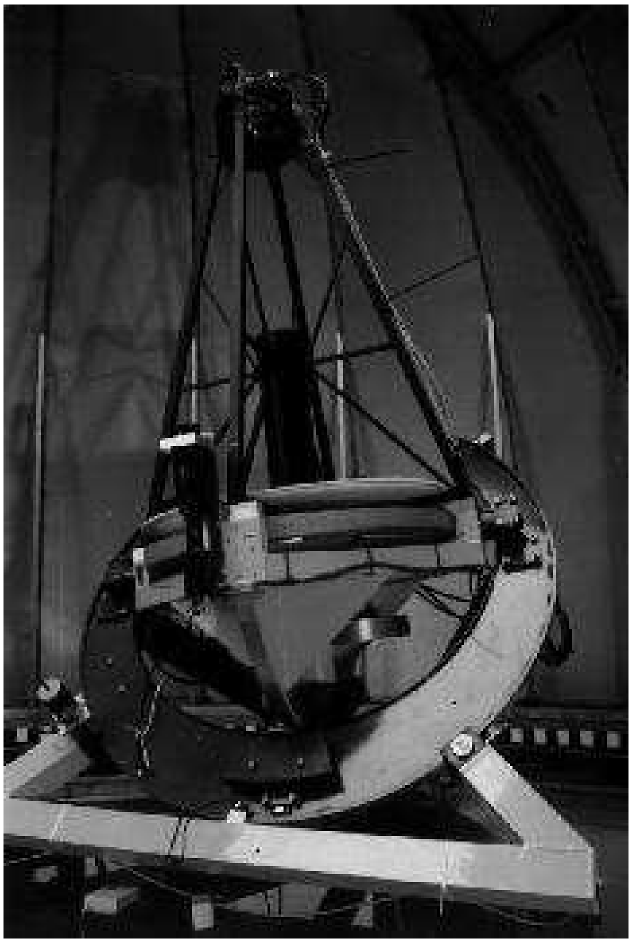

Fig. 2.— The 76 cm Katzman Automatic Imaging Telescope (KAIT) located at Lick Observatory. The world's most successful low z supernova search telescope.

However, the program itself is still not sensitive enough to detect many supernovae, so it requires a careful observer to check through the images and verify possible good candidates. We use various IRAF programs to compare the current images with template images of the same host galaxy taken previously. We do this to determine whether there is indeed something new and re-observable in the CCD image, as opposed to a fleeting asteroid or cosmic ray, for example. For promising candidates, we instruct KAIT remotely to automatically re-observe the field to make sure that the apparent supernova is still visible, and we can sometimes even get same-day verification.

I am happy to say I have been fortunate to discover seven supernovae in the past semesters. Images of the supernovae (1999bh, 1999bx, 1999ej, 1999gb, 200fa, 2001L, and 2001ae) are displayed in the next section of this report. They can also be found on the KAIT website at http://astron.berkeley.edu/bait/kait_lwd.html under 1999, 2000, and 2001 discoveries. Once we make a discovery, it is announced with our name as discoverer to a large fraction of the astronomical community.

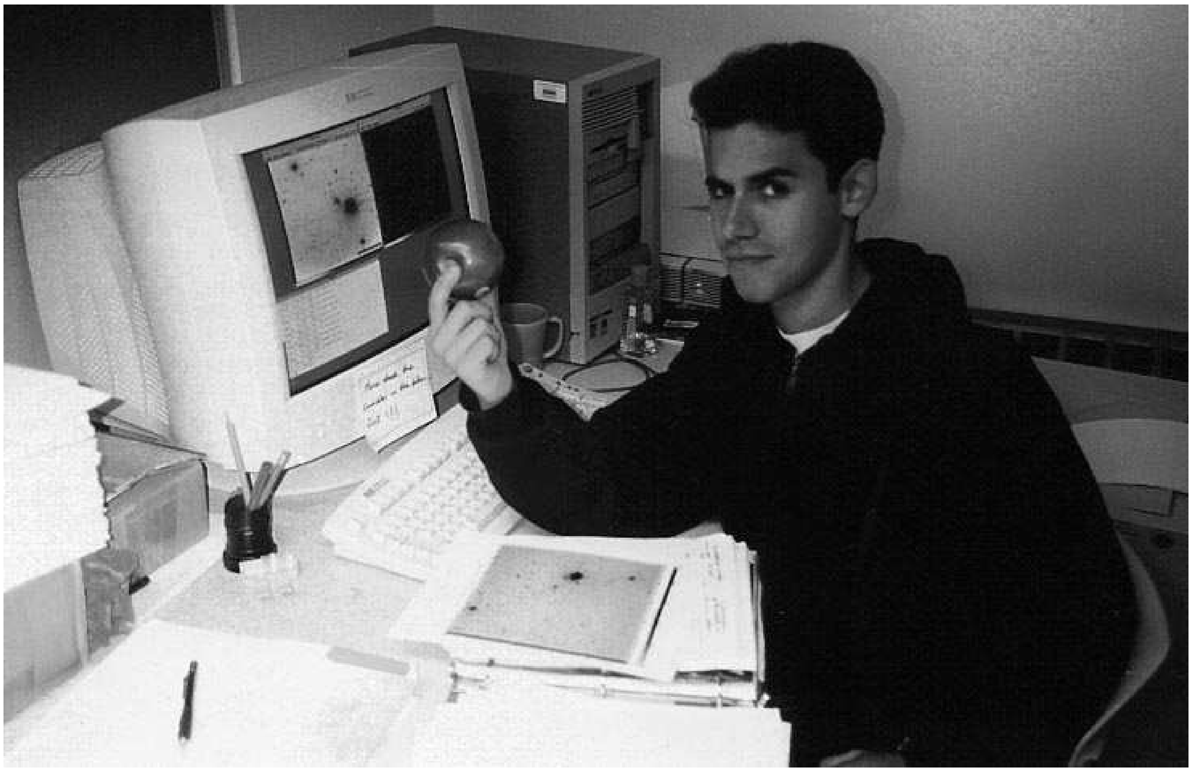

Fig. 3.— Here's a photo of me at "Hercules," the workstation where I check KAIT images. The apple just really wanted to be in the photo, it seems. Although its presence could be interpreted as a reminder that our goal is to study the effects of gravity on the expansion of the universe, in the spirit of Isaac Newton, whose mythical falling apple supposedly led to his understanding of gravity.

3. Discovered Supernova Gallery

When we make a supernova discovery, we notify the International Astronomical Union (IAU)[6], which sends out a mass e-mail relating the discovery to a large portion of the astronomical community. For each supernova I've discovered, I include here the corresponding IAU Circular that details the basic discovery information.[7] I also include here the classification of the supernova as a Type Ia or Type II, for example, although this is not usually included in the original Circular unless we happen to already have spectra of the object.

