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Progress Report on the Berkeley/Anglo-Australian Observatory High-Redshift Supernova Search

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I. Introduction

There are two main efforts related to supernovae in progress at Berkeley. The first is an automated supernova search for nearby supernovae, which was already discussed by Carl Pennypacker at this conference. The second is a search for distant supernovae, in the $z = 0.3$ to 0.5 region, aimed at measuring Ω. It is the latter that I want to discuss here today.

II. The Method for the Measurement

The method we intend to use to obtain a measurement of Ω is illustrated in Figure 1. It involves two steps: i) the discovery of a distant supernovae from exposures of our CCD camera at the Anglo Australian Telescope at different epochs, and ii) the rapid follow-up with spectroscopic and photometric measurements by collaborating observers. These are needed both for the identification of the supernova candidate as a type Ia supernova as well as for the measurement of the redshift. There is now evidence that the type Ia supernova is effectively a standard candle. Further work on this subject is still in progress in conjunction with the Berkeley automated nearby search. Using the combination of measured

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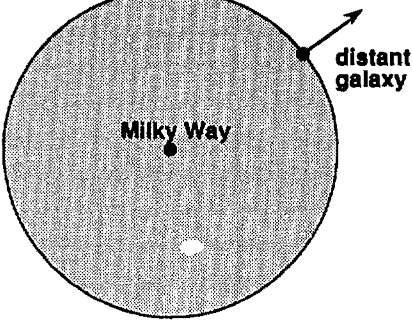
Mass Density from Deceleration

$$\frac{1}{2}mv^2 = \frac{1}{2}mH_0^2R^2 = \frac{GmM}{R} = \frac{4}{3}\pi Gm\rho R^2$$

$$\rho_{critical} = \frac{3H_0^2}{8\pi G} \approx 10^{-29}\,gm/cm^3$$



$$\ddot{R} = -\frac{GM}{R^2} = -\frac{4}{3}G\pi R\rho$$

(if $\rho = \rho_c$, at $z \sim 1$, presently decelleration $\sim 10^{-7}$ cm/sec^2)

Fig. 1

redshifts and luminosity of the discovered supernovae we will be able to plot velocity as a function of luminosity-derived distance. The curvature of such a plot is a measure of the deceleration of the Universe and hence Ω, for a cosmological constant $\Lambda = 0$.

III. What Accuracy Can We Expect?

Figure 2 shows a result from Monte Carlo calculations of the distributions of $q_0 = 1/2\ \Omega$ as a function of the number of supernovae observed. The maximum light of the supernovae was assumed to follow a gaussian distribution with sigma=0.3. The lower figure shows the accuracy to which q_0 can be measured as a function of the number of supernova samples observed. Thus between 10 and 30 measured supernovae should give us a significant new measurement of Ω.

IV. How Good a Standard Candle Is a Type Ia supernova?

Figures 3 and 4 are from supernova compilations due to Barbon, Ciatti, and Rosino and Leibundgut which respectively illustrate both the photometry curve for type Ia supernovae and the redshift vs magnitude distributions for observed supernovae. Figure 5 from Miller and Branch gives the width of the magnitude distribution and shows what may be the effect of extinction due to dust in the parent galaxies. This faint tail can be statistically removed. Alternatively, photometry in the infrared, which suffers less extinction, should not show this tail.

V. The Observation of One Distant supernova By an ESO Group

What gives us the confidence that such a search is feasible is the fact that a distant supernova was discovered by an ESO (European Southern Observatory) group, including our co-worker Warrick Couch. This is illustrated in Figure 6.

