longer time, the shock front should have progressed much further into the antique red supergiant wind and the nebula would have been much larger. It is not likely that we are seeing only part of a much larger nebula: first, it has been over a year since the supernova exploded. But the angular radius of the nebula is only about one light-year. Thus, we are not seeing the apparent superluminal expansion that would be expected if the actual size of the nebula was much larger. And second, the detected flux of [O III] $\lambda$ 5007 has remained approximately constant since February 1, 1988. Therefore we are not seeing the rapid increase in flux that would signal an expanding linear radius of the nebula.

It is also not likely that we are witnessing the interaction of the fast moving outer parts of the supernova envelope with the surrounding medium. In this case the nebula that we see is rather large to be produced by particle interaction from the expanding outer shell of the supernova and, in addition, the X-rays that would be expected to accompany the collisions should be rapidly increasing in strength as the density of particles increases. This is not happening.

Model calculations (Woosley, 1988) show that the final blue supergiant lifetime implied by the diameter of the nebula is the same as the time for the outer stellar envelope to reach equilibrium. But, to explode, the progenitor must form a massive iron core. If, as the Woosley models suggest, the star returns to the blue part of the H-R diagram after helium exhaustion, the mass of the helium core determines the length of time for carbon, neon, oxygen and silicon burning before the final collapse of the iron core to produce the supernova event. This time is dominated by the helium core collapse and the carbon burning lifetime. Woosley finds that stellar models that have about 19 solar masses of material when they are on the main sequence end up with helium cores in about the right mass range to power the SN 1987A explosion. An 18 $M_{\odot}$ star ends up with a helium core near 5 $M_{\odot}$. This star would explode 70,000 years after it switches to the blue supergiant phase. A 20 $M_{\odot}$ star produces a 6 $M_{\odot}$ helium core and explodes after 20,000 years.

These calculations suggest that it will be possible to construct a model that will be a good fit to all the observational data. Rotation, the $^{12}C(\alpha,\delta)^{16}O$ reaction rate, convection, etc. can all affect the lifetime of the last stages of stellar evolution. And, observationally, the radius of the nebula is still somewhat uncertain. The important point to make is that observations of this nebula together with theoretical calculations are likely to provide important additional constraints on SN 1987A models. It is probably fortuitous that the first estimate of the duration of the blue supergiant wind is comparable to the Kelvin Helmholtz contraction time for the progenitor envelope. We observers, therefore, don't have to worry too much about the details of the helium core. The contraction of the outer envelope is decoupled from the details of the inner core physics. We need only to model the outer envelope contraction to obtain the time dependence of the progenitor radiation field that drives the shock wave into the red supergiant wind. This, in turn, will lead to a more accurate velocity for the shock and, hence, a better estimate for the time interval between the time of helium core collapse and the supernova explosion.

Finally, of course, the very existence of the nebula shows that there *was* a red giant phase for the progenitor of SN 1987A. This by itself eliminates all those models that explode before they reach a red giant phase.

This small nebula from the antique red giant wind has proven to be an important new clue for understanding SN 1987A. As the supernova fades, the contrast of the nebula will increase and the spatial information will be easier to obtain. Then the observational constraints can be greatly improved.

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# Deep Photometry of Supernovae


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## 1. Introduction

Supernovae are among the more exciting transient astronomical phenomena. Unfortunately the interest for them appears to fade faster than their luminosity. Only for one fifth of the 637 confirmed supernovae discovered up to the end of 1987, there are sufficient data to describe the photometric evolution; moreover, the majority of the published light curves are limited to the first two or three months after the maximum. On the other hand, the knowledge of the faintest tail of supernova light curves can give useful constraints in the discrimination among different theoretical models (Sutherland et al., 1984). The analysis of data available in literature, allowed Barbon et al. (1984) to investigate the behaviour of the late decline of supernovae. They showed that the late light curves can be described by a single exponential decay with different rates of decline, $<\gamma^{B}_{200^d}> \simeq$ 1.52 mag/100$^d$ for type Ia SNe (half-life 49$^d$.5) and $<\gamma^{B}_{200^d}>$ $\simeq$ 0.81 mag/100$^d$ for type II SNe (half-life 93$^d$), favouring therefore the possibility that the $Ni^{56}-Co^{56}-Fe^{56}$ radioactive decay is the main energy source up to these stages. More recently the bibliographical material of type II SNe has been used by Schaefer (1987a) to test the effect of light echoes in the B-band light curves, but the shortage of observations compelled him to include objects not observed at very late stage. He claimed to find different decline rates and argued that scattered light echo in the circumstellar dust can dominate the shape of the light curves of supernovae. To progress on this subject we decided to start photometric observations of supernovae at intermediate and late stages, extending to much fainter limits the extensive SN survey carried out at Asiago Observatory in the last thirty years by Rosino and collaborators.

