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Youth Academy " Leonardo "
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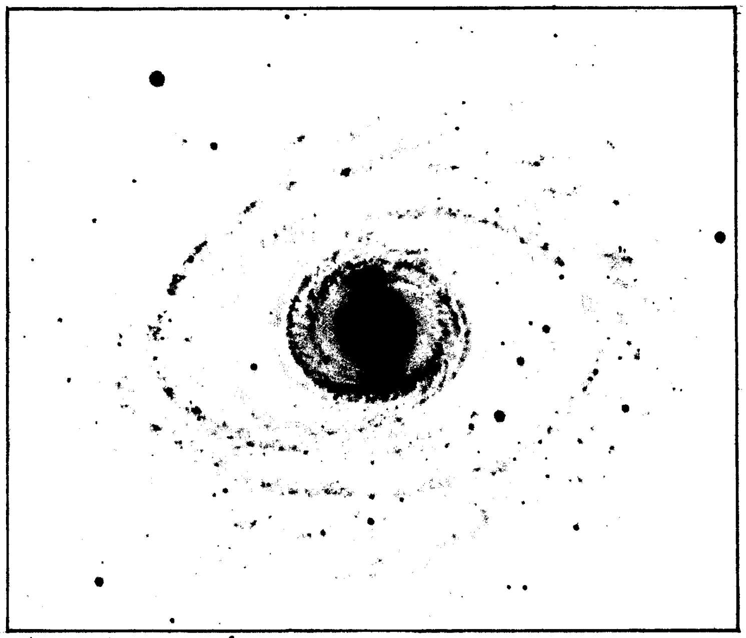
Some notes on

SNe SEARCH WITH CCD's



Višnjan School of Astronomy

AUGUST 07-21, 1993

Visnjan, August 07-21.08. 1993.

Dear friends,

The aim of this booklet is to introduce you to the interesting field of Supernovae (hereafter SNe) and SNe Search. For this reason the articles you will found here are far to be a complete and extensive paper collection on current SNe research status. For our purpouses it's enough to know WHAT the so called SNe are, WHICH is the best way to recognize SNe and WHERE to look for them.

The content of the following pages follow faithfully the main topics of our course on SNe Search. For a few subjects we will talk about without any written reference because, as you could easily imagine by yourselves, the SNe search is at the end mainly based on everyone's experience. This is because for every instrumental equipment and observing site condition you have to choose the best strategy in order to maximize your chances for a discovery.

We don't know, right now, if we'll be successful in our SNe search or not, bu surely if we don't try we have no possibility to discover a SN at all!

Anyway, at the end of our "astronomical holiday" we will surely leave Visnjan with some additional knowledge and new friends.

Best wishes for a successful SN-hunt!

-Giovanni Sostero1 & Vanja Brcicc

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Current theories on supernovae

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There are two major classes of supernovae (SNe) distinguished by their optical spectra, called Type I and Type II. Type I SNe show no evidence for hydrogen in their spectra. This means that they have shed or consumed the bulk of their hydrogen. The spectra of Type II SNe show a normal hydrogen abundance. SN 1987A, which galvanized the community in February 1987, is the latter type.

Each type of SNe in turn has at least two important subcategories. The shape of the light curve suggests two classes of Type II. In one, the brightness drops from maximum in a uniform way. These are known as Type II-linear (SN II-l). In the other class, the brightness hovers at a nearly constant value for a prolonged time, particularly in the visual band. These are known as Type II-plateau (SN II-p). These classes may represent the extremes of a continuum rather than distinct classes, but they prove physically different. One of the most exciting recent developments in the study of SNe has been the realization that some Type I events are not just a little 'peculiar', but represent a major category of SNe. This realization has followed directly from the key discoveries of SN 1983N, 1983V and 1984L by and amateur, the Reverend Robert Evans. The notation Type Ia (SN Ia) has been adopted to denote the classical Type I events, and Type Ib to describe the new category which is a major focus of current research.

Type II SNe occur primarily in spiral galaxies and are associated with the spiral arms or other regions of active star formation. This suggests that Type II arise from massive, short-lived stars that are born and die in the spiral arms. Studies of the light production of SN II-p are consistent with an explosion occurring in the extended envelope of a highly evolved massive star. There are some hints that SN II-l occur in stars with smaller hydrogen envelopes, but the physical basis for distinguishing between SN II-l and SN II-p is not well understood.

The standard assumption is that Type II SNe arise at the endpoint of evolution of single massive stars. The best guesses at the rate of explosions of Type II SNe in our Galaxy suggest that stars with masses in the range of 10 to 20 solar masses must be involved. Lower masses would give too many SNe. Stars with masses greater than about 20 solar masses may explode, but they cannot be the sole progenitors of Type II SNe because they are too few.

Stars with masses below about 8 solar masses form very dense cores composed of carbon and oxygen. Most of these lower mass stars will shed their outer envelopes quietly. If some stars below 8 solar masses retain their envelopes and evolve to a thermonuclear explosion, no neutron star remnant is expected to form. A model based on such a thermonuclear explosion inside a star that has lost most, but not all, of its hydrogen envelope gives a fair representation of the peak light curve of a SN II-l event, but the origin of such a configuration and its ability to match other observational constraints is unclear.

Stars of between perhaps 8 and 12 solar masses burn carbon gently to produce neon and magnesium, but these elements and the surviving oxygen form a dense core. The density becomes so high that the electrons which provide the pressure support for the core are captured by protons in the neon and magnesium, to form neutrons. This reduction of pressure support causes the core to collapse. Oxygen ignites and burns, making elements in the iron peak, but insufficient energy is released to generate an explosion. The core continues to collapse, electron capture goes to completion and a neutron star forms.

For higher masses, from about 12 solar masses to the largest stars seen, $\sim$100 solar masses, the evolution proceeds a bit more simply, but with the same result. All thermonuclear burning takes place during the quiet evolution, with the ash of each burning process being heated to become a fuel in its own right. The result is a structure with multiple layers of increasingly heavy elements and an inner core of iron. When the iron disintegrates, collapse ensues, and rapid electron capture again leads to the formation of a neutron star. This is precisely the evolution dramatically confirmed by the discovery of neutrinos from SN 1987A, which is thought to have resulted in the explosion of a star with organized mass in the range 15–20 solar masses.

Despite the lessons of SN 1987A we do not yet understand the precise mechanism of explosion, whether by core bounce and 'prompt shock' or by a delayed shock pumped by the neutrino energy of the cooling neutrino star. We do not know whether all such massive stars will explode, or whether some may suffer ultimate collapse to make a black hole. To find a 'new' star is relatively easy; but to find a star which is there one night and gone the next would be an amazing discovery!

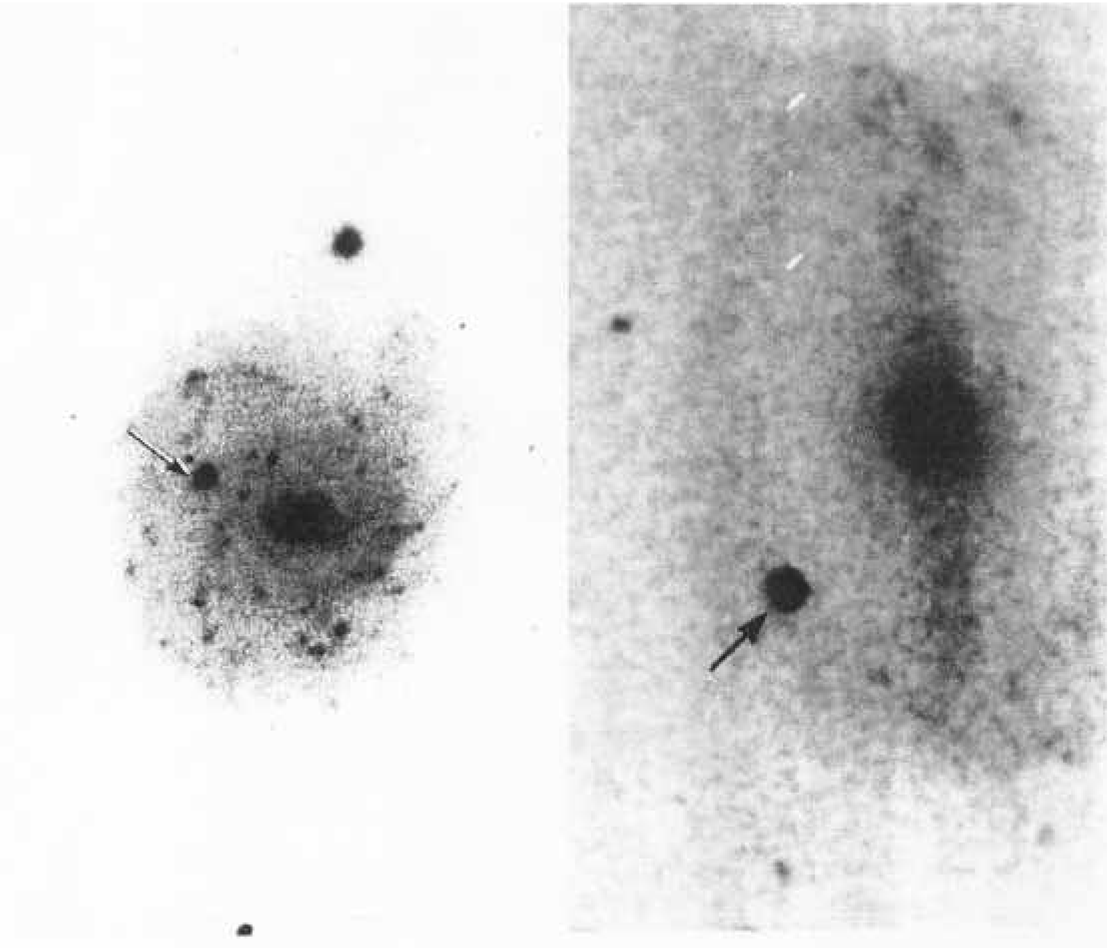
Type Ia SNe occur in all types of galaxies and are particularly noticeable in elliptical galaxies which have never been observed to produce a Type II. The light curves of SN Ia show a very uniform pattern. There is an initial peak and then a long uniform tail in which the power decays in an exponential fashion, within the observational uncertainties. Several lines of work suggest that a model in which light is produced by the radioactive decay of nickel-56 provides a good picture of the observations. Nickel is the natural reaction product of the incineration of elements such as helium, carbon or oxygen, that have equal numbers of protons and neutrons. Nickel occurs naturally in models in which the precursor star is a white dwarf which undergoes a thermonuclear explosion.