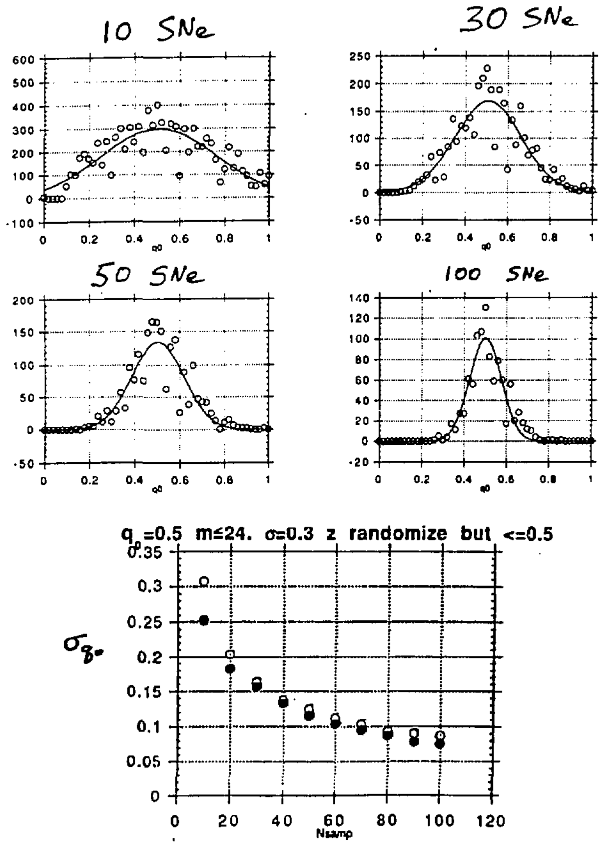


Fig.2 Monte Carlo distribution of "measured" $q_0 = \Omega/2$ for Gaussian distribution ($\sigma = 0.3$) of Type Ia maximum light. Calculations by S. Perlmutter, to be published.

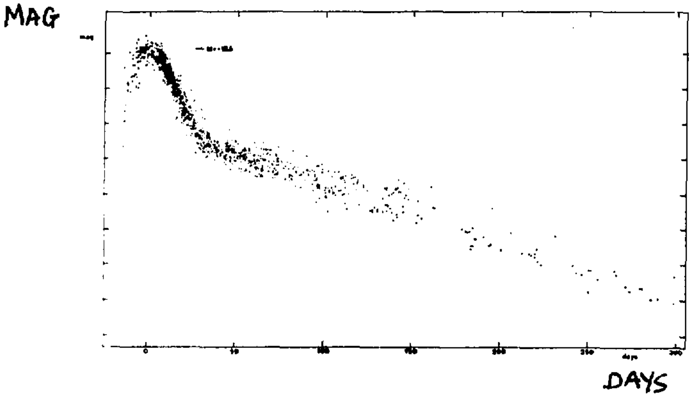


Fig.3 Composite blue light curve obtained by the fitting of the observations of 38 Type I supernovæ. One magnitude intervals are marked on the ordinates. Compilation by Barbon, Ciatti, and Rosino (1974).

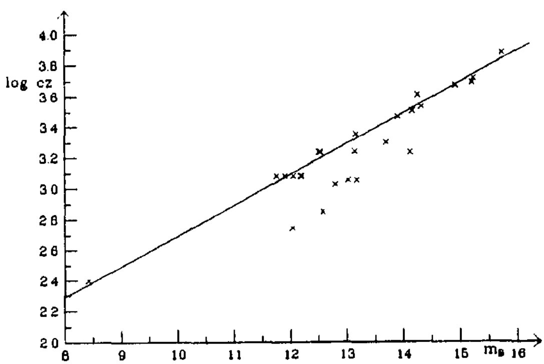


Fig. 4 The Hubble diagram of Type Ia supernovæ at maximum light. Compilation by Leibundgut (1991).