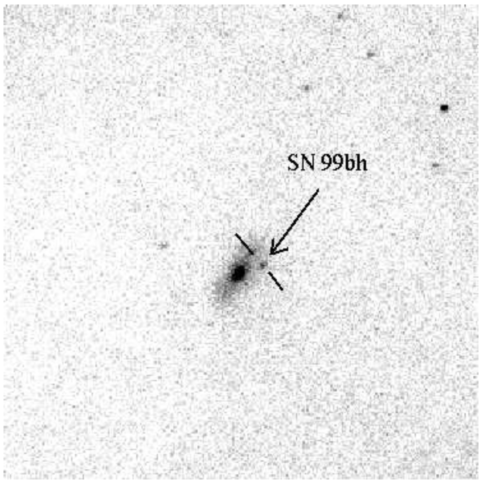

Fig. 4.— SUPERNOVA 1999bh IN NGC 3435 (Type Ia).

IAU Circular No. 7135

Li also reports the discovery by LOSS of another apparent supernova in an unfiltered image taken on Mar. 29.2 UT (mag about 16.8). SN 1999bh was confirmed at mag 17.5 on an earlier image taken on Mar. 24.2 and is located at R.A. = 10h54m46s.97, Decl. = +61o17'20".0 (equinox 2000.0), which is about 10" west and 3" south of the nucleus of NGC 3435. A KAIT image of the same field on Mar. 17.2 (limiting mag about 19.0) already showed a hint of SN 1999bh, and a KAIT image on Mar. 12.2 (limiting mag about 19.0) showed nothing at the position of the supernova. (Host galaxy info : v = 8400 km/s, 1.9'x1.2', Sb). (I was a co-discoverer with Weidong Li.)

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[6]IAU Circular Information - Central Bureau for Astronomical Telegrams, INTERNATIONAL ASTRONOMICAL UNION, Mailstop 18, Smithsonian Astrophysical Observatory, Cambridge, MA 02138, U.S.A. IAUSUBS@CFA.HARVARD.EDU or FAX 617-495-7231 (subscriptions) BMARSDEN@CFA.HARVARD.EDU or DGREEN@CFA.HARVARD.EDU (science) URL http://cfa-www.harvard.edu/iau/cbat.html Phone 617-495-7244/7440/7444 (for emergency use only)

[7]i.e. Discoverer, research group, brightness of the supernova, date, time, name of the supernova, name of the host galaxy, coordinates of the host galaxy, image orientation, location of the object in the field of view, information about pre-discovery images, and information about the host galaxy in which the supernova was discovered.

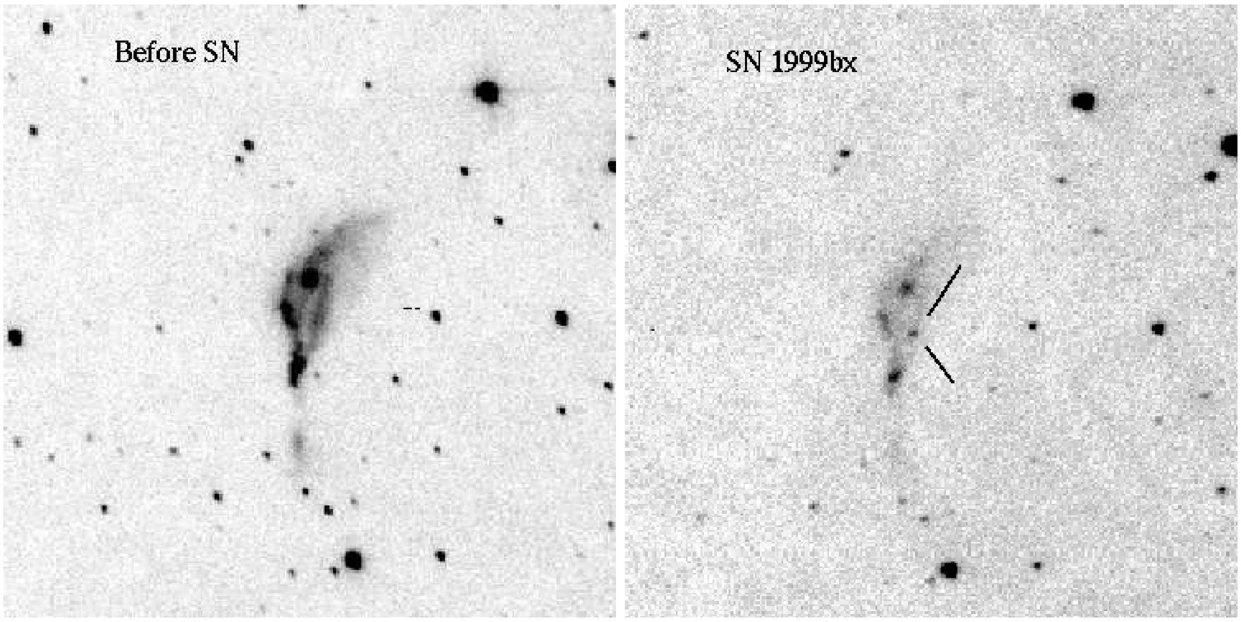


Fig. 5.— SUPERNOVA 1999bx IN UGC 11391 (Type II). (Pre- and Post-Discovery Images)

IAU Circular No. 7154

A. Friedman and W. Li, University of California at Berkeley, on behalf of the Lick Observatory Supernova Search (cf. IAUC 6627, 7126), reports the discovery with the 0.8-m Katzman Automatic Imaging Telescope (KAIT) of an apparent supernova in UGC 11391. SN 1999bx was discovered on an unfiltered image taken on Apr. 26.5 UT (mag about 16.5) and confirmed on Apr. 27.5 under poor seeing conditions. The new star is located at R.A. = 19h01m41s.44, Decl. = +40o44'52".3 (equinox 2000.0). The host galaxy, UGC 11391, has a peculiar appearance (two nuclei) and may be an interacting galaxy pair. The supernova is sitting in the middle of the western ridge that connects the two nuclei, and is about 2".2 west and 14".9 north of the southern nucleus. KAIT images of the same field on 1998 Sept. 22.1 (limiting mag about 19.5) showed nothing at the position of SN 1999bx. (Host galaxy info : v = 4545 km/s).