A widely studied model which has many features observed in SN Ia involves a special form of thermonuclear explosion of a carbon/oxygen white dwarf. In this model, it is argued that carbon burns quickly but does not provide enough overpressure to drive a strong shockwave. Rather, burning is propagated by a subsonic deflagration process in which there is a turbulent heat exchange. This rapid, but subsonic, process will totally disrupt a carbon/oxygen white dwarf, leaving no neutron star. Some unburned or partially burned material will remain in the outer portions of the expanding material as observations seem to demand. This particular model is under current assault theoretically because careful analysis of the carbon ignition process seems to call for the production of a supersonic detonation rather than the subsonic deflagration. This conclusion may be more consistent with the physics, but it does not correspond to observations. A detonation threatens to turn the whole white dwarf into nickel, in contradiction to the observational demand for elements of intermediate atomic mass. Reconciling the physical and observational demands is an exciting challenge!

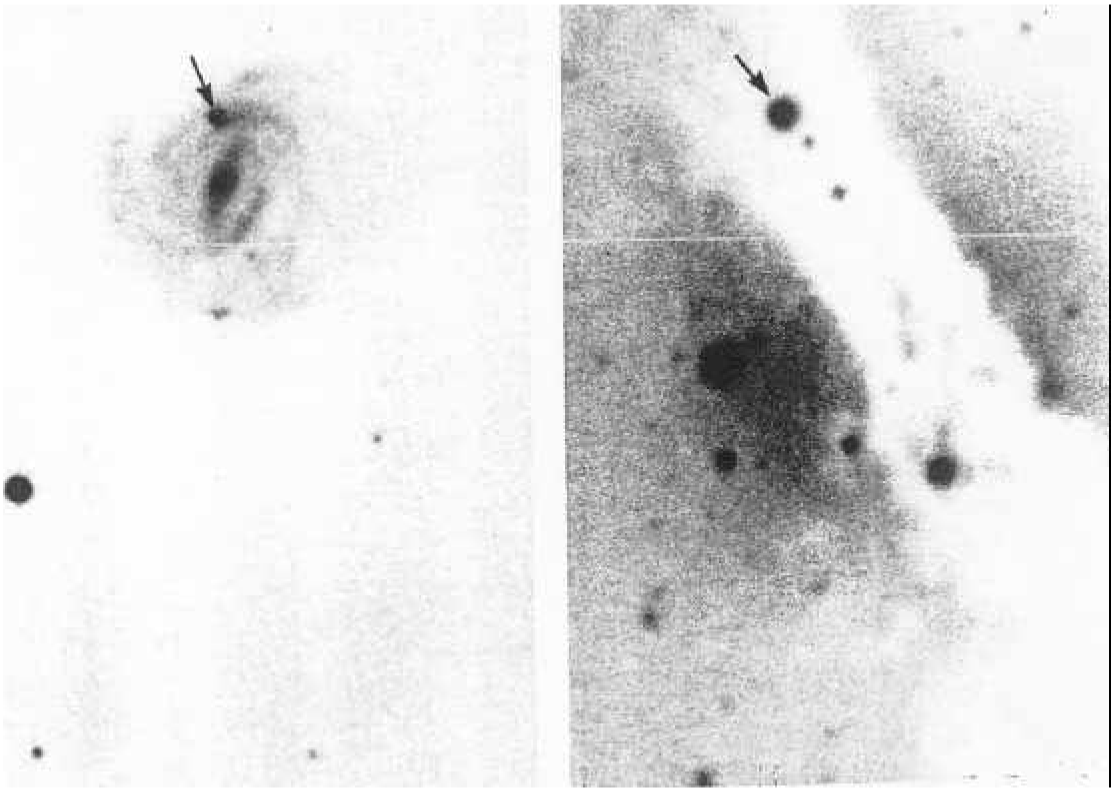
The closely-associated problem also remains to determine which processes of stellar evolution can give rise to exploding white dwarfs and hence SN Ia. A natural suggestion is to transfer mass from a main sequence star onto a white dwarf in a close binary system. Surprisingly, that picture has a number of problems. Nova explosions may whittle the mass of the white dwarf down instead of growing it to an explosive point. In addition, we do not see enough cataclysmic variables with the right properties to account for the rate of occurrence of SN Ia.

An idea currently being explored is that some binary systems may evolve to yield two white dwarfs in orbit. A curious feature of white dwarfs is that those with less mass are geometrically larger, and more susceptible to disruption. As the white dwarfs spiral together, the one with the smaller mass will be destroyed and its matter rapidly dumped upon the more massive white dwarf. This process leads to some configurations not considered previously in stellar structure, and some very interesting prospects for producing explosions.

Unlike SN Ia, Type Ib SNe are closely associated with regions of active star formation and patches of gas ionized by young, massive stars. This suggests that the exploding stars are themselves massive. Since these stars are Type I, they show no evidence of hydrogen and must have ejected any hydrogen envelope. One active current speculation is that SN Ib represent the explosion of the core of a massive star which has lost its hydrogen envelopes in a powerful stellar wind or perhaps by transfer to a nearby stellar companion. If this is the case the mechanism of triggering the explosion is probably the collapse of the innermost core to form a neutron star, the same physical process invoked to explain Type II supernovae. Recent analysis has revealed that SN Ib have appreciable amounts of helium in their ejecta and that as they expand, regions dominated by oxygen are exposed to view. Helium and oxygen are characteristic of the cores of massive stars. If these clues are being correctly interpreted, SN Ib hold great promise to provide a very useful new way to explore the innermost workings of evolving, exploding massive stars.



NGC 991 and its supernova discovered visually by Evans on 28 August, 1984 at magnitude 14.0. (*left*), together with three other supernovae discovered by him in NGC 1433 (*right*), NGC 3367 (*following page, left*), and NGC 5128 (*following page, right*).



Observational definition of supernova types

James T. Bryan, Jr and Harold G. Corwin, Jr

I Introduction

All natural objects occur with a variety of forms. Supernovae (SN) are no exception. Therefore, it is possible to classify them into broad categories according to characteristic features seen in different SN events. Astronomers have done this in two primary ways: spectroscopically and photometrically, and we shall discuss each in turn.

For the most part, we shall limit our remarks to observational considerations. The theoretical interpretation of the observations is still in its infancy – researchers have only tentative ideas of the real nature of these massive explosions, and of the stars that give rise to them. Professor Craig Wheeler's Appendix I in this Handbook discusses some of the current theories of SNe.

