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1987A: The greatest supernova since Kepler

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After a period of initial confusion, we now seem to understand in some detail why a star like Sanduleak −69° 202 gave rise to a supernova like 1987A. The detection of the neutrino burst produced at core collapse has confirmed basic ideas of Type-II supernova causality and energetics (without being able to distinguish prompt from delayed shock ejection). Constraints on the nature of the neutrinos themselves confirm or extend laboratory limits on, and conventional theory for, rest mass, magnetic moment, etc. The unusual early light curve and spectra turn out to be a natural result of core collapse when the star was compact and blue, after passing through a red, extended phase (confirmed by evidence for mixing and mass loss characteristic of red supergiants). Synthesis of about $0.07M_\odot$ of Ni^{56} (as was previously suspected in SN II's with exponentially tailed light curves) has been revealed by a similar light curve and by an infrared line, gamma rays, and hard x rays, all widely believed to reflect the presence and decay of Ni^{56} to Co^{56} to Fe^{56}. A number of puzzles remain concerning unexpected variable soft-x-ray emission, a possible speckle companion, and evidence for extensive mixing, fragmentation, and filamentation. Most of the lessons still to be learned from 1987A probably pertain to the detailed (three-dimensional) structure and composition of evolved massive stars rather than to the basic physics of Type-II supernovae.

CONTENTS

I. INTRODUCTION

Even scientists who have spent the last few years under large rocks cannot help having heard of supernova 1987A in the Large Magellanic Cloud (the associated neutrino burst having readily penetrated the very largest rocks). It was the first naked-eye supernova since that studied by Kepler in 1604, though if it fulfilled the folklore prediction that when there was another astronomer as great as Kepler, there would be a supernova for him to study, we have not yet identified the eponymous astronomer.

Radiative fluxes from 1987A are still changing on times scales short compared to journal publication time scales. Much of what follows must, therefore, be regarded as subject to change without notice. Several conferences have been or will be devoted to the object, and their proceedings provide snapshots of our understanding at various moments (Danziger, 1987; Kafatos and Michalitsianos, 1988; Cannon, 1988; IAU, 1988).

Incidentally, in accordance with a 1985 resolution of the International Astronomical Union (the body charged with deciding matters of astronomical nomenclature), the supernova is unambiguously 1987A. 1987a was Comet Levy. Supernovae are designated by year of discovery (not name of discoverer) and a capital letter indicating order of discovery during the year.

II. THE PROGENITOR

About 10 million years ago, one of many small flurries of star formation in the Large Magellanic Cloud gave rise to a few dozen OB stars in and around a region now called NGC 2044 (Hodge and Wright, 1967; Lucke and Hodge, 1970). A number of these stars have had their magnitudes and spectral types recorded (Sanduleak, 1970; Rousseau *et al.*, 1978). One of them, catalogued as Sanduleak −69° 202, appears to have given rise to the supernova. It had two close companions (also blue), and a number of authors suggested early on that a possible fourth, red, star might have been the actual progenitor (Fabian *et al.*, 1987; Heap and Lindley, 1987; Joss *et al.*, 1988; Testor, 1988).

Several arguments, however, favor Sk −69° 202 itself as the culprit. First, careful photometry and astrometry (Blanco *et al.*, 1987; Walborn *et al.*, 1987; West *et al.*, 1987; White and Malin, 1987; Girard *et al.*, 1988) do not leave much excess light at any wavelength to be credited to a fourth star. Second, IUE spectroscopy during and after the event (Gilmozzi *et al.*, 1987; Sonneborn *et al.*, 1987) indicated that, when the supernova itself faded, only two stars remained, separated by the same distance as the previous companions. Third, and requiring lengthier discussion, it has become clear that blue supergiants can produce core-collapse supernovae and that the resulting light curves, spectra, and so forth should look very much like the observations of 1987A.

Combining observations made before the Sanduleak star exploded with its behavior afterwards, we can describe the progenitor (Arnett, 1987; Grasberg *et al.*, 1987; Woosley *et al.*, 1987; Saio *et al.*, 1988; Shigeyama *et al.*, 1988; Wheeler *et al.*, 1988; Woosley, 1988a; Woosley *et al.*, 1988) as a B3 Ia supergiant with

$V=12.4$, $B-V=+0.04$, visual absorption $A_v=0.5$, bolometric correction $+1.15$, and distance modulus 18.2–18.8 (corresponding to a distance of 43 000–58 000 pc). The bolometric magnitude was, therefore, $-7.8^{+0.3}_{-0.4}$, meaning a luminosity of $4^{+2}_{-1}\times 10^{38}$ ergs/s. The effective temperature was 15 000–16 000 K, and the radius $3\pm 1\times 10^{12}$ cm. To achieve this luminosity, the core mass inside the hydrogen-burning shell must have been $6\pm 1 M_\odot$, corresponding to a main sequence mass of $15-22 M_\odot$, and a main sequence lifetime of about 10^7 yr. Prior to explosion, the star had first mixed significant quantities of helium, CNO-cycle material, and (probably) *s*-process products into its envelope, and then shed between 3 and $10 M_\odot$ of that envelope in a low-velocity, high-density red giant wind, the other $3-10 M_\odot$ of hydrogen-rich envelope being retained. This relatively dense wind material is now about 10^{18} cm from the star, having been replaced near the star by a higher-velocity, but very tenuous, wind shed during the last 10 000 yr or so, when the star had become compact and blue again.

