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The Lick Observatory Supernova Search with the Katzman Automatic Imaging Telescope

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Abstract. The Katzman Automatic Imaging Telescope (KAIT) at Lick Observatory is a fully robotic 0.76-m reflector equipped with a CCD imaging camera. Its telescope control system checks the weather, opens the dome, points to the desired objects, finds and acquires guide stars, exposes, stores the data, and manipulates the data without human intervention. There is a 20-slot filter wheel, including $UBVRI$. Five-minute guided exposures yield detections of stars at $R \approx 20$ mag when the seeing is good ($\leq 2''$).

One of our main goals is to discover nearby supernovae (SNe; redshifts generally less than 5000 km s^{-1}), to be used for a variety of studies. Special emphasis is placed on finding them well before maximum brightness. A limit of $\sim$ 19 mag is reached in the 25-sec unfiltered, unguided exposures of our Lick Observatory Supernova Search (LOSS). We can observe over 1200 galaxies in a long night, and we try to cycle back to the same galaxies after 3 to 4 nights. Our software automatically subtracts template images from new observations and identifies supernova candidates that are subsequently examined by student research assistants. LOSS found 20 SNe in 1998, 40 in 1999, and 36 in 2000, making KAIT the world's most successful search engine for nearby SNe. We also find novae in the Local Group, comets, asteroids, and cataclysmic variables. Multi-filter follow-up photometry is conducted of the most important SNe, and all objects are monitored in unfiltered mode. A Web page describing LOSS is at http://astro.berkeley.edu/~bait/kait.html .

1. Introduction

KAIT is the third robotic telescope in the Berkeley Automatic Imaging Telescope (BAIT) program. The predecessors to KAIT were two telescopes developed at the Leuschner Observatory, which is located about 10 miles east of the University of California, Berkeley campus (U. C. Berkeley). The first telescope, a 0.50-m Cassegrain system built in 1954, was retrofitted with computers and started gathering data automatically in January 1992. In November 1992, it was joined by a 0.76-m Ritchey-Chrétien telescope. The two BAIT systems were fully automated, and were capable of carrying out various kinds of imaging studies such as searching for and monitoring supernovae (SNe); monitoring other time-variable objects like active galactic nuclei, quasars, and novae; studying solar-system objects such as planets, comets, asteroids, and the Moon; and allowing student access for astronomy laboratory classes. The SN search at that time was called the Leuschner Observatory Supernova Search. More thorough discussions of BAIT can be found in Treffers, Richmond, & Filippenko (1992), Richmond, Treffers, & Filippenko (1993), and Treffers et al. (1995).

Over the years the rising cost to maintain and upgrade the Leuschner facility, which has at best marginal weather for observing (often foggy and with mediocre seeing), prompted us to look for a better site for the BAIT program. We found a home for a new telescope at Lick Observatory on Mt. Hamilton, California, in an old but renovated dome which previously housed a 0.6-m telescope. Lick Observatory, located at an elevation of 4200 feet, has better seeing and clearer skies than Leuschner, has a crew of mountain engineers and telescope operators to respond to unforeseen problems, and is only a two-hour drive from the U. C. Berkeley campus. KAIT began taking data around August 1996, and it was officially dedicated on October 25, 1996.

The Lick Observatory Supernova Search (LOSS), the primary project carried out with KAIT, discovered its first SN in 1997 (SN 1997bs — Treffers et al. 1997; Van Dyk et al. 2000). Many improvements were made to the telescope hardware and the system software in 1998, and LOSS discovered 20 SNe that year. 40 SNe were discovered in 1999, and 36 in 2000, making LOSS the world's most successful search for nearby SNe.

In this paper, we report the KAIT system hardware and software in Section 2, the details of the SN search in Section 3, and our conclusions in Section 4.

2. The System Hardware and Software

KAIT possesses a 0.76-m (30-inch) diameter primary with a Ritchey-Chrétien mirror set. The telescope mount, designed by Autoscope Corporation, has a focal ratio of $f/8.2$, which yields a plate scale of $33\overset{''}{.}2$ mm^{-1} at the focal plane. At the back end of the telescope, the primary beam goes through an open aperture in a diagonal mirror, passes through the filter wheel assembly, and gets imaged onto a CCD. For guiding, the peripheral light from the main beam that strikes the diagonal mirror gets reflected into a guider CCD camera, which is mounted on an X-Y translation stage that can move to "pick-off" light from any part of the diagonal mirror.

