THE LIGHT CURVE EPOCHS OF SUPERNOVAE EXPLOSIONS

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ABSTRACT

A brief description of the current state of knowledge for Type II light curves is given, including discussion of some of the remaining problems. The use of supernovae of both types as independent distance indicators is outlined and difficulties are pointed out. A summary of new ideas regarding the origin of Type I light curves is presented.

INTRODUCTION

Supernovae may be divided into two distinct categories, denoted Type I and Type II (SN I, SN II), on the basis of distinguishing light curves and particularly by their spectra (see, e.g. Kirshner, Oke, Penston, and Searle 1973; hereafter KOPS). Type II supernovae show approximately solar composition spectra, while SN I have a conspicuous lack of hydrogen in their spectra. Both types are approximately blackbody with overlaid P-Cygni lines near peak light (KOPS); both involve explosion energies E_0 of order 10^{51} ergs, invested primarily in kinetic energy of expansion, and material velocities in excess of 10^4 km s^{-1} are inferred for each. SN I are $1\overset{m}{.}5$ to $2\overset{m}{.}0$ brighter at maximum than most SN II, and probably are explosions of stars of smaller mass than those which result in Type II events. Numerical studies (e.g., Falk and Arnett 1977, hereafter FA; Chevalier 1976; Grasberg, Imshennik, and Nadyozhin 1971) have been successful in explaining many of the observed properties of SN II, and many of the interesting questions which remain for this type are questions of detail and application: questions of presupernovae mass loss, progenitor masses, use as distance indicators, and the like. Our present knowledge of Type I supernovae is not nearly so certain, though some new and some rejuvenated ideas show promise of providing a clear picture of the physical processes involved in these events as well.

It is impossible here to adequately review all the features of either Type I or Type II supernovae, so I have chosen to address a selected few of the current problems in the field. Our understanding

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of SN II seems the most complete, so I will briefly review the state of our knowledge of these objects. I wish then to turn attention to the use of supernovae as extragalactic distance indicators, and the problems therein. Finally, time permitting, I will attempt to outline recent ideas on the Type I outburst, and hopefully will convey some of the excitement which those of us working on this problem have felt in the last year or so.

TYPE II SUPERNOVAE

Our qualitative understanding of Type II events seems to be good, as evidenced by work by a variety of authors (Falk and Arnett 1973, 1977; Arnett and Falk 1976; Chevalier 1976; Chevalier and Klein 1979; Grasberg, *et al.* 1971). Gross light curve morphology and kinetics have been explained successfully in terms of models in which a core collapse-generated shock wave ($E_0 \sim 10^{51}$ ergs) traverses the red giant envelope ($M_e \gtrsim 3\text{-}10\ M_\odot$) of a massive star. Shock emergence at the photosphere produces high temperatures ($T > 3 \times 10^5$ °K), and results in an approximately 10^3s burst of ionizing radiation ($\int L dt \gtrsim 10^{48}$ erg), mostly ultraviolet and soft X-rays, with a decidedly non-Planckian spectrum (Falk 1978; Klein and Chevalier 1978; see also Lasher and Chan 1979). Shock propagation down the outer density gradient of the envelope produces the high material velocities, $v > 10^4$ km s^{-1}, observed in the early light curve epoch (Falk 1978), and a harder X-ray burst ($\int L_x dt \lesssim 10^{44}$ erg) is expected as the radiation-dominated shock becomes ion-viscous in the outer presupernova atmosphere (Falk 1978; Klein and Chevalier 1978). Rapid cooling of these outermost layers results in a rapid drop in total luminosity following the burst.

The peak light epoch is followed by a longer period of slowly declining or nearly constant *bolometric* luminosity until t ~ 40-100 days, depending upon the mass of the ejected envelope. The shock has accelerated the bulk of the envelope to velocities of order 5000-8000 km s^{-1}, typical of the values inferred from P-Cygni hydrogen and calcium lines observed during this period. The shape of the theoretical *visual* light curve is less certain, although a blackbody approximation apparently suffices for the conversion from total light to B- or V-band luminosity (see, e.g., KOPS). During this "plateau phase" cooling is predominantly adiabatic, and envelope transparency increases because of expansion and the onset of hydrogen recombination, initiated in the outermost material layers. Inferred effective temperatures reflect the recombination front and are nearly constant, $T_e \simeq 6000$°K. The radius of the photospheric surface at first increases rapidly, tied by ionization conditions to material expansion, but retreats in a Lagrangian sense soon after recombination sets in. Inferred material velocities during this phase show a systematic decrease as slower-moving layers of the essentially homologous expansion are exposed. Following envelope transparency, there is another rapid luminosity decline, and the size of the inferred photosphere decreases sharply. At this time inner, non-envelope (mantle) material may be exposed. (For further details of these models, the reader is referred to FA, Chevalier 1976,

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and Arnett 1980.) In the case of SN1969ℓ, details of all these features, including visual light curve morphology and timescales, temperature and velocity evolution, and colors are matched excellently by a single numerical model (Arnett and Falk 1976; Falk 1978).