The explosion of a blue supergiant initially caused some puzzlement—perhaps more in the semipopular press than in the astronomical community. In fact, however, even before 1987A, an assortment of evolutionary tracks for massive stars had terminated with the star still blue (Trimble *et al.*, 1973; Brunish and Truran, 1982; Maeder, 1987). Additional tracks of this type have been published since (Arnett, 1987; Hillebrandt, Höflich, Truran, and Weiss, 1987). These stars remain blue through carbon burning (after which interior evolution proceeds so rapidly that the outer layers cannot respond to it anyway), either because of extensive mass loss (Wolf-Rayet stars being the extreme version of this scenario) or because the low metal abundance appropriate to Magellanic Cloud stars prevents radiation pressure from lifting the outer layers (cf. Shklovskii, 1984, who predicted faint SN II's in irregular galaxies on this basis).

Figure 1 (from Woosley, 1988a) shows a still more relevant evolutionary track for a $20 M_\odot$ star which spends some time as a red supergiant and returns to the blue before exploding. Such loops in the HR diagram are possible because a given set of core and envelope mass and composition parameters does not determine a unique solution to the equations of stellar structure (Paczyński, 1970, 1971). Rather, there are two stable (and often one unstable) structures possible, and which is followed by a particular model calculation depends very sensitively on composition, mass loss, choice of criteria for convective instability, prescription for handling composition discontinuities left by hydrogen burning, and probably other things (Barkat and Wheeler, 1988; Saio *et al.*, 1988; Woosley, 1988a). Which path is followed by a particular real star will then be a similarly delicate function of that star's real properties—composition (including the amount of helium mixed into the envelope), angular momentum distribution, magnetic field structure, and so forth. Rotationally induced mixing (meridional circulation) may also be a significant factor (Weiss, Hillebrandt, and Truran, 1988). Thus we should not be surprised by the simultaneous presence of red and blue supergiants and Wolf-Rayet stars in the vicinity of 1987A, or by the fact that it was one of the blue stars that, on 23 February 1987 (or, rather, some 150 000–170 000 yr before) reached the point of core collapse and envelope ejection. The news of this event first reached Earth in the form of a neutrino burst and, perhaps, gravitational radiation (Amaldi *et al.*, 1988; Saavedra *et al.*, 1988).

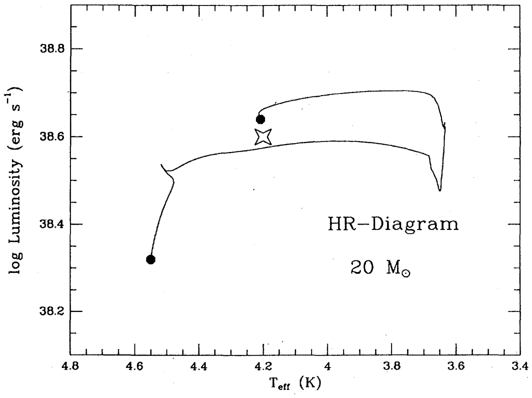

FIG. 1. Evolutionary track of a $20 M_\odot$ star which completes its hydrostatic evolution with a temperature and luminosity very similar to that of the progenitor of 1987A (shown as four-pointed star). The model had a metal abundance one-quarter solar, no mixing due to convective overshoot or semiconvection, and convection according to the Ledoux criterion. [From Woosley (1988a), courtesy of Stanford E. Woosley.]

III. THE NEUTRINO BURST AND ITS INTERPRETATION

Four particle detectors, three of them primarily designed to search for proton decay, each recorded five or more neutrinolike events on 23 February 1987. First detection (and first report), with five counts, came from under Mt. Blanc (Aglietta *et al.*, 1987), about 7.5 h before optical rise. The detectors in Japan (Kamiokande II, 11 counts, Hirata *et al.*, 1987), the United States (IMB = Irvine-Michigan-Brookhaven, 8 counts, Bionta *et al.*, 1987), and the USSR (Baksan, 5 counts, Alexeyev *et al.*, 1987) recorded their events about 3.5 h before optical rise, though only IMB had timing accurate to better than 1 min, and it is an assumption that all three coincide.