Before July 1998, we had been using a Photometrics CCD camera with a Thompson TH 7895 chip as the main detector for KAIT. This is a front-illuminated chip and has rather poor blue response. A new detector, an Apogee

AP7 CCD camera with a SITe 512 × 512 pixel back-illuminated chip (pixel size 24 μm), was installed in KAIT in July 1998. The new CCD camera has much better quantum efficiency than the old one, and its field of view is $6'.8 \times 6'.8$ ($0''.8$ pixel^{-1}). The camera is cooled thermoelectrically by forced air to about 60° C below the ambient temperature.

KAIT has a filter wheel with 20 slots, including a set of standard Johnson *UBV* and Cousins *RI* filters. Five-minute guided *R*-band exposures yield detections of stars at ~ 20 mag when the seeing is good ($\leq 2''$).

A weather station is crucial for robotic observations. The KAIT weather station has an array of sensors monitoring the outside temperature, the relative humidity, wind speed, rain, and clouds. The cloud sensor is an infrared detector with a 12–13 μm filter that points directly overhead. If a single drop of water hits the rain sensor, it closes the dome circuit that directly initiates the closing of the dome slit, bypassing all the control software. As an added safety feature, during normal operation a "keep open" command is issued every two minutes by the control software to the dome slit, without which it automatically closes itself.

There are one workstation and three personal computers (PCs) that control the operation of the system. One PC is responsible for the telescope, the dome, the slit, and the weather station; another PC controls the Apogee imaging camera; the third PC controls the autoguider camera and the filter wheel. These PCs serve as "slaves" that "listen" to the commands given by the "master" computer, the workstation. Upon receipt of a command from the master computer, the PCs go off and execute the orders; meanwhile they cannot receive any more commands. The master computer coordinating the entire operation has to perform several tasks: (1) scheduling observations, (2) forwarding commands to appropriate PCs to perform observations, (3) logging data and error reports, (4) accepting remote logins to change schedules or inspect telescope operation, and (5) allowing manual operations of the system if necessary.

A typical workday for KAIT proceeds as follows. The system starts up at 3:00 pm. The status of all the hardware is checked and initialized, and the observations for the night are scheduled according to all the active request files. When the Sun is 10° above the horizon (usually about one hour before sunset), the dome slit is opened and the CCD camera is cooled. When the Sun is 5° above the horizon, trial flatfield images are taken for the filters that will be used during the night, but usually it is too early and the CCD is saturated in very short exposures. The system then sleeps for a short time and tries to image again. Useful flatfields are taken when the images have reasonable counts. The exposure time is gradually increased to compensate for the darkening of the sky. The final flatfield images are combined for each filter to improve the signal-to-noise ratio.

After flatfield observations are completed, a focus-detecting procedure is executed three times to find the best focus for the telescope. The procedure consists of taking a series of 36 exposures of a bright star in a single image, slightly changing the focus and offsetting the telescope between consecutive exposures. A program then analyzes the image and determines which focus value gave the smallest full-width at half maximum (FWHM) for the star. The entire procedure takes about 5 minutes to run. It is repeated after the first 20 minutes of observations, again after the next 40 minutes, and subsequently every 80 minutes; this is done because the focus of KAIT is not stable.

The arranged targets are observed when the Sun is 8° below the horizon. Each target can be observed and processed in a different manner. For example, photometric observations require the images to be bias subtracted, dark subtracted, and flatfielded; SN search images, on the other hand, are automatically transferred to a computer at the U. C. Berkeley campus to be processed. Observations may use different filters, different exposure times, and may or may not require autoguiding.

During bad weather such as high winds, high humidity, rain, or totally overcast skies, the slit is closed automatically, and the system takes a "nap" for 10 minutes. It tries to do observations again after the nap, and keeps trying every 10 minutes thereafter.

At the end of the night the system is shut down automatically: the dome slit is closed, the telescope is placed at a specific position, and the tracking is turned off. E-mail messages are sent out to users who have requested observations. Many bias and dark-current images are obtained, averaged, and saved for the next night. The system then goes to "sleep" until it wakes up again at 3:00 pm.