II Definition by spectral characteristics

The original definition of SN types was made spectroscopically by Rudolph Minkowski of Mt Wilson Observatory in 1941 and reads as follows:

> Spectroscopic observations indicate at least two types of supernovae. Nine objects . . . form an extremely homogeneous group provisionally called 'type I'. The remaining four objects . . . are distinctly different; they are provisionally designated as 'type II'. The individual differences in this group are large; at least one object . . . may represent a third type or, possibly, an unusually bright ordinary nova. . . .
> No satisfactory explanation for the spectra of type I has been proposed. Two O I bands of moderate width in the later spectra of the supernova in IC 4182 are the only features satisfactorily identified in any spectra of type I. They are, at the same time, the only indication of the development of a nebular spectrum.[1] . . . As compared with normal novae, supernovae of type II show a considerably earlier type of spectrum[2] at maximum, hence a higher surface temperature (on

1 A spectrum resembling that of a planetary or diffuse nebula.

2 Characteristic of 'early' type stars, that is, stars of spectral types O, B, and A.

> the order of 40 000 deg C), and the later spectrum indicates greater velocities of expansion (5000 km/sec or more) and higher levels of excitation. Supernovae of type II differ from those of type I in the presence of a continuous spectrum at maximum and in the subsequent transformation to an emission spectrum whose main constituents can be readily identified (as the Balmer lines of singly ionized hydrogen, H II). This suggests that the supernovae of type I have still higher surface temperatures and higher levels of excitation than either ordinary novae or supernovae of type II.

Minkowski's observations and interpretations stood alone for approximately 30 years as the fundamental definition of SN types. Even today, the basic criterion that he adopted to differentiate between Type I SNe and Type II SNe is still used; Type II's have hydrogen lines present in their spectra, while Type I's do not.

Central to Minkowski's work was a year-long series of spectroscopic observations with the 100-inch Hooker telescope on Mt Wilson of SN 1937C in IC 4182 which set standards for the Type I events. These observations provided a basis for comparison for subsequent SNe which led to Minkowski's recognition of the two types by 1941. Fritz Zwicky in 1965 suggested the existence of no less than five types of SNe, with his Types III, IV, and V represented by only one SN each. However, most astronomers now recognize only Minkowski's Types I and II, but still acknowledge the existence of individual peculiarities within these two types. In particular, Zwicky's Types III to V were probably peculiar Type II events with somewhat unusual light curves and spectral characteristics (see Section III, below).

The introduction of fast image-tube spectrographs and photoelectric spectrometers has brought more detail to Minkowski's longstanding definitions of the basic SN types. In 1974, J. B. Oke and Leonard Searle at the California Institute of Technology provided further elaboration upon the spectral evolution of SNe after maximum light. Using the idea that type is primarily determined by spectroscopic observations – leaving the light curve as a secondary classifier – they found that no clearly distinct groups exist beyond the canonical Types I and II. Here is a synopsis of their description of the post-maximum phases:

Type I

Phase A (0 to 20 days past maximum)

> The spectrum is a smooth continuum involving P-Cygni lines[3] which are usually indicative of a star surrounded by an expanding gas shell.

3 Emission lines with absorption lines of the same element slightly blue-shifted from the emission.

stellar atmospheres; (2) that the effective temperatures range from 10 000 degrees K towards the end of the maximum brightness phase to 5000 – 6000 deg K after two or three weeks; and (3) that even after a year or more, a continuum still appears to exist. . . .

The regular change of the energy distribution with time in both Types I and II indicates that the bulk of the radiation is a thermal continuum rather than a superposition of strong, broad emission lines, as sometimes postulated in the past.

. . . the observations of Kirshner *et al.* (1973) show that there are lines in the spectra of both Types I and II whose shapes resemble those of lines seen in the spectra of P-Cygni stars and of novae shortly after maximum light. These consist of broad emission flanked on their violet edges by broad absorption. . . . In Type II's, which have relatively weak lines, this line shape is clearly seen to be the general shape of most lines, although profiles of the various lines differ in detail. In Type I's, where the lines are strong and crowded, this characteristic P-Cygni profile is clearly discernible in a few particularly strong isolated lines, but it is probably also the basic shape of the components of the blended features in more crowded regions of the spectrum. . . .

The expansion velocities of the outermost layers of the supernova envelopes are [approximately] . . . 15 000 km/sec for Type II's and 20 000 km/sec for Type I's.

Even as some astronomers searched for common characteristics among SNe, others reported occasionally striking differences between different events. Bertola (1964) and Bertola *et al.* (1965) reported observations of two Type I supernovae that did not show the 6150Å feature usually seen in the spectra of these objects. Bertola (1964) also suggested that one of the SNe (1962L in N1073) was considerably fainter than normal Type I's. Recently, two other supernovae with similar spectra [1983N in M83 (Gaskell *et al.* 1986) and 1984L in NGC 991 (Wheeler and Leverault 1985), both discovered by the Reverend Robert Evans] have stimulated interest in possible sub-classifications of Type I's. In a comparative study of Type I spectra, Branch (1986) found two definite subclasses of objects which he calls Type Ia and Type Ib. Type Ia objects are the classical Type I SNe described above by Oke and Searle. The four Type Ib objects are similar but, as just noted, lack the strong 6150Å feature at maximum light. In addition, they do not seem to show most of the features attributed to the so-called 'intermediate-mass' elements ranging from oxygen to calcium that are also common in Type Ia's at maximum. Instead, they are dominated by blends of lines due to neutral helium and singly ionized iron (Fe II) (see e.g. Axelrod 1980 and Wheeler and Harkness 1986). Branch finds that the spectra of Type Ib's do not evolve so dramatically as Type Ia's as the objects fade with time. He therefore

The strongest emission lines occur at 3950, 4600, 5180, 5900, and 8600Å, with many other weaker features strengthening over this time period. A strong absorption feature is usually seen at 6150Å, but no Balmer lines of hydrogen exist in either emission or absorption.

Phase B (20 to 60 days past maximum)

The continuum is relatively smooth but is gaining strength in the red. Nevertheless, the spectrum remains largely unchanged throughout this second phase. P-Cygni lines remain, but are evolving with the absorption gaining strength slowly. New emission lines occur in the region from 5180Å to 5600Å.

Phase C (60 to about 100 days past maximum)

Only subtle changes are noted during this phase, with the emission around 5600Å usually disappearing.

Phase D (roughly 200 to 400 days past maximum)

Radical changes in the relative intensities of the spectral features occur. Strong absorption bands develop to the violet side of the now weak emission lines at 3950Å, 5900Å, and 8600Å. A broad emission feature appears at 7200Å and very strong emission is seen at 4750Å and 5300Å.

Type II

Phase A (0 to 20 days past maximum)

There is a smooth continuum with a strong H-alpha emission line (6563Å). H-beta (4861Å), H-gamma (4340Å), and features at 3950Å. 5150Å, and 5900Å have P-Cygni profiles that strengthen as this phase progresses. P-Cygni absorption features are especially strong in this early phase.

Phase B (20 to 70 days past maximum)

As with Type I SNe, the continuum remains smooth, but reddens. Absorption features become prominent throughout the blue part of the spectrum. A few Type II SNe have had strong P-Cygni features at 6800Å, and a strong emission band at 4600Å has been seen in a few others.

Phases C, D, etc (more than 70 days past maximum)

There are few observations of Type IIs during these later phases. However, the extant observations indicate the continued presence of the continuum, H-alpha in emission, and the appearance of the forbidden lines of Ca II and O I.

In evaluating the then-current understanding of SNe, Oke and Searle identified general spectral characteristics which, when considered with Minkowski's remarks, give more complete insight into the differences – and similarities – between the two main types:

> Recent absolute spectrophotometry of supernovae of both Types I and II (by Kirschner and his colleagues) has served to emphasize (1) that the overall energy distributions are very much like supergiant

suggests that at later phases, the two sub-types become essentially indistinguishable. However, Gaskell *et al.* (1986) have shown that at least one of the Type Ib objects (SN 1983N) had a spectrum eight months past maximum that was quite different than that of typical Type Ia's at the same phase. They also suggest that SN 1985F in NGC 4618 (Filippenko and Sargent 1985) was a Type Ib discovered well past maximum, as its spectrum was very similar to the late-time spectra of 1983N.

Branch (1986) also found that five Type I supernovae showed sufficient spectral peculiarities that they could be fit comfortably in neither sub-class; he has called these simply 'Type Ipec'. He confirms the earlier suggestions (e.g. Bertola 1964 and Wheeler and Leverault 1985) that the Type Ib's – as well as the Type Ipec's – are about 1.5 magnitudes fainter at maximum light than the Type Ia's. Unfortunately, there are so few of these objects known that this relative faintness should not yet be considered well-established.

Recent work with computer models of supernovae explosions deserves mention too. The importance of these models rests in the fact that not only can astronomers make identifications of supernovae spectral lines and predict their light curves (see Section III, below), but that they can also gain insight into the actual physical processes producing the lines and light curves. Making reasonable assumptions about the compositions and masses of highly evolved stars, and the temperatures, rates of expansion, and densities of supernovae shells, Axelrod (1980), Branch and his colleagues (1981, 1982, 1983), Nomoto *et al.* (1984), Wheeler and Harkness (1986 and references therein), and many others have been able to produce synthetic spectra that match the actual supernova spectra in surprising detail. For example, the broad 6150Å feature in Type Ia's is apparently due to a blue-shifted line of ionized silicon (Si II) normally seen at 6355Å. This in turn suggests that this spectral line arises in a chaotic cloud of hot gas approaching us at some 10 000 km/sec, verifying our instinctive notions of the tremendous energies involved in the SNe. As we noted above, Professor Wheeler discusses current ideas about the different models of supernovae and how they relate to the observations in his Appendix, so we will not go into further detail here.