Majority opinion, at least in the United States, has decided to believe the Japanese and American reports, to distrust the European event, and to ignore the Soviet one. Theoretical papers and preprints greatly outnumber the 19 counts being interpreted. At least a plurality conclude (a) that the observations are well fit by $6\pm 3\times 10^{52}$ ergs in $\bar{\nu}_e$, hence $3\pm 1\times 10^{53}$ ergs of total neutrino energy, the binding energy of a $1.4\pm 0.1 M_\odot$ neutron star, coming out from a neutrinosphere radius of 27 ± 15 km at an initial temperature of 4.2 ± 1 MeV, which cooled in 2–5 s, and (b) that this is just exactly what we ought to have seen from a core-collapse supernova (Arafune and Fukugita, 1987; Bahcall *et al.*, 1987; Hari Dass *et al.*, 1987; Kahana, Cooperstein, and Baron, 1987; Mayle, Wilson, and Schramm, 1987; Sato and Suzuki, 1987a, 1987b; Spergel *et al.*, 1987; Suzuki and Sato, 1987; Bludman and Schinder, 1988).

Many of these [and others, Spergel and Bahcall (1988) and references cited therein] also find that the near-simultaneous arrival (within 12 s) of all the neutrinos, independent of energy, constrains the $\bar{\nu}_e$ rest mass to be less than 10–20 eV. This overlaps most laboratory limits and surprises no one. The authors who saw evidence in the arrival times for finite neutrino rest mass (Hillebrandt *et al.*, 1987a; Evans *et al.*, 1988) seem to have been outvoted.

Several other tight, but inoffensive, limits on neutrino properties follow from the observations. These include a charge less than 10^{-17} that of the electron (Barbiallini and Cocconi, 1987), and a magnetic moment less than 10^{-12} of the Bohr magneton [small enough to rule out solving the solar neutrino problem by helicity flipping in the solar magnetic field (Lattimer and Cooperstein, 1988)]. The number of neutrino flavors cannot be more than three (Ellis and Olive, 1987). We can exclude an assortment of masses and lifetimes of heavy neutrinos and other particles that couple to or mix with $\bar{\nu}_e$ (Dar and Dado, 1987; Takahara and Sato, 1987; Raffelt and Seckel, 1988), and a variety of still more exotic processes and couplings (addressed in a number of preprints from CERN and Fermilab). Finally, neutrino oscillation of the MSW (Mikheyev-Smirnov-Wolfenstein) type, widely invoked to reduce solar neutrino detectability, is not ruled out (Arafune *et al.*, 1987; Krauss, 1987). And the equivalence principle still holds (Long, 1988).

One might have hoped that the neutrino burst properties would resolve the longstanding problem of whether ejection from Type-II supernovae occurs via a prompt or a delayed shock (Bruenn, 1987), but the 19 official counts simply do not tell us enough about temperature versus time to distinguish the two (Bahcall, Spergel, and Press, 1988).

As an alternative to ignoring the Mt. Blanc counts, it has been suggested that both bursts were real, the second resulting from further collapse to a black hole or from transition to strange quark matter (De Rújula, 1987; Hillebrandt *et al.*, 1987b; Voskresensky *et al.*, 1987). This choice implies a longer time interval (7.5 vs 3.5 h) between core collapse and optical rise, which can be an advantage (Wampler *et al.*, 1987) or a disadvantage (Shigeyama *et al.*, 1987; Arnett, 1988a; Woosley, 1988a), depending on who is doing the modeling. A separate serious objection is the very large total neutrino energy implied by the Mt. Blanc counts (Schaeffer, Declais, and Jullian, 1987). A similar energetic objection to the Kamiokande counts may have been resolved by recalculation of the incident neutrino angles (Koshiba, 1988). The new distribution is sufficiently isotropic for all 11 events to be induced β decays (rather than one or two direct electron scatterings being required).

The eventual appearance (or nonappearance) of a pulsar will resolve this issue, though not necessarily within the lifetimes of any of the protagonists (especially if neutron stars are not always born with strong magnetic fields).

IV. THE ELECTROMAGNETIC EVENT

A. Onset

A capsule statement of our understanding of Type-II supernovae in general is that the light curves, spectra, and other electromagnetic properties are largely accounted for by a model in which about 10^{51} ergs is deposited (somehow) at the base of an extended red supergiant envelope (Trimble, 1982). Much the same applies to the specific case of 1987A, provided only that the envelope is that of a blue supergiant, compact and with a steep density gradient (Arnett, 1988a; Shigeyama *et al.*, 1988; Woosley, 1988a). A minority view, that $(2-3)\times 10^{51}$ ergs is required (Baron *et al.*, 1987), is worth keeping in mind, because, if true, it would almost rule out a delayed shock as the source of SN II ejection.

