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TITLE

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AN AUTOMATED SUPERNova SEARCH AND THE DESIGN AND STRATEGY

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Abstract
The design considerations for an automated supernova search are reviewed. If supernova are to be found a week after explosion well before light maximum of both Types I and II, and if a rate of finding of 52 per year is justified, then one needs to keep roughly 5000 galaxies under surveillance out of a full set of 15,000 galaxies at ≤50 Mpc distance. For detection at 1% of Type I maximum light requires (1) a 30-inch telescope, (2) 10 photoelectrons per pixel threshold, (3) a 128 × 128 pixel photodetector operating with 3-second integration time, and (4) 2 seconds to slew and settle within 1°. A system designed to perform this function in real-time is described.

1. Introduction
In 1964 it became evident that an automated supernova search was feasible because of the development of computers and automation. Twenty years ago in 1967 the National Science Foundation funded a project at New Mexico Institute of Mining and Technology to develop an automated supernova search. The design and strategy of this project are dictated by several scientific questions that still remain valid today. These are
1. The mechanism of supernova both the explosion and the optical emission.

2. The conditions of stellar evolution that lead to the various supernova characteristics.

3. The relationship of presupernova evolution to the galaxy type in which it is found.

2. Scientific Objective

One possible outcome from an understanding and the assembly of a large statistical data base on supernova would be the possibility of using supernova as the distance scale measurement of our universe. This could either be the Basde-Westerlink method of supernova distance by the luminosity and Doppler shift of its photosphere, or the even more tantalizing possibility that Type I supernova of a given class are sufficiently homogeneous to be used as a standard candle (Colgate 1979). An understanding of the supernova mechanism, both explosion and light curve, demands that many supernova be observed early enough in their light curve. This is so that the shock strength emerging from the photosphere that produces the early light curve can be separated from the later luminosity due to the diffusion of radiant heat from radioactive decay.

3. Early Detection

In the case of Type I supernova, in order that the light maximum be known with accuracy, this requires finding the supernova within a week to ten days of the explosion. Similarly, the observation of the shock wave energy before the radioactive heating requires observation within
one week of the time of explosion. Comparison of the shock derived part of the optical emission as compared to the radioactive heating should enable one to derive the ejected mass and the strength of the explosion. This is particularly pertinent to understanding whether all Type I supernova are thermonuclear or as some of us believe that they are better interpreted as collapse to a neutron star with the same mass ejection mechanism as Type II's. For Type II supernova we would like to know the statistics of those that appear as 1987a versus the standard Type II supernova. The standard Type II are the explosion by core collapse of a star in the red giant stage. The factor of 100 difference in luminosity is one more particular challenge to an automated supernova search.

The first decision that determines much of the strategy of the supernova search is the question of how many supernova need be found and how early in their light curve in order to justify the effort.

4. Useful Discovery Rate

Very early in the project we felt that a discovery rate of one new supernova per week, one week before light maximum, would be our goal. This meant that in the course of the year there was a reasonable probability of finding perhaps one supernova as early as 24-hours old and this would lead to observation of the very earliest high velocity shock ejected matter as was observed in 1987a. In addition one would like to observe these supernova in average type galaxies in order that the galaxy type versus supernova relationship be expressed. This does not mean one should avoid those few galaxies of extremely high supernova
rate, but just that the search should not be planned based on the sole observation of a sufficient number of extreme supernova producers.

5. Number of Galaxies Observed
One is led to expect roughly one supernova per 100 years per average galaxy, and with the requirement of finding one supernova per week, this means that something like 5000 galaxies must be under weekly surveillance at all times. If 5000 galaxies must be under surveillance, one then asks what total number of galaxies must comprise the full set of galaxies of the search, and therefore, what is the typical mean distance at which one can expect these galaxies to lie. With a distance and the luminosity of supernova, one can then design a telescope and detector system necessary to find them. In addition we believe that each observation should be followed by a real-time analysis so that both a rescan can be made for confirmation and immediate observations can start.