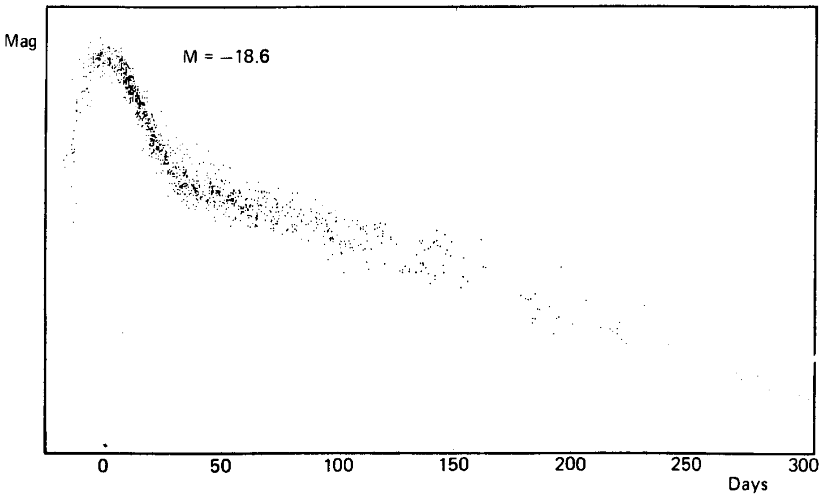
III Photometric properties of supernovae

Photographic and photo-electric photometry have been the other important tools for the observational study of SNe. Photometry and spectroscopy can, of course, be combined into spectrophotometry where arbitrarily small portions of the spectrum are measured for intensity with a photo-electric device. Most spectroscopic observations of supernovae are now made with spectrographs of this type, but photometry with broad-band devices (e.g. photometers equipped with UBV filters, photographic plates, etc.) remains the major method of gaining knowledge of the overall photometric behaviour of SNe.

Working at the Asiago Astrophysical Observatory in the foothills of the Italian Alps, Roberto Barbon, Franco Ciatti, and Leonida Rosino (1973, 1979) have attempted to combine the light curves[4] of several SNe in order to define 'average' light curves for the two SN types. Throughout their work, Barbon, Ciatti, and Rosino used the average maximum absolute magnitude for Type I SNe derived by Charles Kowal at the California Institute of Technology in 1968. This is $M(\mathrm{pg}) = -18.6$. For Type II SNe, they found $M(\mathrm{B}) = -16.45$, virtually the same as Kowal's value, $M(\mathrm{pg}) = -16.5$.[5] Recall, however, that there is a considerable range in the absolute magnitudes of the different subclasses of Type I's. Branch *et al.* (1981) found that SN 1979C in M100, a somewhat spectroscopically peculiar Type II, had an absolute magnitude typical of a Type Ia, that is about two magnitudes brighter than normal Type II's.

Considering the overall similarity of the spectra of Type I's, it came as no surprise to Barbon, Ciatti, and Rosino to find that the light curves are also quite similar, leading to the expectation that Type I's might be used as extragalactic distance indicators.[6] From photographic and photo-

Fig. 3 Type I: average blue light curve from 38 Type I supernovae redrawn from Barbon, Ciatti, and Rosino (1973).



4. Plots of magnitude versus time.
5. Photographic and photoelectric magnitudes are nearly the same at B − V = O, the approximate colour of supernovae at maximum.
6. For a discussion of supernovae as distance indicators, see Bartel (1985) and the many papers and references therein.

electric observations of 38 SNe, they constructed an average blue-magnitude light curve; this is shown in Fig. 3.

From this average light curve, the following points were deduced:

(1) 'Maximum' light (when the SN is within about 3–4 magnitudes of maximum) typically lasts 18 or 19 days.

(2) The rise time from 3.0 magnitudes below maximum to maximum averages 15 days; from 2.0 magnitudes below maximum, 13 days; from 1.0 magnitude below, 10 days.

(3) The time needed to fall 1.0 magnitude below maximum light averages 14 days; to fall 2.0 magnitudes, 23 days; to fall 3.0 magnitudes, 55 days.

(4) Expressed slightly differently, the rate of decay past maximum light averages 0.087 mag/day for the first 30 days past maximum, but decreases thereafter averaging 0.016 mag/day from about 50 days past maximum on.

This slowing of the decline in light causes an inflection point in the light curve 30 to 50 days past maximum, and 2.5 to 3.0 magnitudes below maximum.

Barbon and his colleagues tentatively identified two sub-types within the Type I light curves. Eleven SNe are characterized by relatively narrow maxima and rapid initial declines to the inflection point about three and a quarter magnitudes below maximum; these are the 'fast' Type Is. The 'slow' Type I's are associated with fifteen SNe displaying relatively broad maxima and falling only about 2.5 magnitudes to the inflection point. Both types reach the inflection point 30 to 50 days past maximum. The mean light curves for the 'fast' and 'slow' Type I SNe are shown in Figs. 4 and 5. These two sub-types based on light curves do *not* correspond to Branch's sub-types based on spectra. Dogget and Branch (1985) are also not yet convinced that the distinction between 'fast' and 'slow' Type I's is significant; they find that all Type I light curves are similar enough that they can be combined into a single composite light curve.[7] Only more and better photometric data will resolve these differences of interpretation. This demonstrates vividly just how little we really know about SNe.

The colour evolution of Type I's was also investigated at Asiago. Again, considering the evidence of the spectra, there were no surprises in the average colour curve, shown in Fig. 6. For the first 30 days, the B − V colour rises rapidly, reflecting the reddening seen in the spectrum. Near the inflection point in the light curve, however, the colour curve

7. Some astronomers, however – see Doggett and Branch for references – have suggested that the 'slow' supernovae are brighter at maximum than the 'fast' supernovae.

Fig. 4 Type I 'fast': average blue light curve from 11 'fast' Type I supernovae redrawn from Barbon, Ciatti, and Rosino (1973).

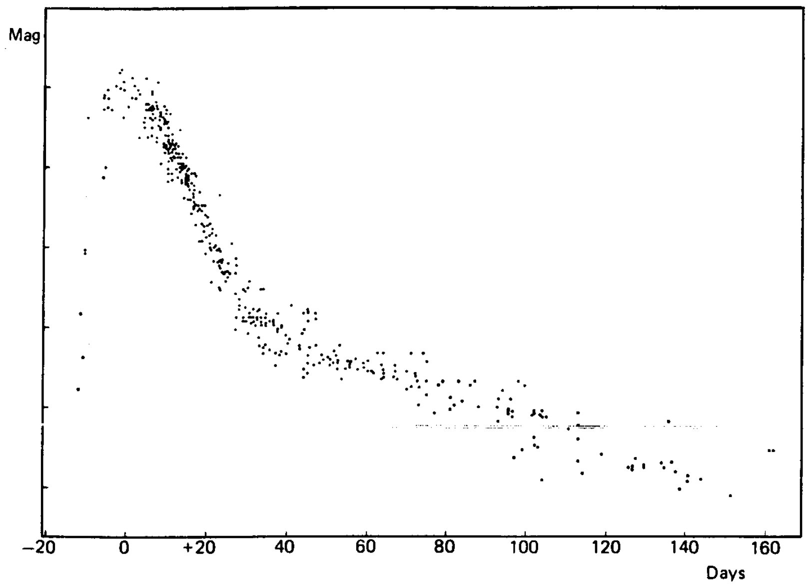
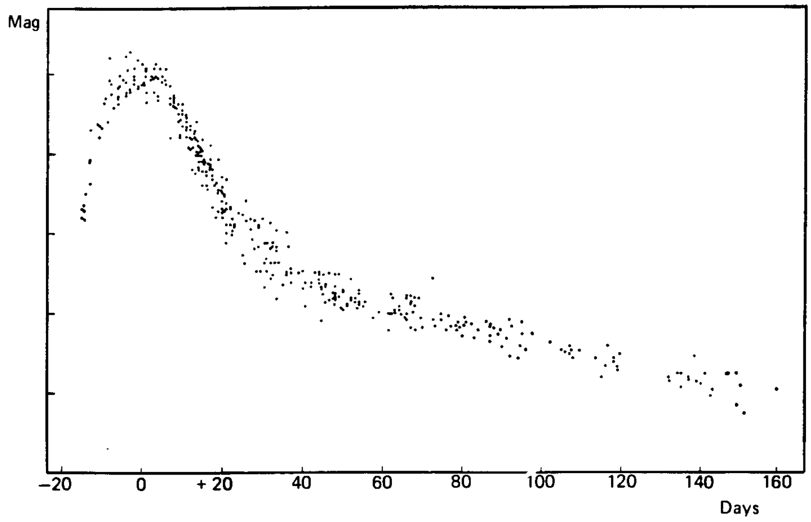