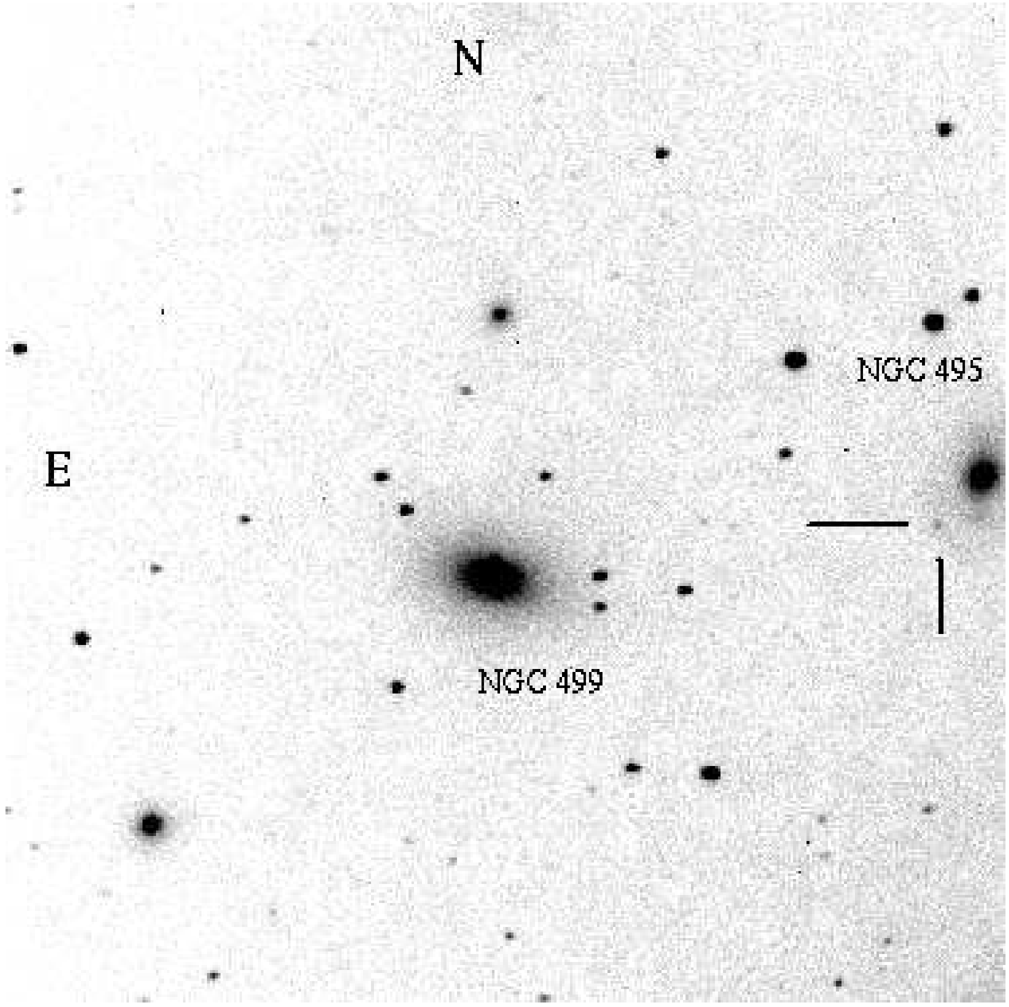


Fig. 6.— SUPERNOVA 1999ej IN NGC 495 (Type Ia).

<u>IAU Circular No. 7286</u>

A. Friedman, J. Y. King, and W. D. Li, University of California at Berkeley (UCB), report the discovery by the Lick Observatory Supernova Search (LOSS; cf. IAUC 6627, 7126) with the 0.8-m Katzman Automatic Imaging Telescope (KAIT) of an apparent supernova in NGC 495. SN 1999ej was discovered and confirmed on unfiltered images taken on Oct. 18.3 and 19.3 UT (both with mag about 18.1). The new object is located at R.A. = 1h22m57s.38, Decl. = +33o27'58".0 (equinox 2000.0), which is 17".7 east and 20".1 south of the nucleus of NGC 495. A KAIT image of the same field on Oct. 15.3 (limiting mag about 19.0) showed nothing at this position. (Host galaxy info: v = 4114 km/s, 1.3'x0.8', (R')SB(s)0/a pec:)

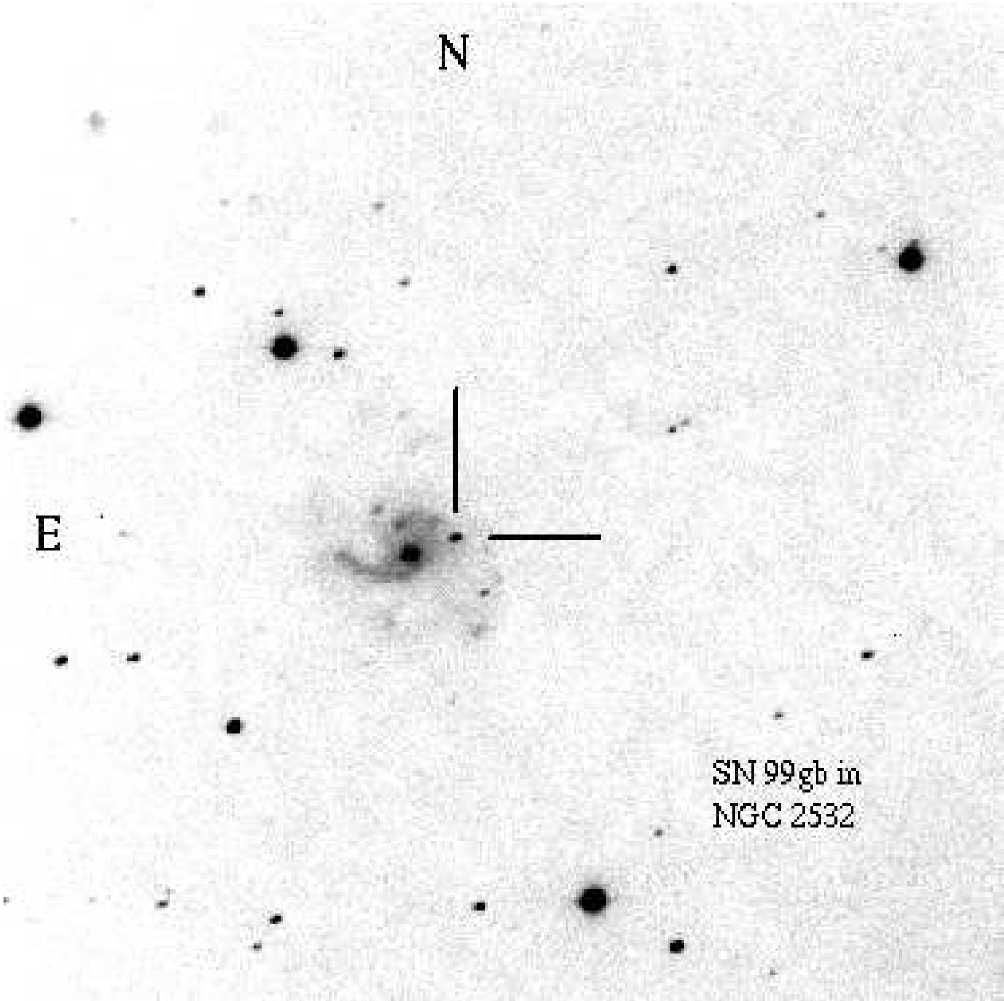


Fig. 7.— SUPERNOVA 1999gb in NGC 2532 (Type IIn).