6. Total Catalogue of Galaxies and Mean Distance
In order to avoid extinction effects one expects to use something like 90° of the sky, and with the typical eight hour viewing period (120°), the combination represents roughly 50% of the observable sky. When one includes a southern exclusion of a third, the total set of galaxies required for monitoring becomes 15,000. If one then uses the mean density of galaxies in the supercluster as 0.02 galaxies per Mpc³ (Allen 1976), then one obtains a mean distance to the set of 15,000 galaxies of 50 Mpc. This then becomes the distance at which a supernova must be found in a typical search galaxy.
7. Observation Rate

The time available for detecting a supernova in our typical galaxy at 50 Mpc is determined by the number of observations that must be made in a single night. We exclude a factor of two because of moon and another factor of two because of weather (optimistic) and determine that we then might optimistically have available two nights a week for good observations in the typical weather patterns of the southwest. Since 5000 galaxies that must be kept under surveillance means that we must observe 2500 galaxies per night in something less than eight hours. This corresponds to observing a galaxy and recognizing whether it has a supernova in the time of roughly 10 seconds.

8. Telescope Stiffness

We planned originally to observe a galaxy field and have a computer processed image determine the presence of the supernova and slew to the next galaxy with its subsequent observation all within the time of 5 seconds. This placed rather stringent limitations on the system. This meant that with a reasonable division of the available time that the slewing should take no more than 2 seconds, galaxy to galaxy, and the integration of the image no more than 3 seconds. Other functions would be overlapped. This division of time determined the estimated stiffness of the telescope necessary in order to slew and settle to a small enough vibration amplitude of a mean distance of 1° between galaxies in 2 seconds. This necessary stiffness is of the order of 3°/s², which corresponds to an oscillating frequency of something like several Hz.
9. Mirror Size

The size of the telescope's primary mirror is determined by the necessity of obtaining enough signal per resolution element (pixel) in the galaxy field per supernova within the integration time of 3 seconds and at a luminosity, a small enough fraction of maximum, to correspond to an early supernova detection. We felt we should be able to detect a supernova in a galaxy at 1% of its maximum luminosity for a typical Type I supernova. One should keep in mind that the typical Type II supernova is of the order of 10% of the maximum of Type I's and now that 1987a has been observed, the blue supergiant Type II's are 1% of maximum luminosity of a Type I supernova. One percent of the luminosity of a Type I supernova, $10^{43}$ ergs/s, corresponds to 3.5 photons per square centimeter per second at the earth assuming a 50% extinction through our own galaxy and earth's atmosphere. We then chose a 30-inch mirror, which with an optical transmission of 50%, gives us roughly $10^4$ photons/second at the input of our photon detector. This photon signal must be converted to a photoelectron signal in either a solid-state detector or a scanning photoelectron detector.

10. Image Detection

At the time of the start of this project there were only image orthicons available and after a period of research led originally by Hynak, Dunlap and Powell of Corralitos Observatory (Hynak and Dunlap 1973), we were finally able to use the newer intensified silicon target vidicons (Colgate, Moore, and Colburn 1975). The advantage of the silicon target tubes is that the signal readout by the electron beam is positive as opposed to a negative deflection signal in an image orthicon. Therefore
the dynamic range of the silicon target tubes is larger, \( \approx 100 \) compared to approximately 10 for the image orthicon. A 10% quantum efficiency therefore gives us a signal of \( 10^3 \) photoelectrons for the average Type I supernova at maximum luminosity. One percent of this is ten photoelectrons total per second. If one divides the optical signal into typically three image elements, this corresponds to three photoelectrons per image element per second. When integrated over three seconds this gives us our threshold detection level per image element of 10 photoelectrons.

A solid-state detector with 50% quantum efficiency would receive 50 electrons per image element, which has been close to the noise figure of cooled detectors in recent years. However the very latest developments for the Hubble Space Telescope have brought this noise number down to ten electrons per image element and so represents a significantly improved sensitivity.

The digitized automatic astronomy telescope project is still based upon an image detection threshold of 10 photoelectrons per image element using an ISIT vidicon. This corresponds to something close to 19th magnitude in the original specifications but is now approximately 17th magnitude where we are no longer using the initial magnetic intensifier.