## 2. Observations

The first observing session was performed at the 1.5-m Danish telescope equipped with RCA 320 × 512 #3 CCD on 17–19 January 1988. The sample of

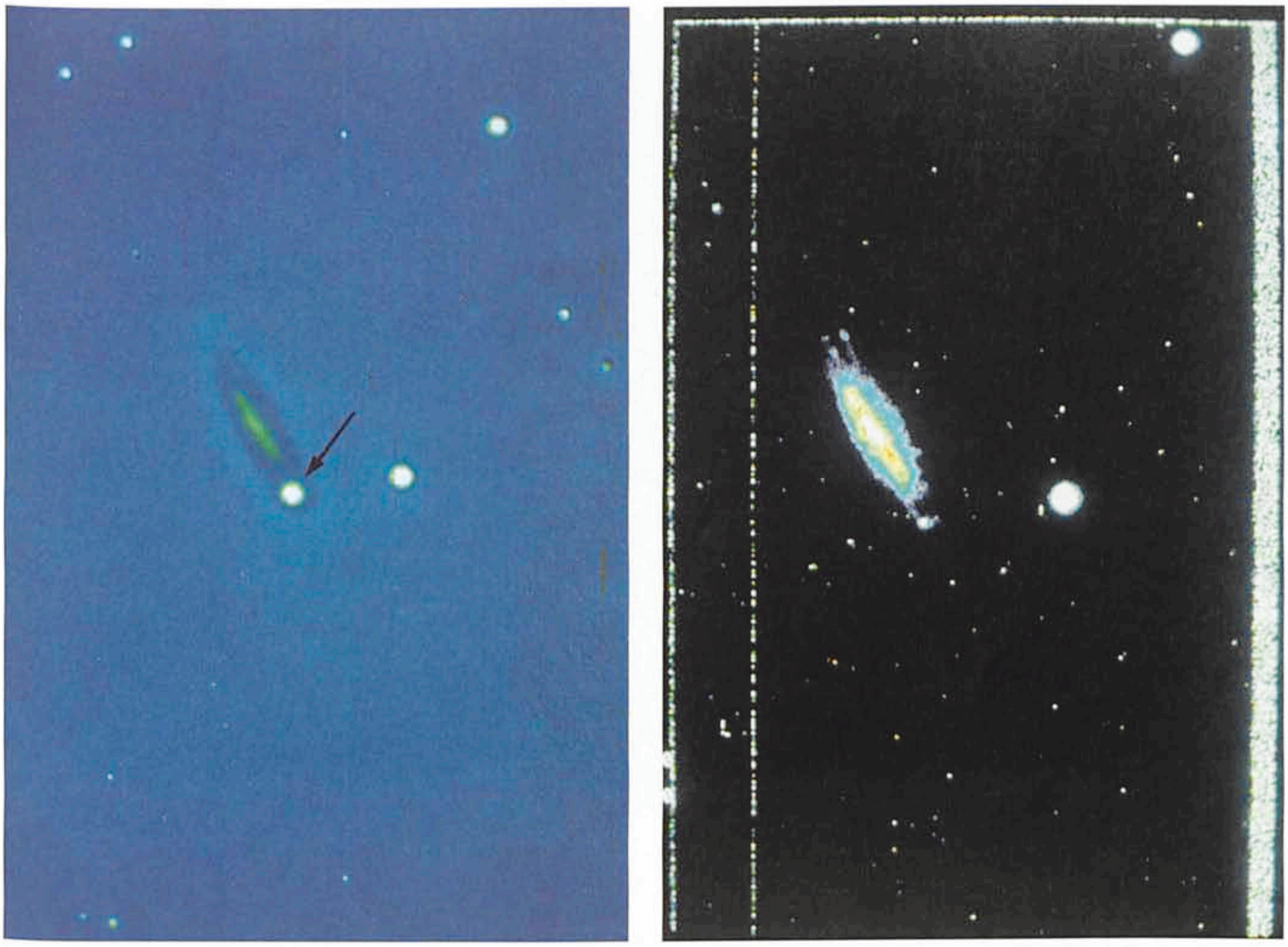

Figure 1. *On the left (Fig. 1a) is represented a V frame of MCG +00-32-01 obtained at the end of April, 1987, when the SN 1987d was at its bright stage. The image on the right (Fig. 1b) shows the same object at the time of our last observation. In both cases North is on the top and East is on the right.*

objects investigated was selected according to the following requirements:

- magnitude in the 19–23 range, estimated by means of the average light curves, for the first decline, and via linear decay rates (Barbon et al. 1984) for the late decline;
- availability of a detailed map of the field containing the supernova at its bright stage;
- existence of photometry at early stages.