IAU Circular No. 7316

A. Friedman and W. D. Li, University of California at Berkeley, on behalf of the Lick Observatory Supernova Search (cf. IAUC 6627, 7126), report the discovery with the 0.8-m Katzman Automatic Imaging Telescope (KAIT) of an apparent supernova in NGC 2532. SN 1999gb was discovered and confirmed on unfiltered images taken on Nov. 22.4 (mag about 16.1) and 23.4 UT (mag about 15.9). SN 1999gb is located at R.A. = 8h10m13s.70, Decl. = +33o57'29".8 (equinox 2000.0), which is 18".6 west and 6".2 north of the nucleus of NGC 2532. At the request of Li, an image taken by T. Puckett with the Puckett Observatory 0.60-m automated supernova patrol telescope on Nov. 23.4 also showed the new object. A KAIT image of the same field on Nov. 14.4 (limiting mag about 18.0) showed nothing at the position of SN 1999gb. (Host galaxy info: v = 5260 km/s, 2.2'x1.8', SAB(rs)c).

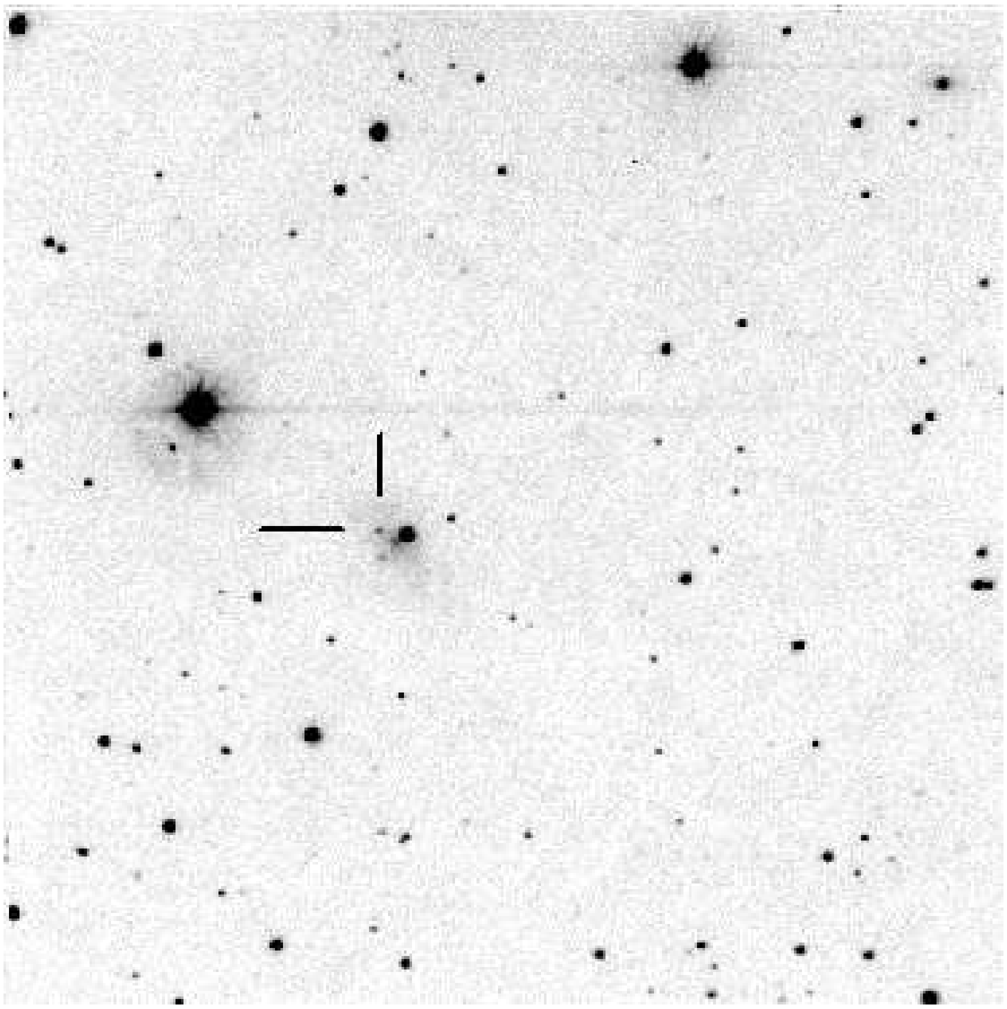


Fig. 8.— SUPERNOVA 2000fa IN UGC 3770 (Type Ia).

<u>IAU Circular No. 7533</u>

A. Friedman and W. D. Li, University of California at Berkeley, on behalf of LOTOSS (cf. IAUC 7514), report the discovery with the 0.8-m Katzman Automatic Imaging Telescope (KAIT) of an apparent supernova in UGC 3770 on an unfiltered image taken on Nov 30.5 UT (mag about 17.3). The SN was confirmed by an unfiltered image taken by M. Schwartz with the 0.5-m Tenagra III automatic telescope at magnitude about 17.0 on Dec 1.2 UT. The new object is located at R.A. = 7h15m29s.88, Decl. = +23o25'42".4 (equinox 2000.0), which is 6".6 east and 4".2 south of the nucleus of UGC 3770. KAIT images of the same field on Nov 24.5 UT (limiting magnitude about 18) and Nov 17.4 UT (limiting magnitude about 19.0) showed nothing at the position of the SN. (Host galaxy info: v = 6378 km/s; 1.0' x 0.6'; 14.9; Im).