We have chosen a minimum of three image elements to encompass 90% of the photon signal from a stellar image because less than this results in too large a fluctuation in the integrated signal from aliasing. In practice we find that for our present system between two and three image elements is a reasonable estimate of the distribution of the light from a stellar image. Of course if one distributes the light in a larger number of pixels, the statistical fluctuation per pixel becomes larger and the detection threshold becomes more uncertain. The detection of a mean
signal of ten photoelectrons per image element naturally has both fluctuations in itself as well as any possible background signal. Here we assume that the integration of the night sky results in a background which is significantly less than the statistical fluctuations in ten photoelectrons per image element.

11. Image Element Size
The background detection threshold of our 10 photoelectrons per image element is of course dependent upon the night sky fluctuations in the same image elements. The selection of the image element size is related both to questions of seeing, telescope quality, and image processing rate of the central host computer. A real-time search of supernova should include the capability of near instantaneous response so that an image that reveals a new object can be rescanned and reinvestigated dependent upon a selection criteria. A real-time search therefore requires the image be processed for new objects within the five second interval of proceeding from galaxy to galaxy. Therefore, depending upon the capabilities of the central processor of the computer used, there is a real premium for minimizing the total number of pixels processed.

12. Pixel Count
The number of pixels is determined by the ratio of the brightness of the emerging supernova compared to the brightness of the whole galaxy. For example, if the whole galaxy were encompassed by one pixel and similarly the supernova within it, then the change in brightness of that one pixel might be used to detect a new supernova, but this incremental change in brightness is small for a typical galaxy, of the order of 1%, for 1% of
the peak Type I supernova luminosity. It is far more efficient from the standpoint of detection to divide the galaxy up into effectively 100 or more pixels and expect to see the emerging supernova as a doubling or more of the intensity of several pixels of the image. The luminosity distribution of a galaxy is highly peaked towards its center and the question of detectability of a point brightening as a function of distance from the center represents a complex algorithm that has been investigated by Pearce (1987). Roughly speaking we want the background luminosity in 10% of the image of the galaxy to be comparable to that of the supernova within our standard 3 pixel stellar image format. This means that the total image of the galaxy could be contained in roughly 3000 image elements or in a frame determined by the Boolean arithmetic $128 \times 128$. An image size of $64 \times 64$ might just meet this requirement of 3000 pixels, but the light distribution among galaxies is sufficiently variable that the factor of two additional size in the format is needed.

13. Angular Pixel Size

The angular size of each pixel is then determined by the size of a typical galaxy at our mean distance of 50 Mpc. The typical galaxy diameter of 25 kpc at a distance of 50 Mpc subtends an angle of $5 \times 10^{-6}$ radians. If this is distributed in 128 pixels and then the angular size of each pixel becomes $2.5$ arc seconds. This is the image scale that we are presently using for our supernova search. Some particularly large or close galaxies naturally spill over the edge and vice-versa. An image size of $2.5$ arc seconds is significantly larger than the average seeing at our mountain site in the Magdalena mountains west of Socorro, New Mexico. And so in order to utilize the higher resolution, better signal
to noise ratio, and the possibility of doing spectra, we felt that the initial telescope and detector should be built with the resolution corresponding to one arc second per image element and with the option to change this focal length ratio from f30 to f12 remotely in several seconds.

14. The Telescope

The requirements of low moment of inertia, 30-inch size, acceleration of 3 arc second/second$^2$, two focal ratios remotely changeable dictated the design of our telescope. Figure 1 shows a schematic diagram with a light weight centrally supported mirror of Schott glass figured by Don Loomis of Tucson Arizona. We chose a fork mount that was a surplus Nike Ajax radar mount. It was reworked and a tripod-like structure is used to hold a lightweight secondary. The secondary can be translated forward and the lens inserted to change the focal ratio. In order to minimize the remote focusing requirement of the telescope, which is a somewhat complex algorithm requiring several moments of a stellar image in the image processing routine, we chose to mount the secondary mirror in series with a thermal element comprised of compressed ethane gas in a bellows and a compensating stiff spring which exactly matched inversely the thermal expansion coefficient of the steel legs of the central support, Fig. 2. This part of the mount has worked successfully for 20 years.

15. The Drive

At the time of the start of this project there were no digital drive systems with the speed and accuracy desired. The desired peak slewing
speed of a radian in 10 seconds meant that the slewing motor's digital logic had to keep up with roughly 20,000 steps a second.