An important feature of the shock model is that it requires no additional energy input, for instance, due to a pulsar, neutron star, or substantial radioactivity, to account for the peak and plateau phases of these events. In at least two cases (SN1969ℓ in NGC 1058, SN1970g in M101), the luminosity is observed to decline only slowly after a rapid drop of 3-5 magnitudes at envelope transparency. Weaver and Woosley (1978) have identified this lingering radiance with radioactive heating of the mantle material at long times, $t > 100$ days.

A so-called "linear decline" class of SN II exists, of which the recent supernova in M100 is an example. These show little or no prolonged plateau phase, but this absence can probably be explained by (a) a smaller envelope mass than for those cases with distinct plateaus, and (b) the accompanying differences in envelope density profile. Mass loss could play a role in these events.

Lest this sound like SN II are too well-understood, let me point out that several fundamental problems still remain. First, no model to date has adequately explained the presence of the visual peak itself. Because no single SN II has been adequately observed on its rising branch, it is not clear that a visual peak of substantial duration (i.e., $\Delta t \gtrsim 10\text{-}20$ days) need be explained, as is the case for SN I. The bolometric peak certainly exists (the "burst" epoch), but the blackbody conversion used to obtain theoretical values for model B- and V-band luminosity does not yield suitably large values to explain observed plateau-type events (see, e.g., Model A in FA). Non-Planckian processes associated with shock breakout may be involved, though thermal bremsstrahlung alone seems adequate.

The X-ray burst has been suggested as a precursor signal of Type II explosions out to distances of order 10 Mpc (and perhaps also for SN I; see below) by Chevalier and Klein (1978b), but none were found in early HEAO-A data (Klein, *et al.* 1979). There are, however, other reasons to examine such a burst; primary among these is the possibility that recombination radiation from burst ionization of a potentially large region ($r > 1$ pc) around the supernova might provide insight into the extent and distribution of circumstellar material lost by the presupernova star. Secondly, the duration, luminosity, and hardness of the spectrum of such a burst could provide important constraints on the initial extent of the presupernova envelope, with harder, lower-luminosity bursts typifying more compact configurations. The structure and extent of the presupernova "atmosphere", which may be modified by mass-loss processes in comparison to the predictions of static-envelope integrations, could also be constrained. Preionization of material in the surrounding medium may have important consequences for the propagation of the supernova blast wave into this medium, and upon the early

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phases of remnant evolution. The ultraviolet excess in SN1979c in M100 reported by Panagia, *et al.* (1980) may have been produced by blast wave propagation into such material (Branch, *et al.* 1980).

The question of whether fluid instabilities exist in the ejecta has only been cursorily investigated. Falk and Arnett (1973, 1977) have suggested Rayleigh-Taylor instabilities might occur on density scale-height dimensions as the shock propagates in the steep outer density gradient, and Chevalier (1976) and Chevalier and Klein (1978) have suggested a similar instability on scales of order 0.1 to 0.3 times the initial envelope radius in the envelope ejecta proper. In either case, density inhomogeneities may have consequences for spectral interpretation and may affect the appropriateness of the blackbody approximation employed in obtaining distance estimates. The questions of grain formation in SN II (Hoyle and Wickramisinghe 1970; Falk, Lattimer, and Margolis 1977) and of likely grain composition (Lattimer, Grossman, and Schramm 1978) are affected by the possibility of mixing by such instabilities if they occur at the mantle-envelope interface.

SUPERNOVAE AS DISTANCE INDICATORS

Three methods are currently applied to ascertain distances to supernova events. The first is a variation of the Baade-Wesselink method, applied first to Type II events (SN1969ℓ, SN1970g) by Kirshner and Kwan (1974; hereafter KK) and more recently to SN1979c by Branch, *et al.* (1980, hereafter BFMRUW). The assumption of blackbody radiance over the observed bands is central, but should be appropriate since the B- and V-band spectral regions are well-represented by Planck continua overlaid by P-Cygni lines which have little net emission or absorption (KOPS), and since the useful phases have an approximately constant effective temperature at $T_e \sim 6000°K$. A second method, applied so far only to SN II, is that of Schurmann, Arnett, and Falk (1979; hereafter SAF), who use detailed numerical models in good quantitative agreement with temperatures, colors, and line velocities of particular events to deduce distances directly by comparing model visual luminosities with observed values. Here, too, the assumption of blackbody radiance plays a crucial role. Type I supernovae show a very homologous set of light curves (Barbon, Ciatti, and Rosino 1974), and Branch (1977, 1979) has used statistically determined peak absolute magnitudes to obtain distances for this type.