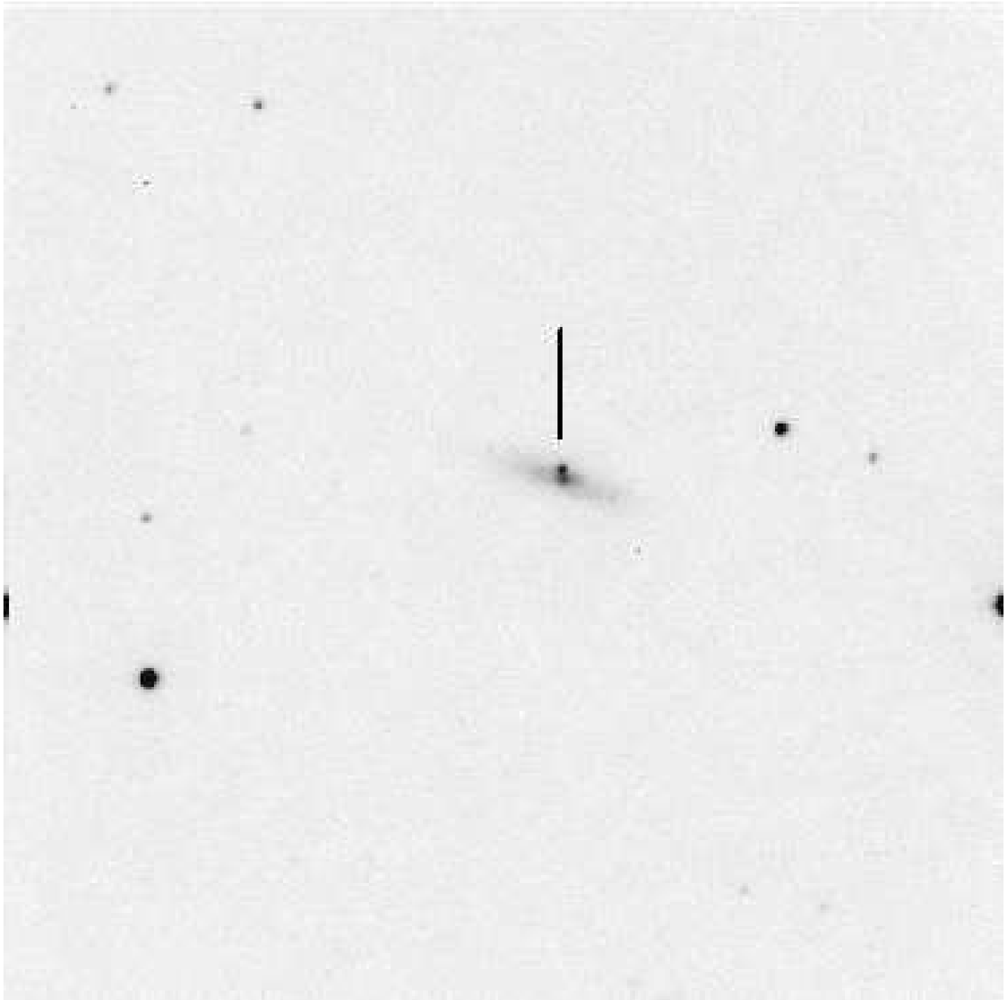


Fig. 9.— SUPERNOVA 2001L IN MCG -01-30-11 (Type Ia).

<u>IAU Circular No. 7566</u>

A. Friedman, W. D. Li, and R. Chornock, University of California at Berkeley, report the discovery by LOTOSS (cf. IAUC 7514) of a supernova (mag about 15.4) on an unfiltered image taken on Jan. 18.4 UT (and confirmed at mag about 15.7 on an earlier image taken on 2000 Dec. 31.4) with the 0.8-m Katzman Automatic Imaging Telescope. SN 2001L is located at R.A. = 11h36m48s.83, Decl. = -8 35'07".0 (equinox 2000.0), which is 0".3 east and 3".8 north of the nucleus of MCG -01-30-11. A KAIT image taken on 2000 Dec. 23.4 showed nothing at this position (limiting mag about 19.0). (Host galaxy info: v = 4567 km/s, 1.3'x0.3', 13.79, SAb: sp).

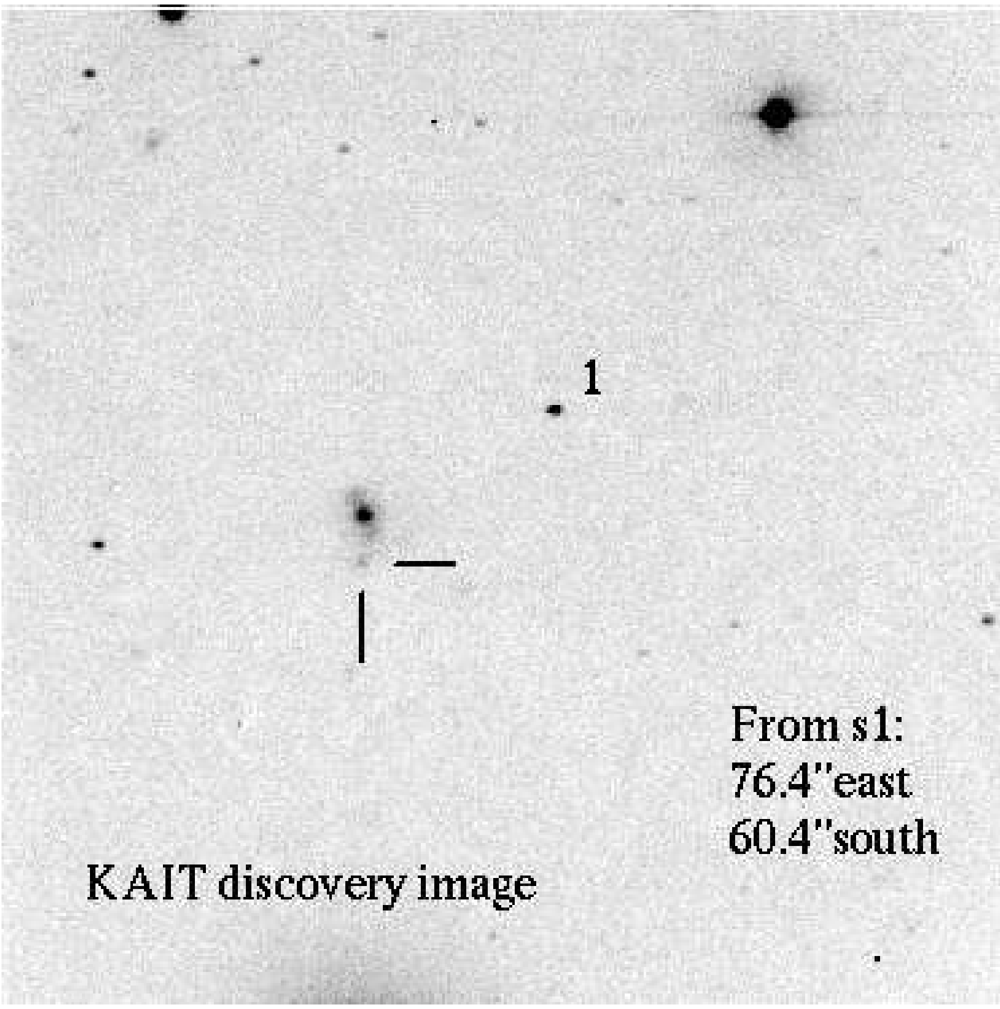


Fig. 10.— SUPERNOVA 2001ae IN IC 4229 (Type II).

IAU Circular No. 7597

A. Friedman and W. D. Li, University of California at Berkeley, on behalf of LOTOSS (cf. IAUC 7514), report the discovery of an apparent supernova (mag about 17.3) on unfiltered images taken on Mar. 15.5 and 16.3 UT with the 0.8-m Katzman Automatic Imaging Telescope (KAIT). SN 2001ae is located at R.A. = 13h22m26s.16, Decl. = -2 25'25".0 (equinox 2000.0), which is 1".0 east and 18".3 south of the nucleus of IC 4229. The new object was also confirmed on an unfiltered CCD image taken by M. Schwartz on Mar. 16.4 with the Tenagra Observatory 0.5-m automatic telescope. A KAIT image taken on Feb. 27.5 showed nothing at this position (limiting mag about 19.0). (Host galaxy info: v = 6984 km/s, 1.0'x0.7', 14.40, (R')SB(r)b pec:).