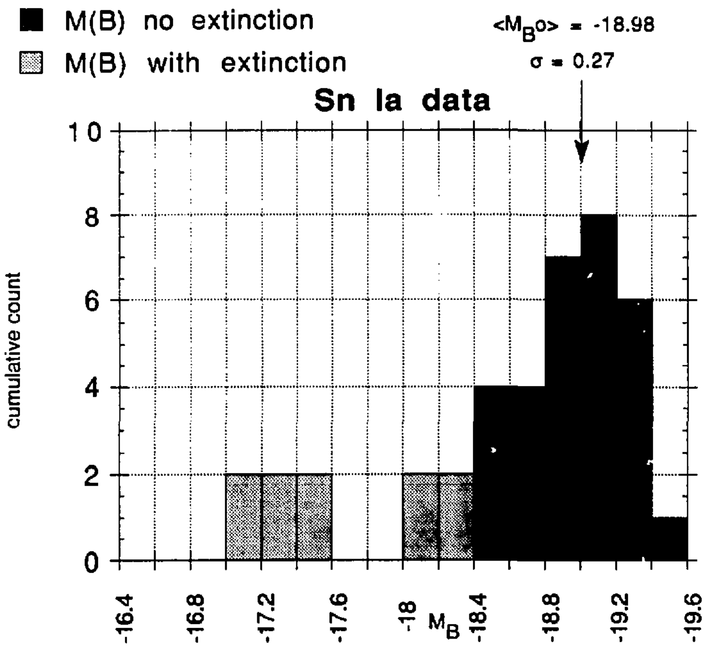


Fig. 5 Histogram of Type Ia supernovæ absolute magnitudes, based on a compilation by Miller and Branch (1990).

ESO Results

The discovery of a type 1a supernova at a redshift of 0.31

Hans U. Norgaard-Nielsen, Leif Hansen, Henning E. Jorgensen,
Alfonso A. Salamanca, Richard S. Ellis, & Warrick J. Couch

NATURE 339, 523-525 (June 15, 1989)

- assume detection below peak

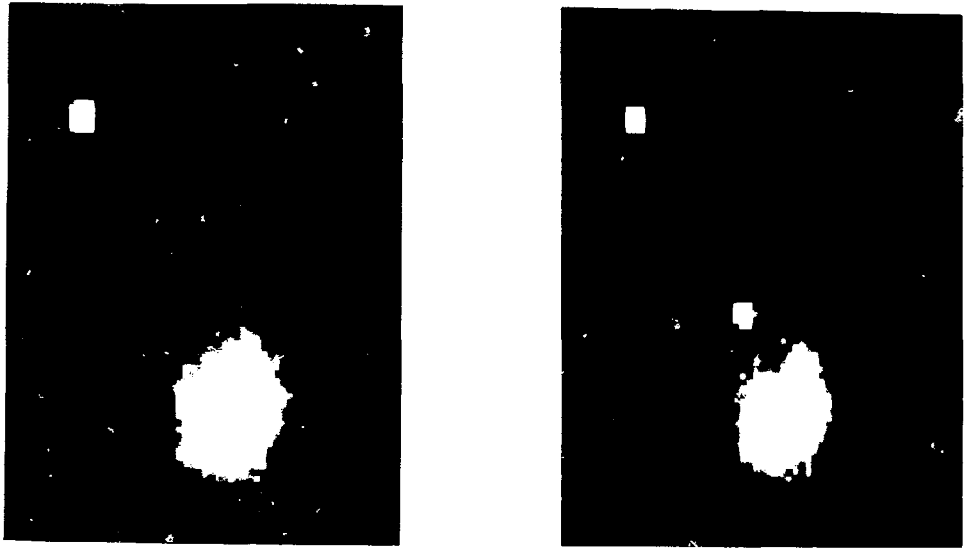
  B(max) $\leq$ 22.4 $\rightarrow \Omega \geq -1.6$
- from luminosity decline, Sept 4 > inflexion

  B(max) $\geq$ 21.5 $\rightarrow \Omega \leq 3$
- fitting light curve (depends on faintest pts)

  $0 \leq \Omega \leq 2$

Results comparable in accuracy to galactic measurements

Fig 6



MAY 8, 1986 MAY 17, 1986

SUPERNOVA IN M99 GALAXY IN VIRGO CLUSTER

Photo by : LBL SUPERNOVA SEARCH TEAM.