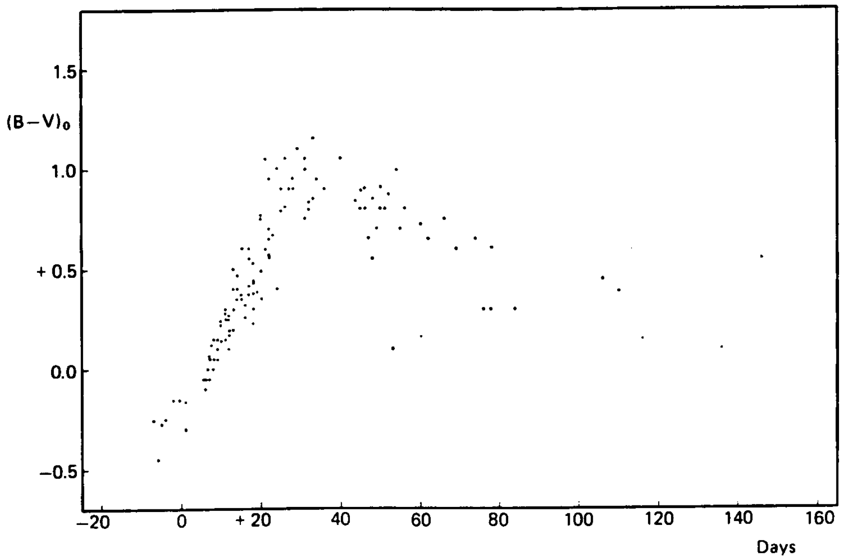
Fig. 5 Type I 'slow': average blue light curve from 15 'slow' Type I supernovae redrawn from Barbon, Ciatti, and Rosino (1973).



reverses direction, and the B − V colour more slowly returns to about 0 (white), the same colour index as is usually observed near maximum.

Type II SNe show more variety in their light and colour curves, so that the construction of 'average' curves is more difficult. However, within the Type II's there seem to be two broad groups characterized by

Fig. 6 Type I: average B − V color curve from 13 Type I supernovae redrawn from Barbon, Ciatti, and Rosino (1973).



the presence or absence of a 'plateau' (a pause in the rate of decline) in the post-maximum light curve.

The plateau sub-type, defined by 15 SNe, evolves in the following manner;

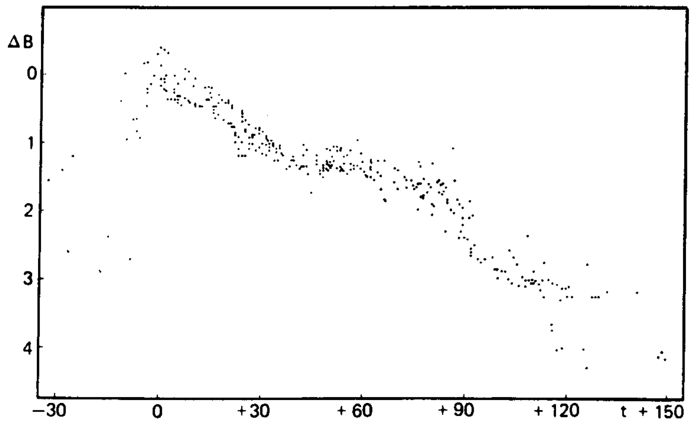
(1) There is an initial rapid decline in the light, amounting to about 1.2 magnitudes over the first 30 to 35 days past maximum.
(2) This is followed by a complete halt or (more usually) a lessening of the rate of decline – the so-called 'plateau' – lasting up to 50 days.
(3) The next 50 days are again characterized by a more rapid decline in the light.
(4) Finally, the rate of decay of the light again slows, but this is not as drastic as during the plateau phase.

The average light curve of the Type II's with plateaus is shown in Fig. 7.

Six other Type IIs studied at Asiago showed either a linear decay, or just a hint of a plateau in their light curves. These SNe are usually called Type II-L and the mean light curve for these is shown in Fig. 8. Doggett and Branch note that the scatter in the data for the light curves is large enough that it is probably not possible to distinguish between Type I or Type II SNe simply on the basis of the light curves alone.

Finally, three SNe tentatively classified as Type II had spectra and light curves that fit comfortably into neither category. As noted above, Zwicky considered these to be the prototype objects for what he called

Fig. 7 Type II 'plateau'; average blue light curve from 15 Type II supernovae with plateaus redrawn from Barbon, Ciatti, and Rosino (1979).



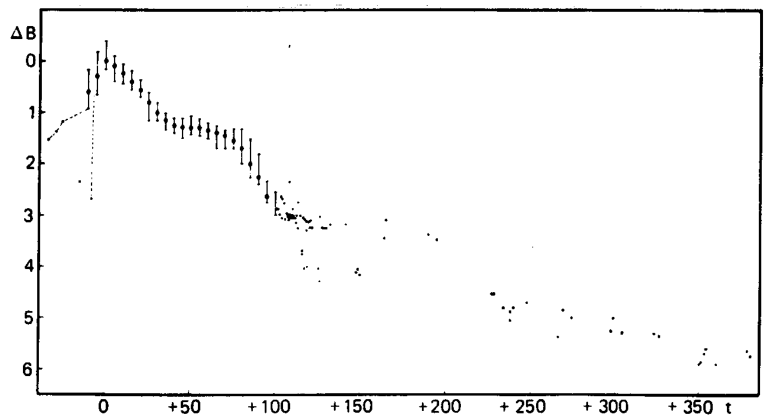


Fig. 8 Type II 'linear': average blue light curve from 6 Type II supernovae with linear light decay redrawn from Barbon, Ciatti, and Rosino (1979).

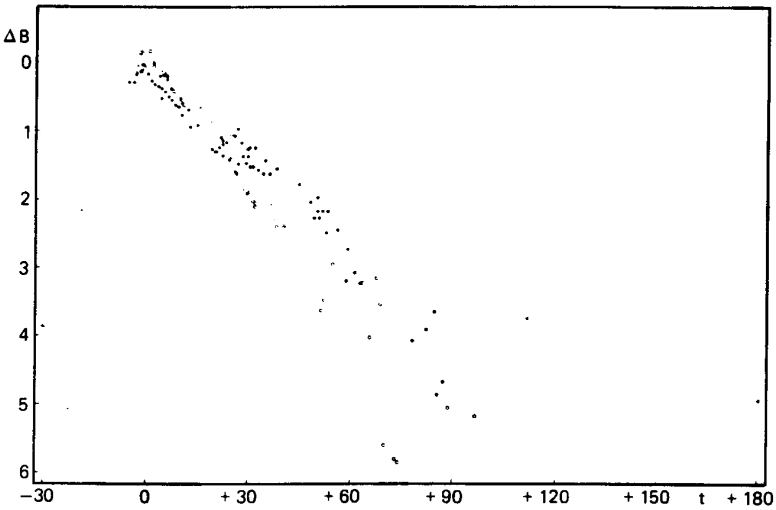
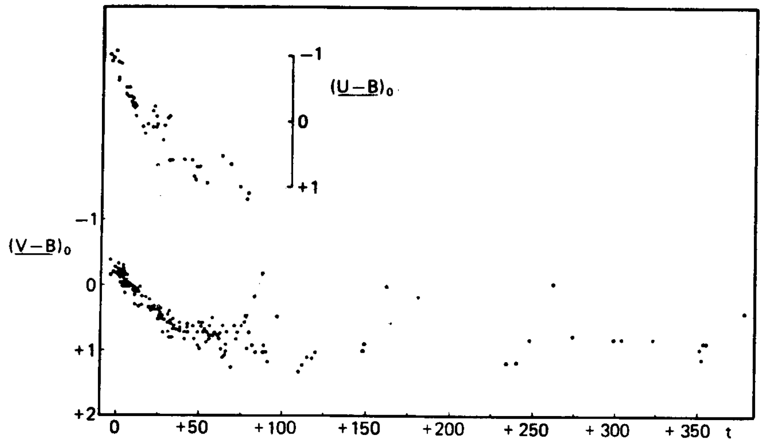


Fig. 9 Type II: average B − V and U − B color curves from 10 Type II supernovae (B − V) and 5 Type II's (U − B), with plateau and linear sub-types shown by dots and open circles, respectively; redrawn from Barbon, Ciatti, and Rosino (1979).