Despite the uncertainties introduced by the blackbody approximation, it is noteworthy that (1) where comparisons of different SN methods to the same event are possible, agreement is good; and (2) for all events to which these methods have been applied, distances result which suggest a small value for the Hubble constant ($H \sim 50$-60 km s^{-1} Mpc^{-1} (c.f., Sandage and Tammann 1976; hereafter ST), in contrast to the growing suspicion that H may be closer to 100 km s^{-1} Mpc^{-1} (e.g., de Vaucouleurs and Bollinger 1979; Aaronson, Mould, and Huchra 1980). The results for various supernovae of Type II are collected in Table 1. Application to an event outside the local supercluster has not yet been

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made, but would certainly shed light on the question of local infall toward Virgo. It is important to determine how accurate these approaches are, since supernovae could provide a "ladder-independent" distance scale. Such a determination will require a detailed fit to observations over many spectral regions presently poorly sampled, including X-ray and ultraviolet, and may involve the calculation of detailed time-dependent, non-LTE, hydrodynamic "atmospheres".

TABLE 1

Authors	SN1969ℓ (NGC 1058)	SN1970g (M101)	SN1979c (M100)
KK	12 ± 3 Mpc	6 ± 3	-
SAF	13.7	7.3	(20-25)
BFMRUW	-	-	23 ± 5
ST	14.3	7.2	22
Panagia, et al.	-	-	24 ± 5

TYPE I SUPERNOVAE

The apparent homogeneity of these events - both with respect to light curves and spectra - is at once an important clue to their nature and a source of confusion as to the physical processes and pre-explosion configuration which produces them. Because they are the only SN type observed in elliptical galaxies, accepted wisdom has held them to be low-mass, Population II objects. However, recent statistical arguments (Oemler and Tinsley 1979) and observations of gas in ellipticals (Knapp, et al. (1979)) as well as the success of Lasher's (1975) shock model for the peak epoch, and arguments by Falk (1980) which suggest a minimum ejected mass ~ 2 $M_\odot$, have led to the suspicion that the canonical view needs careful re-examination. The greatest difficulty in accounting for SN I has been to explain the observed long-term exponential visual luminosity decline, in several cases observed to $t > 600$ days. The suggestion that the exponential was due to radioactivities synthesized in the explosion was first made by Burbidge, Burbidge, Fowler, and Hoyle (1957) and later by Colgate and McKee (1969). B^2FH suggested ^{254}Cf as the likely source, but far too little is synthesized to account for the event; Colgate and McKee suggested ^{55}Ni → ^{56}Co → ^{56}Fe decay, but the exponential decay timescales were "wrong". In both cases, expansion is expected to modify any natural exponential by a power law. The He-fluorescence mechanism of Morrison and Sartori (1969) required several order of magnitude too much energy.

Recently, calculations have affirmed the notion that the "exponential" may be due to a fortuitous balance of energy-deposition versus growing nebular transparency to the γ-rays and positrons produced by ^{56}Co decay in the ejecta (Colgate and Petschek 1980; Arnett 1979; Chevalier 1980). For example, Colgate and Petschek propose an explo-

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sion of a compact star, ejecting 0.5 $M_\odot$ of matter, of which 0.25 $M_\odot$ is initially ^{56}Ni. They claim that not only is the exponential tail accounted for, but that the peak can also be explained with the same parameters but their energetics appear to be incorrect. A central assumption seems to be that an as yet unspecified process converts essentially all the deposited energy into Fe-fluorescence in B- and V-bands (Meyerott 1980). However, observations of SN1972e in NGC 5253 by Kirshner, et al. (1973) imply a substantial non-visual luminosity. The question of bolometric corrections is again central. Appreciable nonvisual radiance implies larger masses of ^{56}Ni to be synthesized, which places in turn different constraints on mass and explosion energies, and hence on dynamical models for the explosion mechanism.

There may in fact be some intrinsic variation in the ratio of total peak luminosity to total tail luminosity, as evidenced by the "fast" and "slow" subtypes discussed by Barbon, et al. (1974). Branch (1980) sees no evidence for the expected Co in spectra of SN1972e as late as 40 days, implying the presence of overlying and shielding material. The possibility therefore exists that, in at least some Type I events, initially extended structures may be implied; in such cases, shock-deposited energy must play a role in peak energetics.