For each object B, V and R frames were obtained with 40, 25 and 20 minutes typical exposures, which allowed to reach a $S/N \geq 10$ for a $V = 23$ supernova with a typical seeing of 1.2 arcseconds. Preliminary reduction of the B and V frames, including de-biasing, flat-fielding and flux measurements, was carried out with MIDAS package at the Observatory of Padova. The calibrations were performed using Landolt's standard stars, obtaining colour terms remarkably similar to previous determinations at La Silla. The inspection of the material has pointed out that, for the determination of the magnitude, each object has to be treated individually, and moreover that particular care has to be devoted to the subtraction of the local galaxy contribution, which, at low level, can affect strongly the measurement. When possible, for objects visible also in the northern latitude, the maps of the SNe were secured at Asiago, in other cases, good quality maps of supernovae kindly provided by B. Leibundgut, C. Pollas, R. Evans and M. Wischnjewsky have been very useful. In fact, even for objects with precise absolute position it is very difficult to go back to the position of the supernova at this faint stage when no other bright stellar objects are present on the frame, an accurate determination of the galaxy centre being usually very difficult. The easiest identification was that of 1986e in NGC 4302 for which King (IAU Circ. 4206) reported the position relative to a near foreground star. Therefore, for such a programme it should be recommendable that astrometrists give positions relative to near stellar objects.

Table 1 reports the list of objects, their type, the phase at the time of the observations and the preliminary determinations of the magnitude in the B and V systems. The typical magnitude at maximum light for all our objects was $B = 14 \div 15$. We estimate the accuracy of our measurements to be about 0.1 mag. for objects brighter than 21 mag. located in regions with smooth and uniform background, rising up to 0.5 mag. in the most unfavourable cases, i.e. 23 mag. objects situated in very confused regions. In the last column we report the expected magnitude of each object at the time of observation assuming the linear decline determined by Barbon et al. (1984) for the corresponding supernova type. At the time of the preparation of this communication, no detailed investigation on such objects is available, so the date and magnitude at maximum light are not accurately known. The predictions are then thought to bring an indetermination of 0.3 magnitudes in the expected value of the magnitude of the supernova at the phase of the observations.

## 3. Discussion

From the inspection of Table 1 two facts appear evident:

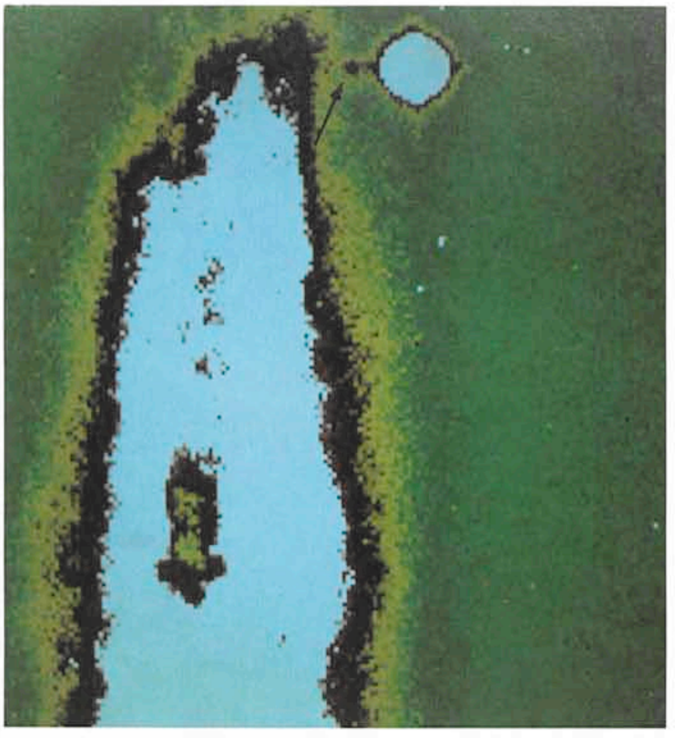

Figure 2. *V frame of SN 1986e in NGC 4302. North is on the top and East on the left.*