Types III, IV, and V, but noted that the data were incomplete for all three events. Doggett and Branch prefer to call these 'Type II-pec' rather than to create new classes containing just one object each.

Doggett and Branch also find it impossible to assign definite types to the two most recent supernovae in our own Galaxy, Tycho's and Kepler's SNe of 1572 and 1604, respectively. For these two objects, we have only crude light curves that can be fit by either a Type I or a Type II-L light curve. Nevertheless, they consider that a Type I classification is probably correct for at least Kepler's object, as it occurred several hundred parsecs from the plane of our Galaxy – Type II's appear preferentially in the spiral arms of galaxies; the arms are usually confined to the central planes of galaxies. Tycho's SN was only 60 to 100 parsecs out of the plane of the Galaxy, so this criterion cannot be applied to it.

Barbon, Ciatti, and Rosino summarize the colour changes for Type II's as follows:

> In the first days after maximum, we observe negative values of colour indices, which are followed by reddening in the supernova light. Only the [absorption-corrected] B − V curve, which extends over a larger time interval [than the U − B curve], gives an indication of . . . a halt in the reddening after about 120 days following the outburst. . . . This trend differs from that of Type I's, . . . which show a definite inflection point at about 30 days after maximum. Type II's appear to cover the same colour range, though at a slower rate.

Figure 9 shows the average B − V and U − B colour curves for Type II SNe. The U − B curve in particular is not well-known due to a lack of observations.

Without the patient and willing guidance of Professors David Branch and Craig Wheeler, this Appendix would have been a much poorer reflection of the current state of supernova research. We are grateful for the time and information that they gave us.

References

Axelrod, T. S. (1980). In *Type I Supernovae*, ed. J. C. Wheeler (Austin: University of Texas), p. 80.
Barbon, R., Ciatti, F., and Rosino, L. (1973). *Astron. Astrophys.* **25**, 241.
Barbon, R., Ciatti, F., and Rosino, L. (1979) *Astron. Astrophys.* 72, 287.
Bartel, N. (ed). (1985). 'Supernovae as Distance Indicators', Berlin: Springer–Verlag, *Lecture Notes in Physics*, No. 224.
Bertola, F. (1964). *Annals d'Astrophysique*, **27**, 319.
Bertola, F., Mammanno, A., and Perinotto, M. (1965). *Asiago Obs. Contrib.* No. 174.
Branch, D. (1986). *Astrophys. J. (Letters)* **300**, L51.
Branch, D., Buta, R. J., Falk, S. W., McCall, M. L., Sutherland, P. G., Uomoto, A. K., Wheeler, J. C., and Wills, B. J. (1982). *Astrophys. J. (Letters)* **252**, L61.
Branch, D., Falk, S. W., McCall, M. L., Rybski, P., Uomoto, A. K., and Wills, B. J. (1981). *Astrophys. J.* **244**, 780.
Branch, D., Lacy, C. H., McCall, M. L., Sutherland, P. G., Uomoto, A. K., Wheeler, J. C., and Wills, B. J. (1983). *Astrophys. J.* **270**, 123.
Doggett, J. B. and Branch, D. (1985). *Astron. J.* **90**, 2303.
Gaskell, C. M., Cappellaro, E., Dinerstein, H. L., Garnett, D. R., Harkness, R. P., and Wheeler, J. C. (1986). *Astrophys. J (Letters)* **306**, L77.
Filipenko, A. V. and Sargent, W. L. W. (1985). *Nature* **316**, 407.
Kirshner, R. P., Oke, J. B., Penston, M. V., and Searle, L. (1973). *Astrophys. J.* **185**, 303.
Kowal, C. T. (1968). *Astron. J.* **73**, 1021.
Minkowski, R. (1941). *Publ. Astron. Soc. Pacific* **53**, 224.
Nomoto, K., Thielemann, F.-K., and Yokoi, K. (1984). *Astrophys. J.* **286**, 644.
Oke, J. B. and Searle, L. (1974). *Ann. Rev. Astron. Astrophys.* **12**, 315.
Wheeler, J. C. and Harkness, R. P. (1986). In *Proceedings of the NATO Advanced Studies Workshop on Distances to Galaxies and Deviations from the Hubble Flow*, ed. B. F. Madore and R. B. Tully, in press.
Wheeler, J. C. and Leverault, R. (1985). *Astrophys. J. (Letters)* **294**, L17.
Zwicky, F. (1965). In *Stellar Structure*, ed. L. H. Aller and D. B. McLaughlin, Chicago: University of Chicago Press, p. 367.

APPENDIX A

Formulae for manipulating distances and distance moduli for galaxies
If the apparent magnitude of a galaxy is m and its absolute magnitude is M, then the distance modulus μ is given by

$$\mu = m - M. \tag{1}$$

The distance modulus is just the difference between the galaxy's apparent and absolute magnitudes. If two galaxies of the same absolute magnitude are at different distances from us, the nearer galaxy will appear brighter and will have a smaller distance modulus since its apparent magnitude is numerically smaller.

Since this formula also applies to all objects within a galaxy (all have the same distance modulus), we can rewrite equation (1) and input the maximum absolute V magnitudes of supernovae and the distance modulus of the galaxy to find the apparent V magnitude at which we might expect to see supernovae in a given galaxy:

Type I	Type II	
$m = \mu - 18.5$	$m = \mu - 16.5.$	(2)

There is a small complication introduced by a galactic extinction– absorption and scattering of light by dust in our own galaxy. This makes objects seen through the dust appear fainter (i.e. it numerically increases the magnitude):

$$m_{\text{apparent}} = m_{\text{true}} + A_V. \tag{3}$$

Here m_{apparent} is the magnitude as we observe it at the telescope, and A_V is galactic extinction in the visual part of the spectrum. To take this into account, we must rewrite equation (1) replacing m with the right side of equation (3):

$$\mu_{\text{true}} + A_V = m_{\text{apparent}} - M \tag{4}$$

noting as we do that we must also introduce A_V on the left side of the equation in order to balance it. Note also that because the apparent magnitude helps to define the distance modulus (equation (1)), the distance modulus is also affected by galactic extinction. Finally, using the maximum absolute magnitudes for the two types of supernovae from equation (2), we rewrite equation (4) as:

$$\text{Type I: } m_{\text{apparent}} = \mu_{\text{true}} + A_V - 18.5 \tag{5a}$$

$$\text{Type II: } m_{\text{apparent}} = \mu_{\text{true}} + A_V - 16.5. \tag{5b}$$

As a matter of interest, the relationship between distance in megaparsecs and distance modulus in magnitudes is:

$$D^{\mathrm{Mpc}} = 10^{[(\mu/5)-5]} \tag{6a}$$

or

$$\mu = 5 \log[D^{\mathrm{Mpc}}] + 25. \tag{6b}$$

The table below shows the correspondence between distance modulus and distance (in megaparsecs – Mpc – and millions of light years – Mly). The table was constructed using equation (6) above, and can be used, by interpolation, to find the distances to any galaxy listed in the Atlas.

μ	D_{Mpc}	D_{Mly}	μ	D_{Mpc}	D_{Mly}
23.0	0.4	1.3	30.0	10.0	32.6
23.5	0.5	1.6	30.5	12.6	41.1
24.0	0.6	2.1	31.0	15.8	51.7
24.5	0.8	2.6	31.5	20.0	65.1
25.0	1.0	3.3	32.0	25.1	81.9
25.5	1.3	4.1	32.5	31.6	103
26.0	1.6	5.2	33.0	39.8	130
26.5	2.0	6.5	33.5	50.1	164
27.0	2.5	8.2	34.0	63.1	206
27.5	3.2	10.3	34.5	79.4	259
28.0	4.0	13.0	35.0	100	326
28.5	5.0	16.3	35.5	126	411
29.0	6.3	20.6	36.0	159	517
29.5	7.9	25.9	36.5	200	651

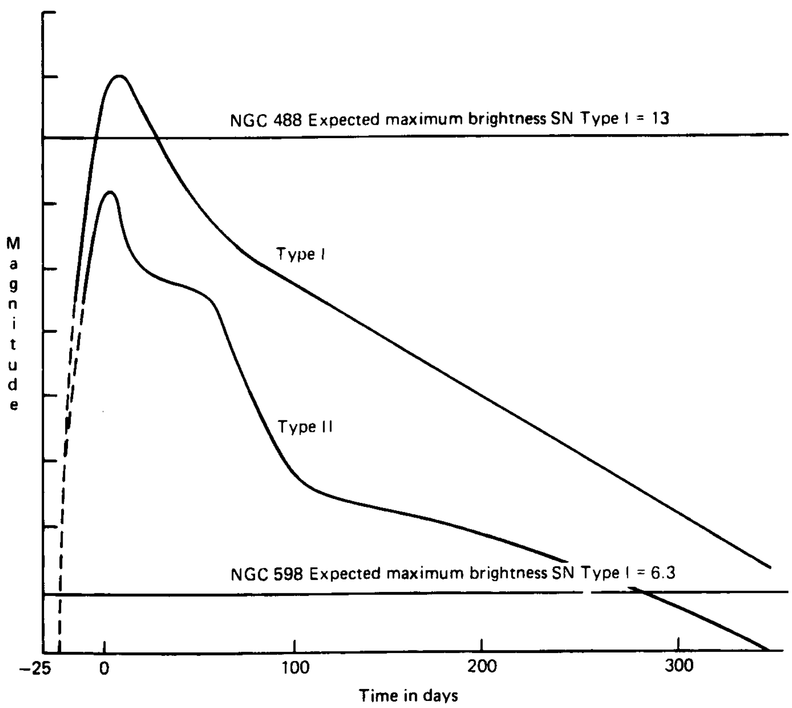
APPENDIX B

Light curves and expected visibility of a supernova

Figure 1 enables an observer to calculate the expected period of visibility of SNe in individual galaxies with respect to an observer's limiting magnitude.