3. The Lick Observatory Supernova Search (LOSS)

The primary science project carried out with KAIT is LOSS, whose sample consists of about 5,000 galaxies. The majority of the LOSS galaxies come from the Third Reference Catalogue of Bright Galaxies (de Vaucouleurs 1991), and the others are from the Uppsala General Catalog of Galaxies (Nilson 1973). We could have selected a larger number of galaxies to increase the number of SN discoveries, but we chose to use the restricted sample (at least for our initial search) in order to find most of the SNe well before maximum brightness.

The galaxies are observed with 25-second unfiltered and unguided exposures, and the typical limiting magnitude of the images is $\sim$ 19. Much effort has been made to improve the efficiency of the system, which rose to about 100 images per hour by early 2001. KAIT can observe over 1200 images in a clear winter night. Because of this high efficiency, we can cycle back to the same galaxies after 3 to 4 nights.

The program to automatically process images and detect SNe is an important part of LOSS because with many images observed each night, it is very difficult to visually compare the images to find new objects — it is time-consuming, and one can easily miss SNe in complicated regions. The LOSS image processing software consists of many programs written in C, Fortran, and

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IRAF scripts, which combine to perform all necessary tasks for image processing: making (and replacing) templates, image subtraction, candidate detection, and checking of results.

The template-making program studies each image and stores in several files properties such as the positions of the stars, the set of stars used for point-spread-function (PSF) matching and intensity transformation, and the locations of the saturated stars.

The image-subtraction routine is one of the most important programs for LOSS. It first detects the stars in the new image, then uses their positions to compute the shift and rotation between the new and the template images, and subsequently aligns them. The PSF-matching stars are used to make the two images have the same PSF. An intensity-transformation region, which is usually an area that includes one of the PSF-matching stars, is studied in both images to derive the intensity ratio between them. The intensity of the new image is then transformed to that of the template. After these transformations, the new and the template images have the same intensity level, the same PSF, and are properly aligned. The subtracted image is then obtained by a simple arithmetic subtraction of the template from the new image.

The candidate detection program finds all new objects in the subtracted images, and classifies them into one of the following categories: (1) residual from imperfect subtraction, if the candidate is within a certain radius of a bright star; (2) cosmic ray, if the candidate has a very small FWHM; and (3) real SN candidate.

Each day, a research assistant (from a group of several undergraduate students, and sometimes graduate students) uses the result-checking program to examine the results of the image processing. The new image, the template, and the subtracted image are all displayed on the screen, with the SN candidates marked with red circles and the cosmic rays with green circles. Promising SN candidates are then reobserved, and the confirmed SNe are reported to the Central Bureau of Astronomical Telegrams, where the International Astronomical Union Circulars are issued. The undergraduate assistants also sometimes identify SNe that were missed by the detection program (e.g., those near poorly subtracted stars, or those that are fainter than the automatic detection limit).

LOSS found one SN in 1997 (SN 1997bs), 20 SNe in 1998, 40 SNe in 1999, and 36 in 2000. Tables 1 and 2 list the SNe discovered in 1998 and 1999, respectively. Because of the small interval between LOSS observations of a given galaxy, most of the LOSS SNe were discovered well before their maximum brightness. For this reason, LOSS provides excellent SNe for individual detailed studies. The LOSS SN sample is also ideal for statistical studies of SNe, such as the SN rates in galaxies of different Hubble types.

LOSS also discovered 4 novae in nearby galaxies (e.g., M31) out of the 7 discovered worldwide in 1998, and 7 out of 11 in 1999. Two cataclysmic variable stars were discovered in 1998 and one was discovered in 1999.