4. Photometry

I took a six-month break from the group during the Spring 2000 semester when I studied abroad at the University of New South Wales in Sydney, Australia. Since returning, I've continued working with the Filippenko group on a new research project in addition to the supernova search, where I am learning how to perform photometry, the precise measurement of the brightness of astronomical objects. I am in the process of working with Dr. Weidong Li, our resident expert on KAIT and key technical member of our group, to learn how to perform aperture and point-spread-function (PSF) fitting photometry on individual supernovae, along with the technique of galaxy subtraction. I now spend most of my time in the group focusing on the photometry project, while occasionally helping to train new undergraduates to do the supernova search.

It will be useful here to briefly discuss the theory of photometry. The following section will eventually become part of a training primer I am writing to help new undergraduates learn how to perform photometry with KAIT. The primer will include a general theory section that describes the foundations of photometry, independent of the astronomical object in question and independent of the observing instrumentation and analysis software. I will follow this with a section detailing the specifics of performing photometry on supernova images with KAIT. I will not go into those esoteric software details here, but I will discuss the theory of differential photometry in the next section. The following discussion assumes a basic familiarity with observational astronomy, i.e. magnitudes, pixel detectors, photons, sky background, etc. The training primer will not make this assumption, since it is directed towards students who might possibly have no astronomy background whatsoever.

4.1. Photometry Theory: Differential Photometry

Photometry is the precise measurement of the brightness of stars. To measure brightness, we want to know how many photons are incident on our detector, per unit time per unit area, and convert this number to astronomical magnitudes. However, this number is often very difficult to measure directly. What we can measure is the number of photons, N, that are actually detected in a given exposure time, t, in a given frequency band determined by your filter. By measuring these numbers again for a star of known magnitude under identical observational conditions, we can apply the technique of differential photometry to determine the brightness of our star. Using the technique of aperture photometry, we measure the sky background in an annulus around our star, and extract the star signal by subtracting the sky background from a small circular aperture containing the star.

To measure brightness, we want to know the flux density F_ν, i.e how much energy is hitting our detector per unit time, per unit area, in the relevant frequency interval, and convert this number to magnitudes. From the equation below, knowing the star's luminosity (i.e power per unit frequency interval), L_ν, we can get a distance, d.

$$F_\nu = \frac{L_\nu}{4\pi d^2} \ \text{ watts m}^{-2}\text{ Hz}^{-1}. \tag{1}$$

For a detector of area A, frequency band $\Delta\nu$, and photon detection efficiency η_ν, that measures N photons in a time t, we can also express F_ν as

$$F_\nu = \frac{Nh\nu}{At\Delta\nu\eta_\nu}. \tag{2}$$

However, as noted earlier, this number is often very difficult to measure directly. What we can measure directly is the number of photons N that are detected in a given exposure time t for a given filter. By measuring these numbers again for a star of known magnitude under identical observational conditions, we can apply the technique of differential photometry to determine the brightness of our star.

To do so, we must become familiar with the stellar magnitude system, where in general, the difference in magnitude between two stars is given by

$$m_\nu{}^* - m_\nu = -2.5\ log_{10}\left(\frac{F_\nu{}^*}{F_\nu}\right), \tag{3}$$

where $m_\nu{}^*$ is the magnitude of your star, m_ν is the magnitude of your standard star, and where $F_\nu{}^*$ and F_ν represent the flux of your star and your standard star, respectively. The reference scale is defined by the star Vega, which is defined as having $m_\nu = 0$ at all wavelengths. Setting $m_\nu = 0$ in the above equation, we can write the above equation in terms of the flux of Vega, $F_{\nu 0}$,

$$m_\nu{}^* = -2.5\ log_{10}\left(\frac{F_\nu{}^*}{F_{\nu 0}}\right) \tag{4}$$

Noting that from Equation 2, $F_\nu \propto (N^*/t^*)$ (where N^* is the total number of photons detected from your star and t^* is the exposure time), we can take advantage of the fact that the difference in magnitude of two stars is in terms of their flux ratio, which under identical observational conditions allows us to cancel the terms that are difficult to measure, namely A, $\Delta\nu$, and η_ν, leaving everything in terms of N^*, t^*, N, and t, where the latter two refer to measurements made on your standard star. From these relations, and some algebra, we can see that

$$m_\nu{}^* - m_\nu = -2.5\ log_{10}\left(\frac{N^* t}{t^* N}\right) \quad \Rightarrow \tag{5}$$

$$m_\nu{}^* = m_\nu - 2.5\ log_{10}\left(\frac{N^*}{t^*}\right) + 2.5\ log_{10}\left(\frac{N}{t}\right). \tag{6}$$

Using this equation, we can determine the magnitude of a selected star $m_\nu{}^*$, provided we also measure a standard star of known magnitude m_ν under identical conditions. Fortunately, many astronomers have done the difficult work of determining the magnitudes of a large numbers of standard stars using absolute photometry, where they actually measure the numbers we avoided measuring with differential photometry. These standard stars thus provide the foundation for the much easier task of differential photometry.

4.2. Photometry With KAIT

To perform photometry with KAIT, I start with a data set of dozens of follow-up CCD observations in different filters (U, B, V, R, and I) taken by KAIT starting from the date of discovery and extending for several months to a year. I then perform photometry on each image in order to produce the supernova's light curves in all the relevant filters. I am currently working with IRAF software packages, graphing scripts, occasionally Microsoft Excel, and several programs written by Weidong Li with the long-term goal of producing light curves for as many as 30 Type Ia supernovae.

To begin the process, using IRAF software packages, I performed photometry on a "practice" supernova (SN 2000cx), that occurred far from the nucleus of its host galaxy, and compared my light curves with the data that Weidong had already reduced, getting consistent results. That particular supernova has been discussed in great detail in the recent paper by Weidong, Alex, and their collaborators (Li et al. 2001) listed in the references. I am now in the process of learning galaxy subtraction, to deal with supernovae that occur closer to the nucleus of their host galaxy, and currently working with SN 1998dh. Galaxy subtraction is necessary because we want to isolate the light coming from the supernova alone and remove contaminating light from the host galaxy. If we have template images of the galaxy taken before the supernova explosion, this process is straightforward. In most cases, however, we do not, which means we must wait a year or so until the supernova fades and then take a calibration image of the host galaxy which we can subsequently subtract from our supernova images.

During the rest of this semester, and in the Spring before I attend graduate school, I plan to continue working with the group and apply the techniques of galaxy subtraction and PSF photometry to generate the light curves for SN 1998dh and a number of the 30 or so Type Ia supernovae that we have followed extensively with KAIT. Most of them have data that are simply waiting idly while we try to get good calibration images of the host galaxy, without which we can't even begin to do any of the galaxy subtraction or photometry. I also plan to help train the new undergraduates in the group, so we can efficiently approach the task of reducing the considerable amount of supernova data we have.

When we eventually publish these light curves, I will end up as second or third author on a paper along with Weidong and Alex, where we present the addition of the new data to our sample. The work is of considerable interest to astrophysics, especially to those in the supernovae field, as we would effectively be extending the current useful database of nearby supernovae by roughly 30%. In addition, our light curves are better sampled than those previously published (i.e. more follow-up images, closely spaced in time), and would likely become the new "training set" with which to compare all subsequent Type Ia supernovae light curves, providing even stricter tests of the accelerating universe result. All in all, I feel like I am making a positive contribution to the group, learning a tremendous amount, and definitely preparing me for possible Astrophysics research in graduate school, although right now I am leaning significantly towards astrophysics theory rather than observational astronomy, due mostly to the huge number of tantalizing unsolved problems I have been introduced to in the context of both my academic and research experiences here at Berkeley.