Fig. 7

XBB865-4125

VI. How Can We Find supernovae?

First I want to show one figure from the nearby search which illustrates one of the procedures we follow in the distant search. Figure 7 illustrates the discovery of supernova 1986I. The supernova is clearly seen as a third object in the right hand figure. The discovery method is to subtract the reference image from the new image and look (automatically!) for stellar objects that appear in the subtracted image. The difference in the distant search is that a supernova candidate is not completely resolved from its host galaxy in the new image, and what we have to look for is the change in intensity between a reference and a new image.

Our procedure is to take the new image at one to 12 months after the reference image. So far we have had successful images taken at the AAT with our CCD and focal reducer illustrated in Figures 8 and 9. The epochs are: November 30, 1989; December 28, 1990; January 23, 1990; November 13 and November 18, 1990. Unfortunately runs scheduled for April, May, and August 1990 as well as January 1991 were not taken due to bad weather. Each night of observing we take about 50 images on the 1024 x 1024 pixel Thomson CCD. The length of exposure is 5 minutes. However in order to avoid cosmic rays with direct impact on the CCD, or other activation of pixels due to local radioactivity, we take two 2.5-minute exposures which we then add together in the computation stage. To accept an object as a real candidate, we demand that the 2 independent new images agree within 25%. This is summarized in Figure 8. Our search strategy is summarized in Figure 10. We expect about 1 type Ia supernova per night of observation as summarized in Figure 11.

VII. Computational Techniques

Each image gives us 1 million pixels. Thus the 2 X 50 images taken per night of observation yield about 100 million pixels,with 16 bits of information each. The problem that faced us is to analyze and compare with the 50 million pixels from the reference images within as short a time period as possible so that any supernova candidates do not have time to fade appreciably. So far due to the speed limitations of current computers at the telescope we could not perform image subtractions within this time constraint but had to develop an alternative technique of data handling. The method we developed consists of performing photometry on all the identified

1989. Construction of a CCD 1024 x 1024 pixel plane with demagnifying F/1 lens for the

AAT four-meter telescope

1 pixel ↔ 1.05 arc sec.

Thus the entire CCD corresponds to a 17 x 17 (arc min)^2 area of the sky.

Here the philosophy was to maximize the area covered which meant that one had to sacrifice resolution.

A new 16x larger CCD consisting of four 2048 x 2048 pixel planes is on the drawing board. If we use this to get a factor 10 in area sampled, we will still get improved resolution.

Fig. 8

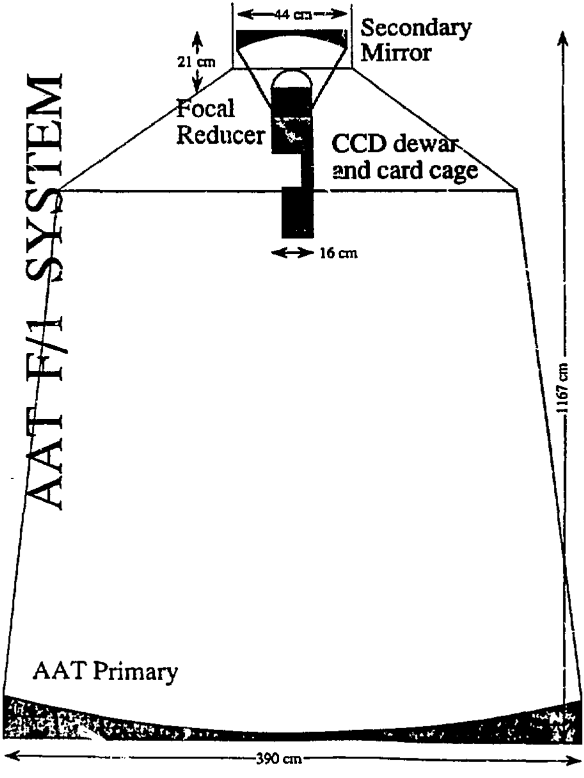


Fig 9 Schematic diagram of high redshift supernova detection hardware. The system uses the Anglo Australian Telescope (3.9 meter primary mirror), de-magnifying optics and 1024 x 1024 CCD at the prime focus. The focal reducer converts the beam into a final F/# of one at the focal plane.