In the figure the average visual light curves for Type I and Type II SNe are given, with the vertical axis indicating brightness (shown in approximately one magnitude intervals) and the horizontal axis defining the time in days. The expected maximum brightness of Type I SNe for a particular galaxy are given in the Notes section of the appropriate chart, and the peaks of the light curves are equated with these values. The

Fig. 1 Average visual light curves for supernovae types I and II.



difference between the expected maximum brightness and the observer's limiting magnitude is stepped off the vertical axis and a horizontal line is drawn at that level. The horizontal distance between the ascending and descending branches of the light curve then represents the period of visibility.

The expected maximum brightness of SN Type I and II for the galaxy NGC 598 is magnitude 6.3 and magnitude 8.3 respectively. If these values are equated to the peaks of the light curves for NGC 598 then a Type I SN will typically be about 7.7 magnitudes brighter than the observer's limiting magnitude and a Type II will be about 5.7 magnitudes brighter. The observer's limiting magnitude in this example is represented on the graph as the line NGC 598. This indicates a period of visibility of 360 days for a Type I SN and a little less than 300 days for a Type II SN after they have reached maximum brightness. NGC 488 is expected to produce Type I SNe of magnitude 13.1 and Type II of magnitude 15.1. Again, if the observer's limit is magnitude 14.0 a period of approximately 40 days exists to catch a Type I SN and no opportunity exists to discover a normal Type II SN. Therefore telescopes with limiting magnitudes fainter than 14.0 are required to discover SNe lying in the more distant galaxies. It is recommended that the observer evaluate the chances of detecting a SN in each galaxy before commencing the search. If the observer's limiting magnitude is not at least one magnitude fainter than the maximum expected brightness of a Type I SN for that galaxy, then the probability of discovery is poor.

The rising supernova

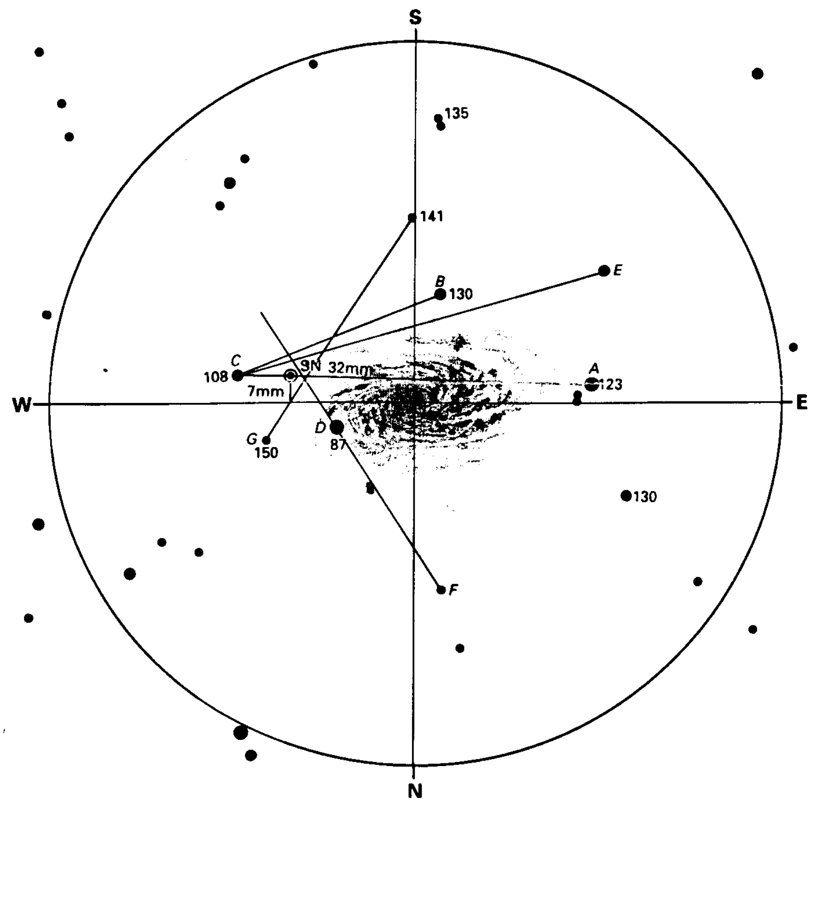
The most valuable SN discovery occurs before the SN reaches maximum brightness, i.e. on the ascending branch of the light curve. Astrophysicists are anxious to study SNe that are in the early stages of development because very little is known about the initial progress of a SN outburst. Most SNe have been observed only along the descending branch of the light curve. The period from the beginning of the SN explosion to its maximum brightness is believed to be in many cases as short as several days. Accordingly, an observer's chance of making a pre-maximum discovery is limited. Therefore frequent searches are required to enhance the chance of a valuable pre-maximum discovery (see the discussion in Appendix II).

APPENDIX C

It is necessary to determine the position and magnitude of the suspected SN as accurately as possible. First, circle its approximate position on the chart, preferably on a transparent overlay. Secondly, draw sets of lines between the field stars to refine its position. For example, in Fig. 2 the position of the suspect is above the line *CA* but below the lines *CB* and *CE*. This defines its position fairly closely in declination (north/south). The lines *FD* and *GH* then refine its position in right ascension (east/west). Once the position of the suspect has been plotted as accurately as possible, a ruler may then be used to measure its distance in millimetres left or right from the centre of the galaxy. This measurement in the horizontal will provide the offset in terms of right ascension. A similar measurement vertically provides the offset in terms of declination. Remember that the centre of the galaxy is located at the intersection of the north, south, east, and west markers. In the case of an SN occurring in the Magellanic Clouds, determine its location by right ascension and declination.

To convert offset measurements to arc seconds, multiply both distances in millimetres by 10 for charts with a scale of 10 seconds per millimetre, and similarly by 20 for those charts with a scale of 20 seconds per millimetre. The observer is cautioned *not* to make diagonal measurements. This will contravene the International Astronomical Union telegram convention for measuring the offset of a SN.

Fig. 2 Determining the position of a supernova.



APPENDIX D

LIST OF GALAXIES TO LOOK FOR SNe
-first half of the night-

NR.	OBJECT	CONSTELLATION	MAGNITUDE	REFERENCE MAP
1)	NGC 6503 (M102)	Dra	11.0	Thompson & Brian
2)	NGC 6946	Cep	11.0	Thompson & Brian
3)	NGC 3031 (M81)	Uma	8.0	Thompson & Brian
4)	NGC 3034 (M82)	Uma	9.5	Thompson & Brian
5)	NGC 5457 (M101)	Uma	8.0	Thompson & Brian
6)	NGC 2685	Uma	11.0	Hubble Atlas of G.
7)	NGC 2950	Uma	11.0	Hubble Atlas of G.
8)	NGC 3065	Uma	12.0	Hubble Atlas of G.
9)	NGC 5055 (M63)	Cvn	9.5	Thompson & Brian
10)	NGC 4736 (M94)	Cvn	9.0	Thompson & Brian
11)	NGC 5194 (M51)	Cvn	9.0	Thompson & Brian
12)	NGC 4258 (M106)	Cvn	9.0	Thompson & Brian
13)	NGC 3992 (M109)	Cvn	10.5	Thompson & Brian
14)	NGC 5962	Ser	11.5	Hubble Atlas of G
15)	NGC 6181	Her	12.0	Hubble Atlas of G.
16)	NGC 6814	Aql	11.0	Hubble Atlas of G.
17)	NGC 7217	Peg	11.5	Thompson & Brian
18)	NGC 7331	Peg	10.5	Thompson & Brian
19)	NGC 7335	Peg	14.5	Thompson & Brian
20)	NGC 7336	Peg	16.0	Thompson & Brian
21)	NGC 7337	Peg	15.5	Thompson & Brian
22)	NGC 7340	Peg	15.0	Thompson & Brian
23)	NGC 7640	Peg	11.5	Thompson & Brian
24)	NGC 7479	Peg	11.5	Thompson & Brian
25)	NGC 7457	Peg	11.0	Hubble Atlas of G.
26)	NGC 7741	Peg	11.5	Hubble Atlas of G.
27)	NGC 7742	Peg	11.0	Hubble Atlas of G.
28)	NGC 0023	Peg	12.0	Hubble Atlas of G.