Table 1. LOSS SN discoveries in 1998

SN name	Host galaxy	Date of discovery	mag at discovery	SN type
1998W	NGC 3075	Mar 16	17.3	II
1998Y	NGC 2415	Mar 16	18.3	II
1998bm	IC 2458	Apr 21	17.6	II
1998bn	NGC 4462	Apr 17	17.4	Ia
1998cc	NGC 5172	May 15	18.1	Ib
1998cu	IC 1525	Jun 29	18.4	II
1998de	NGC 252	Jul 23	18.4	Ia-pec
1998dh	NGC 7541	Jul 20	16.8	Ia
1998dj	NGC 788	Aug 08	16.1	Ia
1998dk	UGC 139	Aug 19	17.6	Ia
1998dl	NGC 1084	Aug 20	16.0	II
1998dm	MCG -01-4-44	Aug 22	16.8	Ia
1998dt	NGC 945	Sep 01	17.7	Ib
1998dx	UGC 11149	Sep 10	18.3	Ia
1998eb	NGC 1961	Sep 17	17.8	Ia
1998ef	UGC 646	Oct 18	15.2	Ia
1998en	UGC 3645	Oct 30	18.4	II
1998es	NGC 632	Nov 13	14.6	Ia-pec
1998fa	UGC 3513	Dec 25	18.2	IIb
1998fe	NGC 6027D	Jul 19	18.0	...

Note: See Filippenko (1997) for a discussion of SN types.

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Table 2. LOSS SN discoveries in 1999

SN name	Host galaxy	Date of dis.	mag at discovery	SN type
1999A	NGC 5874	Jan 10	18.3	II
1999ac	NGC 6063	Feb 26	15.2	Ia-pec
1999bg	IC 758	Mar 28	15.5	II
1999bh	NGC 3435	Mar 29	16.8	Ia-pec
1999br	NGC 4900	Apr 12	17.5	II
1999bu	NGC 3786	Apr 16	17.5	Ic
1999bw	NGC 3198	Apr 20	17.8	IIn
1999bx	Anon.	Apr 26	16.5	II
1999by	NGC 2841	Apr 30	15.0	Ia-pec
1999bz	UGC 8959	May 01	17.6	Ic
1999cd	NGC 3646	May 14	17.9	II
1999ce	Anon.	May 16	18.3	Ia
1999cl	NGC 4501	May 29	16.4	Ia
1999co	Anon.	Jun 18	17.4	II
1999cp	NGC 5468	Jun 18	18.2	Ia
1999cq	UGC 11268	Jun 25	15.8	Ib/c
1999cw	MCG-01-02-00	Jun 28	14.2	Ia-pec
1999da	NGC 6411	Jul 05	17.0	Ia-pec
1999dg	UGC 9758	Jul 23	16.7	Ia-pec
1999dh	IC 211	Jul 23	15.4	II
1999dk	UGC 1087	Aug 12	16.7	Ia
1999do	MRK 929	Aug 20	17.4	Ia
1999dp	UGC 3046	Sep 02	18.2	II
1999dq	NGC 976	Sep 02	16.3	Ia-pec
1999eb	NGC 664	Oct 02	16.2	IIn
1999ec	NGC 2207	Oct 03	17.9	Ib
1999ed	UGC 3555	Oct 05	17.8	II
1999ej	NGC 495	Oct 18	18.1	Ia
1999ek	UGC 3329	Oct 20	18.1	Ia
1999em	NGC 1637	Oct 29	13.5	II
1999ew	NGC 3677	Nov 13	16.5	II
1999gb	NGC 2532	Nov 22	16.2	IIn
1999gd	NGC 2623	Nov 24	16.6	Ia
1999ge	NGC 309	Nov 27	15.6	II
1999gf	UGC 5515	Nov 24	18.2	Ia
1999gm	PGC 24106	Dec 15	17.3	Ia
1999go	NGC 1376	Dec 23	15.5	II
1999gp	UGC 1993	Dec 23	17.3	Ia-pec
1999gq	NGC 4523	Dec 23	14.5	II
1999gs	NGC 4725	Dec 28	19.3	...

Note: See Filippenko (1997) for a discussion of SN types.

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The KAIT CCD camera has quite a small field of view, yet two comets were caught in the course of LOSS. Comet C/1998Y2 (LI) was discovered on December 25, 1998 (Li 1998), and Comet 1999E1 (LI) was discovered on March 13, 1999 (Li & Modjaz 1999).