4.3. Images of Supernovae 2000cx and 1998dh

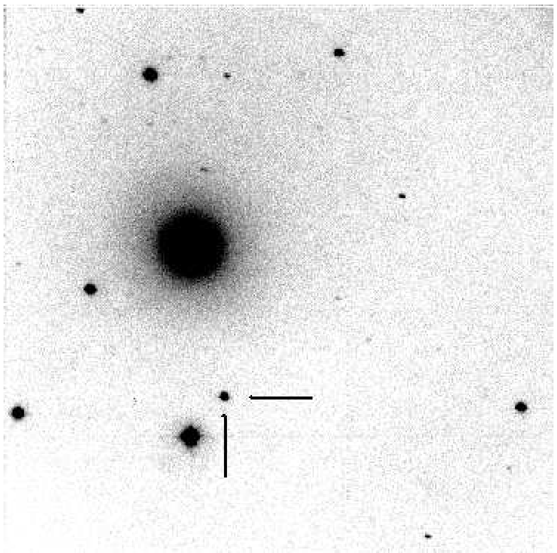


Fig. 11.— Supernova 2000cx in NGC 524. Notice that the supernova occurred at the outskirts of its host galaxy, allowing us to use the simple technique of differential aperture photometry, without having to perform the more complicated galaxy subtraction.

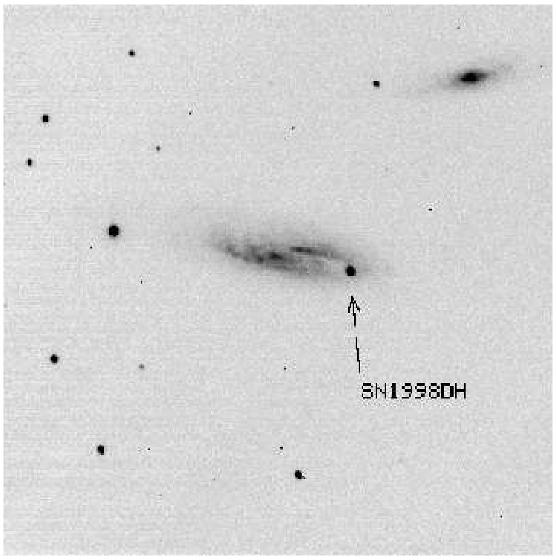
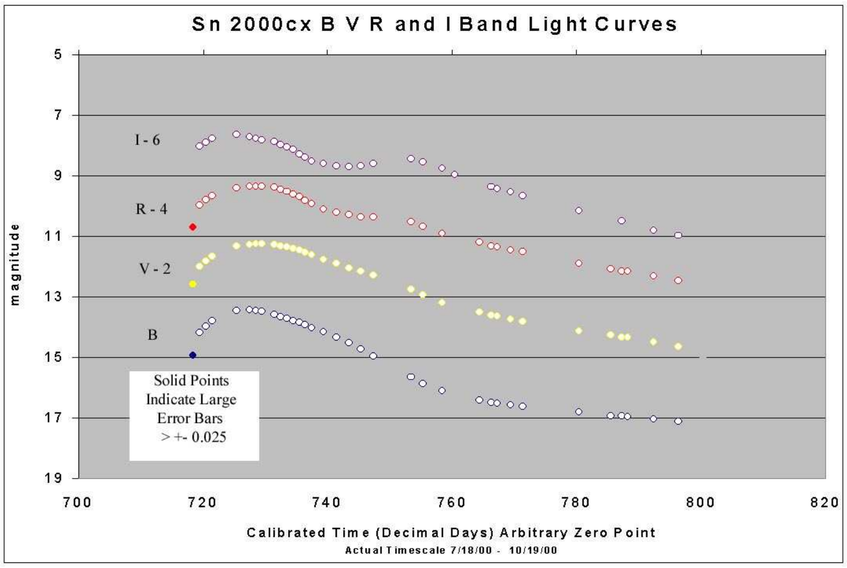


Fig. 12.— Supernova 1998dh in NGC 7541. Notice that this supernova occurred in the disk of its host galaxy, necessitating galaxy subtraction. This is the current supernova for which I am generating the light curves.

4.4. Light Curves of Supernova 2000cx



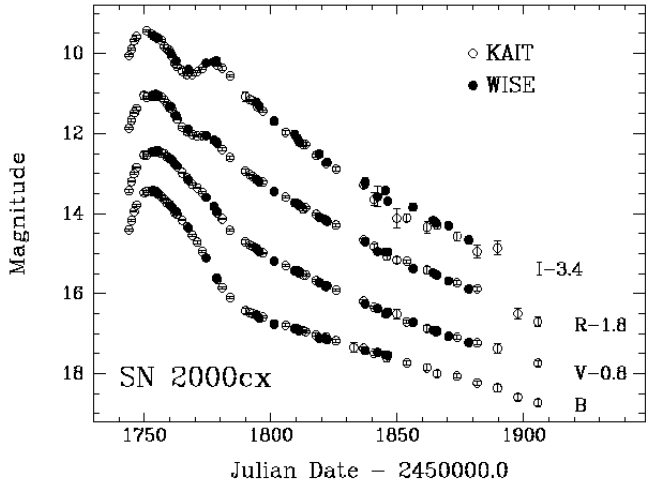


Fig. 13.— My B, V, R, and I-band light curves for SN 2000cx plotted on the standard magnitude scale vs. time in days (with arbitrary zero point). The peak magnitudes of the light curves in the different bands are arbitrarily shifted for clarity of presentation. Notice each light curve rising to a maximum followed by a decline. Notice also the second peak in the I and R bands. Below we have the published light curves of SN 2000cx taken from (Li et al. 2001). The scales are not the same, but the two sets of light curves are consistent.

5. Astronomy 122: The Infrared Undergraduate Astronomy Laboratory

This semester, I have also been involved in the perpetual motion experience that is the UC Berkeley Undergraduate Infrared Astronomy Laboratory taught by Professor James Graham. The amount I have learned in a mere 15 weeks has been exponential at the very least. In order to write up my labs, I have had to develop a competent familiarity with the Unix operating system, become proficient programming in IDL (Interactive Data Language), and learn to use the LaTeX document formatting language, in addition to the conceptual core material of the lab. The learning curve is pretty steep, and in a very short time we all become pseudo experts. There are very few courses that can boast such things. So far, in addition to Unix, IDL programming, and LaTeX I have learned a tremendous amount regarding statistics, error analysis, CCD pixel array imaging, and how to take images of stars with a robotic telescope (the Leuschner Observatory 30-inch telescope and Infrared Camera). These are some of the fundamental tools of a modern day astronomer.