Search Strategy

1. Observe >50 wide fields (17'x17'), each containing >1000 objects of which >100 are galaxies at z = 0.3–0.5. (Exposure time: 2 x 150 seconds.)

2. Repeat observations after a month or so and look for brightness variations in these ~100,000 objects.

   Find
   - Quasars
   - Variable Stars
   - Active Galactic Nuclei (AGN)
   - Supernovae

3. Distinguish the supernovae (and a few AGN) from the others by high resolution imaging:

   The supernovae (and occasional AGN) appear on resolved, "fuzzy" galaxies, while the other objects all look like "sharp" point-source stars.

4. Follow up the supernovae with spectra and photometry.

Fig. 10

Supernova Discovery Rate

rate per galaxy (type Ia)	1 per 500 years
useful galaxies per image	100 galaxies
supernova visibility	1/12 year
number of images to find one supernova	60 images
observation time per supernova	6 hours

one type Ia supernova per night

Fig. 11

objects, about 1000 to 1500 per image. We then compare the photometry results between the reference images and the new images. Moreover, there was also the problem of data transfer from the images taken at the AAT to Berkeley where more extensive computing power is available to us. Using a NASA computer network, we were able to send our list of reference objects to Australia and compare the images in real time over there. Using a 32 Mbyte memory system we installed at the AAT computer, this allowed us to complete the analysis and find potential supernova candidates within 36 hours from the time the images were taken. Our procedure is summarized in Figure 12. In Figure 13 we show a typical observed magnitude distribution for 1 image.

VIII. Results from the "Engineering" Runs

The runs of November 30, 1989; December 28, 1989; and January 23, 1990 were used for taking reference images as well as "engineering" runs for developing our data handling methods. In these runs we found 5 candidates for further examination selected by the criteria in Figure11. Of these, two candidates turned out upon measurements at the NTT (European Southern Observatory's "New Technology Telescope") to be located at a galaxy. At this early stage in our program development the time taken for the analyses was too long to be able to still take a spectrum of the potential supernova. For one of these we also had further circumstantial evidence that we were dealing with a supernova by the fact that the size of the image increased between the 2 observations in November and January respectively. Also the increase in intensity we had observed, about 0.4 in magnitude, has since disappeared on later observations. Figure 14 shows the images as observed on November 30 1989 and January 23 1990 respectively. Figure 15 shows a contour plot of this candidate from November 30 while Figure 16 illustrates one of the difficulties we encountered which so far necessitates visual inspection of candidates, namely the occurrence of occasional streaks in our images These streaks are believed due to reflections of bright stars in our optical system and do reoccur in our new images. However they tend not to reoccur in precisely the same position and hence they would make it on to our candidate list of objects that have changed by more than 20% in intensity.

SEARCH FOR SNe BY INTENSITY RATIOS
(Using VISTA Program)

Reference image 5 minutes, new images 2 x 2.5 minutes, one month later.

1. Align the images with a Matching program.
2. Find location of all objects with Apparent Magnitude < 23.5.
3. Compute Integrated Intensities inside a 2.5 arc second radius
   I_R (Ref), I_N (New) = $I_1 + I_2$.
4. Take intensity ratios of corresponding objects $r = I_N/I_R$.
5. Cuts to accept potential candidate:

   (i) $r > 1.1$ or $r < 0.9$
   (ii) $|I_N - I_R| > 800$ counts
   (iii) inside fiducial region
   40 pixel border (15% less)

6. Cuts to accept intermediate candidate:

   (i) $|I_N - I_R| > 900$ counts
   (ii) $0.75 < I_1/I_2 < 1.25$
   (iii) Only 1 object in a 10 x 10 pixel box

7. Final candidates:

   (i) Check photometry with radii of 2.0, 2.5, 3.5, and 5 arc seconds.
   (ii) Check on distance to bright object (from contour plot).
   (iii) Compare candidates with Subtraction method.