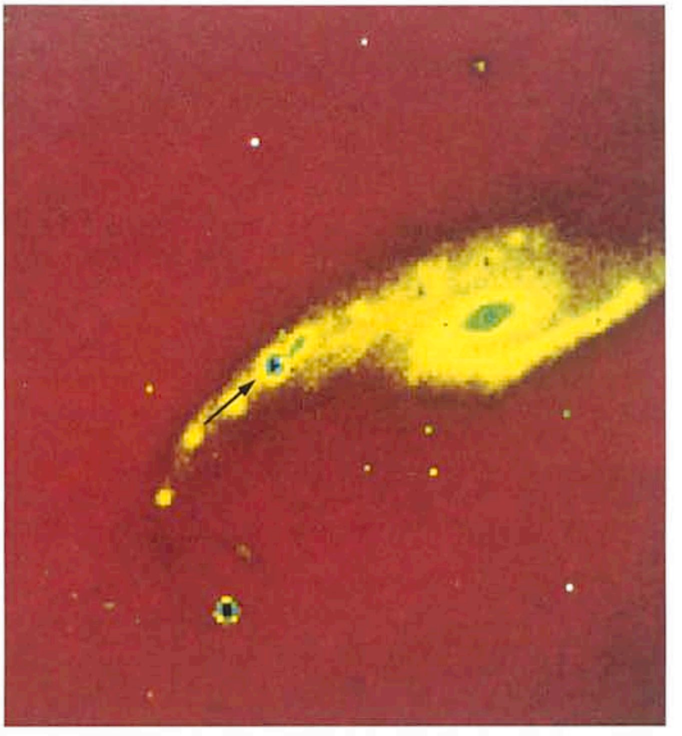

Figure 3. *The arrow indicates the SN 1987f in NGC 4615 on a (B-V) frame. North and East as in Fig. 2.*

– The correspondence between the observed and the estimated magnitudes via linear decline for the objects of the sample is fairly good. A slight systematic trend to increase the previous value of the slope at the late decline stage may exist. Therefore, the input of energy from light echoes seems to play a minor role compared to the supply from radioactive decay (at least for the objects of the sample).

– The value of the colour index must be taken with care; before discussing the intrinsic properties of the objects, the reddening due to the galactic and internal absorption of the parent galaxy has to be taken into account. Nevertheless, even without the correction, it appears that SN Ia colour curves tend to stabilize around (B-V) $\simeq$ 0 in analogy to the SN Ia 1972e in NGC 5253 (Ardeberg and de Groot, 1974). The situation for the type II SNe is less clear because the observed B-V colour index could be strongly contaminated by the underlying H II region. A more complete analysis of data after the reduction of photometry at intermediate stages and of the R frames at late stages, will make possible to account for reddening and to determine accurately the individual fading rate, thus providing better constraints to SNe evolutionary models.

## 4. SN 1986g in Cen A

Finally we spend a few words on SN 1986g in NGC 5128, which recently has been pointed out as one of the best candidates (Schaefer 1987b) for the detection of light echoes. A V frame was obtained on May 20, 1987 with the same equipment as for the other objects, and with similar conditions. The precise position has been determined by means of a previous frame, obtained when the SN was near maximum light and the magnitude has been carefully measured via Daophot and Inventory programmes. The calibration of the frame has perfectly confirmed the magnitudes of the field stars used for relative photometry by Phillips et al. (1987) and Schaefer. Since the colour index of the type Ia SNe during the late decline is almost constant, one might expect that $\gamma^B \approx \gamma^V$ and in fact, from the last tail of the V light curve (Phillips et al.) and our measurement (at phase $374^d$), we obtain a rate of decline, $\gamma^V \simeq 1.77$ mag/$100^d$, which is comparable to both the $\gamma^B$, $\simeq 1.88$ mag/$100^d$ by Phillips et al., and with the quoted $< \gamma^B >$ decline rate. Even in this case, hence, our results show no significant effects due to echoes (at this stage). The only indication, in this sense, seems to come from Schaefer's B estimate of June 1987, that induces to look at the SN 1986g as the only doubtful case among the observed ones.

TABLE 1

| List of objects | | | | | | |
|---|---|---|---|---|---|---|
| Supernova | | Type | Phase days | Observed | | Expec. |
| | | | | B | V | B |
| 1985p | NGC 1433 | II | 820 | 22.5 | 22.4 | 22.1 |
| 1986e | NGC 4302 | II | 645 | 22.3 | 21.9 | 22.4 |
| 1986i | NGC 4254 | II | 610 | – | 23.4 | 23.4 |
| 1986l | NGC 1559 | II | 470 | 19.8 | – | 20.2 |
| 1986o | NGC 2227 | Ia | 390 | 23.0 | 23.0 | 22.4 |
| 1987d | MCG + 00-32-01 | Ia | 270 | 20.3 | 20.4 | 19.9 |
| 1987f | NGC 4615 | II pec | 290 | 20.0 | 18.7 | 20.2 |
| 1987k | NGC 4651 | II | 180 | 20.0 | 19.6 | 19.4 |
| 1986g | NGC 5128 | Ia | 374 | – | 20.3 | V 20.1 |

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