Follow-up observations for the discovered SNe are emphasized during the course of LOSS. Our goal is to build up a multicolor photometric database for nearby SNe. Because of the early discoveries of most LOSS SNe, our light curves usually have good coverage from pre-maximum brightening to post-maximum decline. Moreover, all SNe discovered by LOSS are automatically monitored in unfiltered mode as a byproduct of our search. Examples of our light curves of SNe are presented in Figure 1. Journal papers that summarize part of the LOSS data include the study of SN 1997br (Ia; Li et al. 1999), SN 1997bs (IIn; Van Dyk et al. 2000), SN 1998bu (Ia; Jha et al. 1999), SN 1998de (Ia; Modjaz et al. 2001), SN 1999cq (Ic; Matheson et al. 2000), the rise time of SNe Ia (Riess et al. 1999a, 1999b), the peculiarity rate of SNe Ia (Li et al. 2001), and observations of SNe Ib/Ic (Matheson et al. 2001). Several more papers are now in preparation.

4. Conclusions

In this paper we reported the hardware and software control system of KAIT and the details of LOSS. KAIT is a fully robotic telescope that operates by itself without human intervention. LOSS discovered a total of 96 SNe in 1998–2000, making KAIT the world's most prolific search engine for nearby supernovae.

The successful operation of KAIT demonstrates the obvious benefits of robotic telescopes: they are far more efficient than humans at performing repetitive tasks, and do not make mistakes because of physical fatigue. They eliminate the need for astronomers to travel great distances for observing, therefore saving them both time and money, especially on marginal observing nights/days. Robotic telescopes need little human support, which frees telescope operators to perform other duties. Complete automation permits a telescope to be operated at a site that is ideal for science but not for human habitat. Finally, the astronomical community can greatly benefit by coordinating automated telescopes at different places in order to observe targets of opportunity if one site is down. It also prevents redundant observing of targets, thereby increasing the overall operation and the science efficiency.

As telescopes with increasingly larger collecting areas dominate the astronomical scene, many small telescopes below 2-m aperture are slowly being phased out due to the cost of operation. But as witnessed with KAIT and other similar systems (numerous examples of which are described in these *Proceedings*), small automated telescopes unveil new realms of observations that were once thought to be unfeasible because of the demand on the time and stamina of an observer. Moreover, robotic telescopes provide invaluable learning experiences for astronomy students, and offer exciting exercises for laboratory curricula. Automation of small telescopes will allow them to continue occupying a unique role in astronomy for many years.

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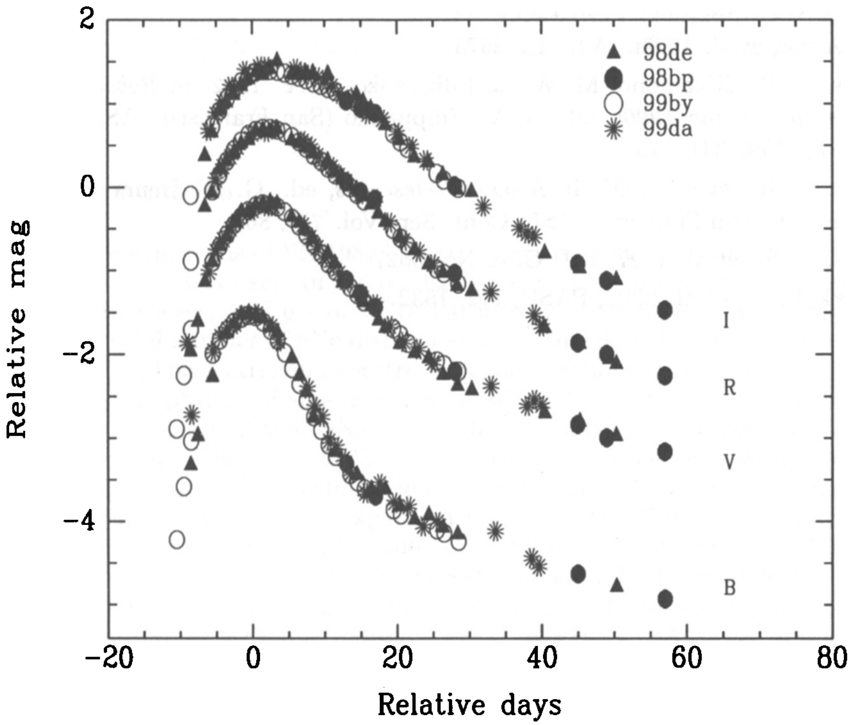

Figure 1. Examples of SN Ia light curves obtained during the course of LOSS.

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