Fig. 12

Objects found Nov '89 & Jan '90

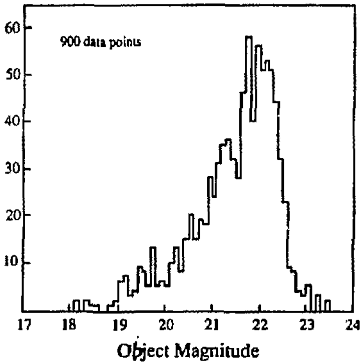


Fig. 13 Our observed object's apparent magnitude distribution for one images. Matched objects only.

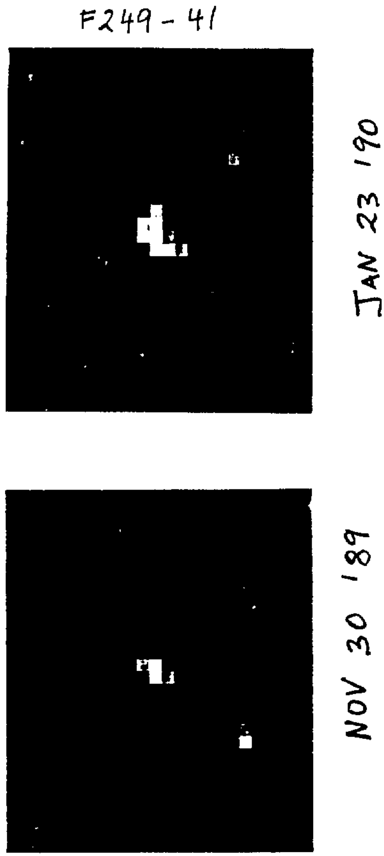


Fig. 14 The galaxy in F249-41 which has changed in magnitude and appears to have changed in shape as well.

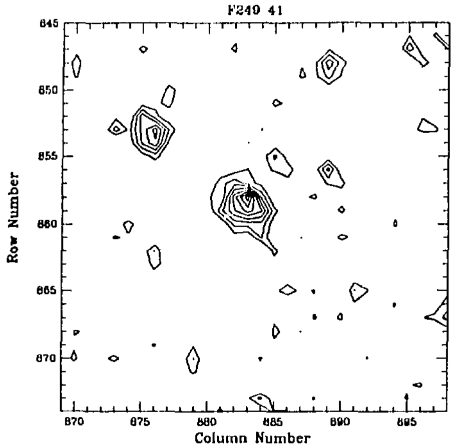


Fig. 15 Contour plot of the variable object identified as a galaxy by Jorge Melnick of the European Southern Observatory, using the NTT.

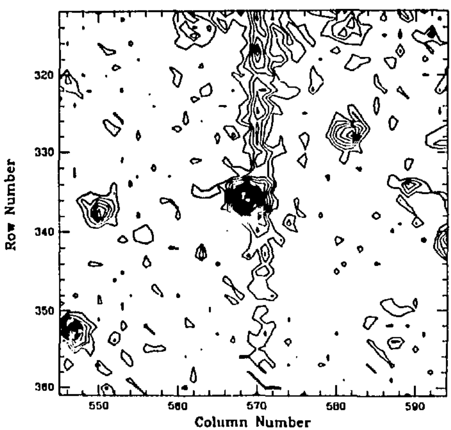


Fig. 16 Example of "Streak"

IX. Results From the Most Recent Run

Since January, 1990 our only clear nights at the AAT occurred on November 13 (2 X 50 images) and November 18, 1990 (2 X 30 images). For this run we had not expected to be able to complete our analysis in time for timely follow-up. We surprised ourselves with the breakthrough that we were able to analyze all the data in less than 36 hours! Figure 17 shows the distribution of "magnitude change" versus "apparent magnitude" for one image from the night of November 13, 1990. Superimposed on this we show those events which were picked up as candidates in the 50 images. These consist of a mixture of variable quasars,which we are following in a separate study, and possible supernovae.