One has to perform something like 25 logical steps with 20-bit arithmetic to slew the telescope to the accuracy desired, namely one arc second per step. This speed of $2 \times 10^4$ meant that the arithmetic and logic driving the motor system had to be fast by the then current standards. As a consequence this required a special purpose computer because the current-day microcomputers were not then available. We used stepping motors with feedback logic and gearing to give us this slewing accuracy and speed.

16. Slewing Accuracy and Fiducials

The telescope is mounted on the top of a steel tower at the southern end of the ridge defining the Magdalena mountains. The seeing at this site is frequently considerably better than one arc second so that our image sizes are distributed in roughly two pixels dependent more upon the focus of the readout beam of the tube than on the optics of the telescope. The current slewing accuracy corresponds to a generation of a random error of the order of several arc seconds per slew so that the system requires the updating of its coordinates by recognizing a guide star. Hence, our tactic is to divide the sky into boxes defined by hour angle (15°) and 6° of declination, each with a guide star. The coordinates are updated after the search of the set of galaxies in each box. The initial coordinates of the telescope are established by micro-switches on right ascension and declination which give a position of the telescope sufficiently accurately to find a guide star.
17. Image Tube

The detector used is an intensified vidicon. Originally a magnetic intensifier with a red sensitive photocathode and a hard glass window was used in addition to the SIT vidicon. The current search is being operated without the magnetic intensifier so that our threshold is now 17th magnitude with 6 seconds of integration. The intensified silicon target vidicon requires refrigeration to -30 C. The cooler is based on the usual freon technology. A heated quartz window prevents frost at the entrance of the cold box and ahead of this is mounted a spectrograph which can be completely computer controlled as are all functions on the telescope. The spectrograph is a cross dispersed Echel which would allow in five orders something like 5 Å resolution per image element. The spectrograph has not been used because of the complexity of the current system, although it was brought up to operational status with automatic guiding on a mirror slit and full analysis of standard stars.

The silicon target vidicon requires a sequence of beam erases at the identical beam and target conditions that are used in the image readout. The sweep speed of the beam is limited by the digital transmission rate of the microwave link between the mountain and the campus, ≈ 10⁶ baud. The readout time is 12 µs per pixel for 8 bits per pixel and thus a third of a second to read out a frame. As a consequence the target preparation of ten beam erases require three seconds of time. With the following 6 seconds of integration this is a minimum of 9 seconds per galaxy. Computer processing increases this currently to about 20 seconds, so we are not operating at the original planned rate of 5 seconds per galaxy. The system, however, has been operational with the recognition and alignment of galaxy fields since Feb. 1987. This is discussed in the accompanying article by Eric Pearce.
18. Weather

Weather monitoring by the computer must be accomplished in real time. We use a rain gauge to detect water by electrical conductivity, a humidity detector to determine humidity, temperature and a bolometer to detect sky cloud cover. In addition wind is monitored such that winds high enough to distort the image by telescope vibration are avoided. Thus five weather monitoring systems must operate and result in an affirmative signal before the dome can be opened. In addition, of course, the sun and the moon must also allow dark-sky astronomy. These many factors restrict the useful operating time to a small fraction of the total. If the equipment isn't extremely reliable, the small fraction will be further reduced. The feasibility of a completely automated supernova search is demonstrated by this system.

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**References**


Fig. 1. — The principal telescope parts and dimensions are shown for the secondary mirror, its support cage and light baffles, the primary mirror and its baffles, the primary's cell, the lens that rotates into place behind the primary for f/18 observations, the spectrograph, the TV sensor system, and the fork arms.

Fig. 2. — Schematic diagram of the secondary mirror assembly. The 4.6-inch (11.6-cm) diameter Carvit secondary is shown held at its pierced center to an inner cylinder containing a spring and a bellows filled with ethane gas in equilibrium with its liquid. The combination temperature-pressure displacement nearly compensates the effect of thermal temperature variation on telescope focus. When so commanded by the computer, the system changes between f/18 and f/500 in a few seconds by allowing compressed air to enter one of the two inlets, shifting the inner cylinder with secondary toward or away from the primary about an inch while simultaneously inserting or removing a lens (not shown) behind the primary. At the top of this figure are the separate motors for fine adjustment of each focus (used only after large seasonal temperature changes).