I do not mean to sound too pessimistic, for real progress has finally been made in explaining these beasts. For the first time in twenty-five years, a viable physical mechanism to account for the exponential tail may be in hand!

CONCLUSIONS

I have tried to outline what we think we know about supernovae, and also to indicate what we don't know well enough, or at all. What stands out is a need for committed, systematic observational coverage of events of both types whenever they occur, including photometry and high-resolution spectra from the UV to the infrared, and with concurrent X-ray observations where possible, in order to constrain increasingly complicated theoretical models. Spectral coverage twice a week would be useful, from the very earliest times post-discovery, to the latest possible. Early UV and X-ray coverage would help elucidate structure in the outer presupernova layers and circumstellar material. Late-time spectra are imperative for constraining SN I models (Axelrod 1980), and for investigating the exposure of freshly synthesized mantle material as the SN II envelope becomes transparent. Wide spectral coverage may be the only way to arrive at accurate bolometric corrections. With diligent effort, and some good luck, supernovae can become reliable diagnostic probes of the interstellar medium and extragalactic distance indicators. We may even know someday what actually causes these spectacular events.

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DISCUSSION

COLGATE: Chevalier and Raymond put an upper limit of 4 x 10^{46} ergs for the energy in the Strömgren sphere formed during a Type I supernovae. Doesn't that mean that the peak of the light curve cannot be caused by a shock which would give more than 10^{48} ergs?

FALK: The energy emitted from a Type II supernova shock is 10^{48} ergs or more, but the shock from a smaller Type I supernova down by a couple orders of magnitude in radius might emit fewer ionizing photons because energy is used in an adiabatic expansion. A real question is whether there is an intrinsic difference, that is not reddening in the galaxy, between the fast and slow subtypes of Type I supernovae. For those extended structures the shock deposited energy must make a difference in the peak light. The peak cannot come from the nickel decay in these cases.

COLGATE: Are there any Strömgren spheres of Type II supernovae which might have been looked at?

FALK: The supernova in M100 went off in a H II region. The problem is that you have trouble disintangling the supernova photons from those of the earlier O star. You need to look for more energetic ultraviolet transitions that would be intense enough and last long enough to see. High resolution spectra would be useful.

A. COX: Is the reason that you don't have an exponential decay in a Type II supernova the fact that the cobalt is buried so deeply?

FALK: Either that or there isn't enough of it at late times. The envelope does become transparent about day 60-100, depending on the mass. In 1969ℓ and for a couple points for 1970g, there are hints that after coming down that plateau phase you see it level out again. Something is keeping it going. It may be latent heat in the mantle, or a hot neutron star underneath. It also could be a tenth of a solar mass of cobalt for which the energetics are about right.

A. COX: Is the cobalt actually produced during the explosion or previously in earlier evolution?

FALK: Presumably during the explosion you get high enough temperatures to go to nuclear statistical equilibrium and you produce Ni^{56}. Most of it gets swallowed by the core. Depending on models, a star of 6-8 $M_{\odot}$ or even at the Chandrasekhar limit on an accreting white dwarf may be totally or partially disrupted giving Ni^{56} which has been produced at very high temperatures. There is a problem with Type I supernovae that there is definitely some overlying matter that blankets the Ni^{56}. It is maybe 0.3-0.5 $M_{\odot}$ mostly helium with some Si and Ca. Nothing is available in the Ni spectrum and you don't see Co at the late times, even though it is seen during the peak epoch. Co must be buried, and the early spectrum does put constraints on the model. We really don't know what the progenitor configuration looks like.

A. COX: I thought the difference between Types I and II was mainly the absence or presence of a hydrogen envelope.

FALK: That's true. The Type II's are solar looking with the dominant lines the hydrogen Balmer series. For Type I's, there is no evidence for hydrogen in the spectra, and they are not very P Cygni look-

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ing. They have a lot of late time continuum, making line identification difficult.

STARRFIELD: Do you think Lasher's work on Type I supernovae is the complete story?

FALK: No. The exponential requires Ni^{56} or something like that as the energy source, and that is present at the peak light. If more energy is needed, it must come from the shock. Binary scenarios or white dwarf collapse exclude extended configurations, but maybe there is overlying matter which hides the cobalt somehow.

STARRFIELD: Someone has a cobalt identification which decays away exponentially with the right time scale.

FALK: Axelrod captures all the positions, whereas Colgate lets β transparency occur. The energetics are, therefore, different. Late time spectra show some features getting stronger and then decaying away, and they can be identified with cobalt III forbidden transitions.

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