At that stage we needed to use follow-up observations at another observatory,with better seeing and a finer image resolution to differentiate quasars from supernovae. Quasars have point source image shapes, while supernovae occur in galaxies which have 'fuzzy' images. We were able to get confirmatory measurements on five of the objects. These turned out to be stellar, and thus presumably quasars. The others were not followed up for lack of time. We believe that we have now resolved this problem by developing several techniques to differentiate supernova candidates from quasars, without needing follow-up observations. These techniques include using a data base with the time history of all our repeated measurements. We also use an image shape analysis of our data based on the FOCAS program developed by Jarvis, Tyson, and Valdes. With this ability to preselect we expect in future to follow-up only those candidates which are likely to be supernova.

The arrows in Figure17 indicate those objects which showed a change in magnitude from November 13 to November 18. Finally the "D" indicates the location of the ESO event as observed on the Danish telescope. In Jan 1991, when everything was ready, the weather did not cooperate and we did not get any data.

X. Conclusion and Future Plans

We have demonstrated that we can detect supernova of about 23rd magnitude and brighter. In future runs, which are now scheduled at the AAT we should be able to observe and measure spectra with the help of our collaborators sufficiently rapidly to catch and identify a supernova. Our plans now are to build and deploy a

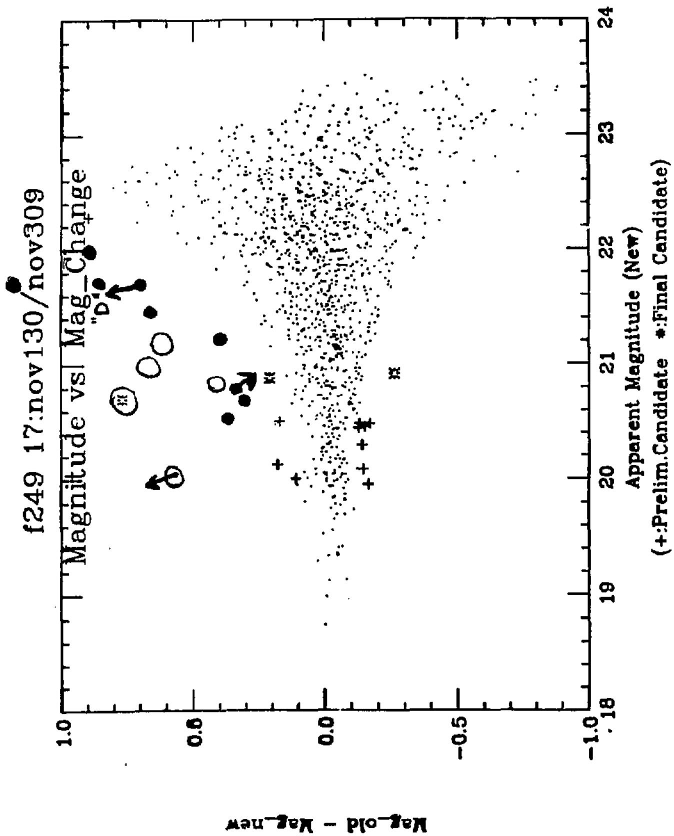


Fig. 17 Magnitude change vs. apparent magnitude for one image (solid small dots). Superimposed are (solid larger circles) all candidates from approximately 50 fields with large increase in magnitude on November 13, 1990, compared to November 30, 1989. Arrows also show change of three objects that changed from November 13 to November 18, in 1990. Circles indicate objects identified as stellar. The "D" indicates the approximate values of the Danish/ESO supernova.

f249 168, 1990:01:23, RUN 68, REGION D

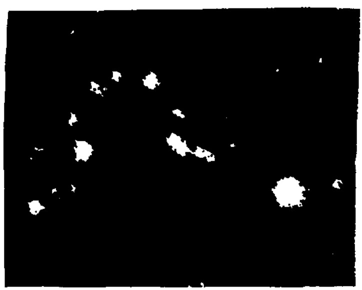


Fig. 18 A configuration observed in one of our images.

much larger CCD of four 2048 X 2048 chips. This should allow us to achieve the goals set out in this talk. While we have not yet measured Ω, we did observe the configuration shown in Figure 18.

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