The lab material has also been integrally related to my supernova research. My third lab report (out of 5), *"Photometric Observations with the Leuschner Telescope and Infrared Camera,"* considerably solidified my understanding of the photometry I have done for supernovae. Instead of simply using part of the massive IRAF software package infrastructure, or programs written by Weidong Li, this time I wrote the software to perform differential aperture photometry on individual stars from the ground up. Even though using the programs clearly requires an understanding of the underlying theoretical motivations and major workings of the program, it is no substitute for writing the program yourself. I have already applied what I have learned in this laboratory toward teaching some of the new undergraduates in my research group about differential photometry, hopefully providing them with a big picture view of what we are doing and why we are doing it in the first place. And I've even used my LaTeX knowledge to produce this very document. But on a broader level, the programming skills I acquire in this lab will be generally applicable to whatever topics I pursue as a theoretical astrophysicist. And perhaps most importantly, through this lab, I am learning more about what it takes to write a concise, clear, and honest scientific paper, and to present my results to a community of my peers.

6. The Big Picture: The Accelerating Universe

To tie things up, I would now like to discuss the major results of my research group and how my own research fits into the big picture. I find it quite important to maintain an understanding of why I am doing what I'm doing, and as such, I feel compelled to make sure I can explain it to anyone who is genuinely interested. I say this because I could easily search for supernovae and produce light curves successfully without really having a grasp on why I am doing the research or why anyone is interested in these things in the first place. Personally, I can not do science in a vacuum. As such, I always try to maintain a sense of the big picture and where I fit in.

In any case, as mentioned before, the major result of the High-Z Team, first announced in 1998, was that the Type Ia supernovae for which we we obtained light curves had peak brightnesses consistently 10 - 15% dimmer than would be expected from a coasting expanding universe with no acceleration or deceleration. When I joined the group in early 1999, the result was even more controversial than it is now because it flew in the face of conventional wisdom that the universe was surely decelerating, as gravity should eventually overcome the energy from the initial expansion. The results also resurrected serious interest in Einstein's Cosmological Constant Λ, which in theory could provide a cosmic antigravity force, which resists normal gravity and causes the acceleration. As it happened, the accelerating universe results were obtained independently through work done by the Supernova Cosmology Project headed by Dr. Saul Perlmutter at the Lawrence Berkeley National Laboratory. This gave both of our groups more confidence in a result that initially, neither team was willing to believe, let alone publicize to the astronomical community. Since then, crucial independent tests of the possible cosmological models have been performed using data from the Cosmic Microwave Background (CMB), most notably from the MAXIMA, BOOMERanG, and DASI experiments. These results are also consistent with the supernova results. Thus the present consensus from the astronomical community is that we have an accelerating universe with a nonzero cosmological constant, and an unwieldy list of questions regarding the true physical basis for this phenomenon.

6.1. Type Ia Supernovae

To use Type Ia supernovae to answer cosmological questions, we first look at a supernova's spectrum to determine its redshift. We can then classify it as a Type Ia supernovae if the spectrum is characterized by the lack of Hydrogen lines and the presence of strong Si II absorption. We use Type Ia supernovae in particular because there is strong theoretical basis for the idea that all Type Ia supernovae can be treated as "standard candles", in the sense that their intrinsic brightness does not vary much amongst populations of Type Ia supernovae exploding over cosmological timescales and thus at different redshifts. The assumption comes from the fact that we believe Type Ia supernovae occur due to the thermonuclear disruption of white dwarf stars near the Chandrasekhar mass limit of roughly 1.4 solar masses. Since these white dwarfs are thought to explode at roughly the same mass, and since mass is the major factor determining the luminosity of the explosion, it is thus reasonable to conclude that the intrinsic brightness of these explosions should be roughly uniform. This allows us to make the assumption that Type Ia supernovae can be treated as "standard candles", in the sense that their intrinsic brightness does not vary much amongst populations of Type Ia supernovae exploding over cosmological timescales and thus at different redshifts.

Assuming that Type Ia supernovae are perfect standard candles, we can use them as relatively robust cosmological distance indicators. Traditionally, we get a distance by measuring the supernova's apparent peak brightness from its observed light curve, and comparing it with that of other Type Ia supernovae that exploded in galaxies whose distance we have determined independently, for example using Cepheid variable stars. Knowing both the distance and the intrinsic brightness of the supernova, we can compare the apparent brightness we observe to the apparent brightness we would expect to see from models with or without cosmological acceleration, and test which model is most consistent with observations.

However, comparison between high and low redshift supernovae in different environments is necessary to justify the assumption that Type Ia supernovae can indeed be used as reliable standard candles. Other effects, such as evolution of the chemical composition of successive generations of these objects, or reddening by interstellar dust, could in theory change the intrinsic brightness of Type Ia supernovae as a function of redshift. Testing this assumption and providing the foundation for the understanding the high redshift supernovae is a primary focus of the particular supernova search that I am involved in. We look for nearby, low redshift supernovae ($z < 0.1$), whose spectra and light curves we determine and then compare and combine with those of the high redshift supernovae found by the High-Z Team. By comparing both high and low redshift supernovae, we can test for chemical evolution of the progenitor systems, and extend our tests of cosmological models to regimes that require both high and low redshift data points.

7. Conclusion

The supernova search is a great way for students to become involved in undergraduate research and make an impact quickly while still having a ways to go in regard to learning astronomy. Having done the search, it was a good idea to move onto photometry, which I hope to finish next semester and end up as second or third author in a paper with Weidong and Alex. My understanding of photometry has risen exponentially this semester even though I haven't had a tremendous amount of time to actually do any research for the supernova group. I had been doing KAIT photometry for supernovae for over a year, but I had been using mostly automatic programs and IRAF packages, which allowed me to get through the process without really understanding the fundamentals of photometry. Thanks to the Infrared Astronomy Laboratory course, I basically had to write the software from the ground up and re-invent the wheel. The idea of performing differential photometry which involves measuring more tractable quantities than absolute photometry is fantastic to me, now that I finally get it. And now as the senior undergraduate in the group, I hope to pass on that understanding to our younger members.

As a potential theoretical astrophysicist, I'm glad I have had the opportunity to work for so long in an observational research group. My future work will be better for it if I never forget the symbiotic nature of the connection between theory and experiment. I'm interested in pursuing several questions in graduate school which relate to my undergraduate research, including the theory of Type Ia supernovae, testing the assumptions behind the accelerating universe results, and investigating the physical basis for the cosmological constant Λ. Unfortunately, I don't have the time to go into them here. That's for the rest of my career.

8. Acknowledgments/References

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2. Li W.D., Filippenko A.V, Friedman, A. et al. "Photometric Observations of 30 Nearby Type Ia Supernovae." Paper In progress.

3. Last April, as part of my honors thesis, I spoke at the Berkeley Undergraduate Research Poster presentation organized by the Society of Physics Students, discussing the accelerating universe results and my role in the supernova search.

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