LIST OF GALAXIES TO LOOK FOR SNe
-second half of the night-

NR.	OBJECT		CONSTELLATION	MAGNITUDE	REFERENCE MAP
29)	NGC 0221	(M32)	And	9.0	Thompson & Brian
30)	NGC 0224	(M31)	And	4.5	Thompson & Brian
31)	NGC 0205	(M110)	And	9.0	Thompson & Brian
32)	NGC 0891		And	11.0	Thompson & Brian
33)	NGC 0404		And	10.0	Hubble Atlas of G.
34)	NGC 0598	(M33)	Tri	6.5	Thompson & Brian
35)	NGC 0672		Tri	11.5	Thompson & Brian
36)	NGC 0925		Tri	10.5	Thompson & Brian
37)	IC 1727		Tri	12.0	Thompson & Brian
38)	NGC 7606		Tri	11.5	Thompson & Brian
39)	NGC 0772		Ari	11.0	Thompson & Brian
40)	NGC 1156		Ari	11.5	Hubble Atlas of G.
41)	NGC 0488		Psc	11.0	Thompson & Brian
42)	NGC 0628	(M74)	Psc	10.0	Thompson & Brian
43)	NGC 0524		Psc	10.5	Hubble Atlas of G.
44)	NGC 0718		Psc	11.5	Hubble Atlas of G.
45)	NGC 1023		Per	10.5	Thompson & Brian
46)	NGC 7727		Aqr	11.5	Thompson & Brian
47)	NGC 7724		Aqr	13.0	Thompson & Brian
48)	NGC 0253		Scl	7.0	Thompson & Brian
49)	NGC 0247		Cet	9.5	Thompson & Brian
50)	NGC 0157		Cet	11.0	Thompson & Brian
51)	NGC 1068	(M77)	Cet	10.0	Thompson & Brian
52)	NGC 0578		Cet	11.5	Thompson & Brian
53)	NGC 0720		Cet	11.0	Thompson & Brian
54)	NGC 0908		Cet	11.0	Thompson & Brian
55)	NGC 0926		Cet	11.0	Thompson & Brian
56)	NGC 1055		Cet	11.5	Thompson & Brian
57)	NGC 1087		Cet	11.5	Thompson & Brian
58)	NGC 1073		Cet	11.0	Thompson & Brian
59)	NGC 1090		Cet	12.5	Thompson & Brian
60)	NGC 1094		Cet	13.5	Thompson & Brian
61)	NGC 0615		Cet	11.5	Hubble Atlas of G.
62)	NGC 2523		Cam	12.0	Hubble Atlas of G.
63)	IC 0342		Cam	9.0	Thompson & Brian

APPENDIX E

M81 FIELD: UBVRI COMPARISON STARS MAGNITUDES

GSC NR.	V	B-V	U-B	V-R	R-I	CHART ID
4383.0434	12.45	+0.63	+0.11	+0.39	+0.76	12.4 overline
.0308	11.78	+0.69	+0.16	+0.40	+0.80	11.8 overline
-	11.62	+0.53	-0.04	+0.33	+0.69	11.6 (near 14.1)
.0928	11.90	+0.50	-0.08	+0.30	+0.60	11.9 overline
.1123	13.65	+0.57	-0.09	+0.34	+0.69	13.6 overline
.0224	11.85	+1.30	+1.29	+0.68	+1.29	11.8 underline
.1023	14.73	+0.46	+0.12	+0.36	+0.60	14.7 overline

Photometric Systems

A knowledge of an object's distribution of spectral energy enables astrophysical interpretation. The observations must therefore be made in well defined spectral bands that are isolated with filters. Several photometric systems exist that essentially differ by the spectral characteristics of the filters. The basis of any photometric system is precise observation of standard stars using a set of filters. These stars are obviously known to be non-variable to within a specified level of accuracy.

The most commonly used photometric system is the one defined by Johnson and Morgan,[2] known as the UBV system (for Ultraviolet, Blue, Visible). The equivalent wavelength and the width at half-maximum in the spectral bands are given below:

	R	B	V
$\lambda 0$ (Å)	3600	4400	5500
$d\lambda$ (Å)	700	1000	900

By "equivalent wavelength" we mean the wavelength of the braycenter of the product of the filter's transmission weighted by the CCD's spectral response.

Subsequently, Johnson and Morgan's system was extended into the red and near infrared:

	R	I
$\lambda 0$ (Å)	7000	9000
$d\lambda$ (Å)	2200	2400

The most commonly used system today for working with CCD's is the Kron-Cousins' UBVRI.[3] The characteristics of this system allow us to take greater advantage of the sensitivity of modern detectors in the near infrared. It therefore differs from the Johnson-Morgan system in the R and I bands:

	R	I
$\lambda 0$ (Å)	6500	8000
$d\lambda$ (Å)	1000	1500

Some observers work in an intermediate system u,v,g,r called Thuan and Gunn's [4] that extends into the infrared (i band).[5] The choice of spectral bands in this system, whose characteristics are given below, allows, among other things, the rejection of parasitic spectral lines of the night sky.

	u	v	g	r	i
λ0 (Å)	3530	3980	4930	6550	8200
dλ (Å)	400	400	700	900	1300

There are equations that enable the translation of one photometric system into another. Here is the "bridge" between Johnson's (index j) and the Cousins' system (index c):

$$V_c = V_j$$

$$(V - I)_c = 0.713(V - I)_j \qquad (V - I)_j < 0$$
$$(V - I)_c = 0.778(V - I)_j \qquad 0 < (V - I)_j < 2$$
$$(V - I)_c = 0.835(V - I)_j \qquad 2 < (V - I)_j < 3$$

$$(R - I)_c = 0.856(R - I)_j + 0.025$$

$$(V - R)_c = 0.73(V - r)_j - 0.03 \qquad (V - R)_j < 1$$
$$(V - R)_c = 0.62(V - r)_j - 0.08 \qquad 1 < (V - R)_j < 1.7$$

The bands of a photometric system must be isolated by a careful choice of filters that are adapted to the detector's spectral sensitivity. As an example, the U band of the initial UBV system is obtained by observing through a Corning 9863 filter, the B band with the Corning 5030 joined to the Schott GG13, and the V band with a Corning 3384 filter, all of them associated with a type 1P21 photomultiplier. The latter's photocathode has a very different spectral response from a CCD. With a CCD (silicon response), for Cousins' UBVRI system, the following set of filters is chosen:

U : 1 mm UG2 + $CuSO_4$

B : 1 mm BG12 + 2 mm BG18 + 2 mm CG385

V : 2 mm GG495 + 1 mm BG18 + 1 mm WG305

R : 2 mm OG570 + 2 mm KG3

I : 3 mm RG9 + 1 mm WG305

Note that the filters' thicknesses have been included. In this assembly, WG305 (a clear filter), is transparent to UBVRI—its function is to equalize the optical thickness for all spectral bands and, consequently, one does not have to refocus every time a filter is changed. All these filters are referenced in the Schott Company's catalog, except the $CuSO_4$ which is, in fact, a transparent cell containing liquid copper sulphate (sometimes a $CuSO_4$ crystal is substituted). Note that the combinations of filters that isolate a band in the visible are carefully masked for the infrared, i.e., the infrared is not transmitted. This masking is done with "cold" filters such as the BG18 or the KG3. Never trust appearances to decide that a filter is opaque to the infrared because the eye is insensitive to this radiation. We should remember that silicon's spectral response favors the infrared over the visible. If we use a blue filter that is approximately masked, the measurements will actually be made in the infrared. That is not really what we are trying to do! Colored filters used for photography are not masked at all. All the filters with Wratten gelatin (Kodak) are completely transparent from about 700 nm. Even interference filters have surprises in store for us in this domain. To know whether a filter that has to work in the blue or the visible is correctly masked, make an image with an incandescent lamp through the filter in question, then redo it with the same filter combined with a BG18. There should be no observable difference in signal level between the two images.

With thick substrate frontside illuminated CCD's (TH7852, TH7863), the U band is inaccessible because of the low sensitivity in the blue.

If we are using interference filters, we have to make sure that they are crossed by light beams that are parallel or only very slightly divergent because spectral transmission depends on the rays' incident angle. The filters should be placed on a sliding mount or a wheel so they can be chosen quickly.