The main points on which the behavior of 1987A differed from that of normal SN II's are (a) it brightened in hours rather than days (McNaught, 1987a, 1987b, 1987c), (b) its peak bolometric luminosity of $9^{+4}_{-3}\times 10^{41}$ ergs/s (Catchpole *et al.*, 1987; Hamuy *et al.*, 1988) was about 10% that of a typical SN II (the error bars reflecting both uncertainty in distance to the progenitor, and some disagreement between absolute fluxes measured at different observatories; cf. Figs. 2 and 3), (c) its continuous and line spectra in optical, IR, and UV all

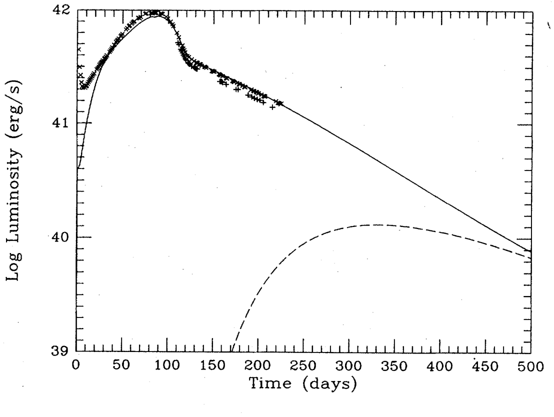

FIG. 2. Model light curve for 1987A fitted to bolometric luminosity data from CTIO (lower points) and SAAO (upper points). The model assumes an initial radius of 3×10^{12} cm, an explosion energy density of 0.75×10^{17} ergs/g, the presence of $0.07 M_\odot$ of Ni^{56}, and some mixing of heavy elements through the hydrogen envelope. The dotted line indicates a prediction of the rate of gamma-ray escape. This particular model includes a 10^{40} ergs/s pulsar, and it is clear that anything brighter would lead to a contradiction between data and model. [From Arnett (1988b), courtesy W. David Arnett.]

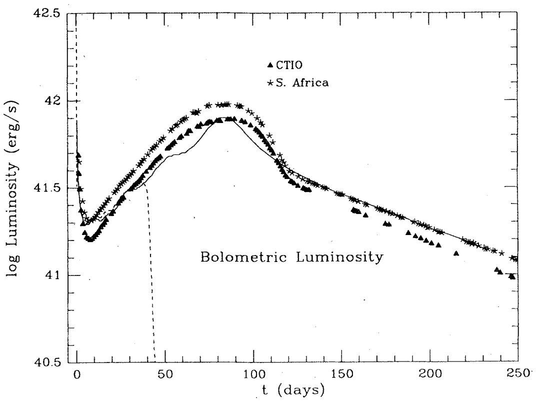

FIG. 3. Model light curve for 1987A fitted to bolometric luminosity data from CTIO (lower points) and SAAO (upper points). The model assumes an envelope mass of $10M_\odot$ (with a gradient of helium composition through the hydrogen-rich ejecta), an explosion energy of 1.4×10^{51} ergs, and the presence of $0.07M_\odot$ of Ni^{56}. The dashed line is the predicted light curve in the absence of the Ni^{56} contribution. [From Woosley (1988a), courtesy Stanford E. Woosley.]

changed in days rather than weeks, implying very rapid decreases in effective temperature and photospheric velocity with time (Bouchet *et al.*, 1987; Blanco *et al.*, 1987; Cristiani *et al.*, 1987; Danziger *et al.*, 1987; Hanuschik and Dachs, 1987; Kirshner *et al.*, 1987; Menzies *et al.*, 1987; Wamsteker *et al.*, 1987), and (d) its radio emission also turned on and faded quickly, reaching a peak only 10^{-3} that of previously detected SN II's, and expanding in less than 48 h to a size resolved away by VLBI (Turtle *et al.*, 1987; Bartel *et al.*, 1988). All these turn out to be comprehensible consequences of the hot, compact envelope structure of the progenitor.

Taking the last point first, radio emission from a handful of previously detected SN II's has been modeled as the product of ejecta shocking a surrounding circumstellar shell made of the relatively dense, slow-moving wind of a red supergiant. The faint fast character of the 1987A emission means that the material available for shocking was much more tenuous than usual, as expected for a blue supergiant wind (Chevalier and Fransson, 1987; Storey and Manchester, 1987).

Equally straightforward explanations apply to the first three points, pertaining to light curves (Hillebrandt, Höflich, Truran, and Weiss, 1987; Schaeffer, Casse, *et al.*, 1987; Shigeyama *et al.*, 1987; Arnett, 1988a, 1988b; Woosley, 1988a; Woosley *et al.*, 1988) and spectra (Branch, 1987; Lucy, 1987; Höflich, 1988; Lucy, 1988; Wheeler, Harkness, and Barkat, 1988). The shock sent on its way (somehow) by core bounce gets out quickly (having not very far to go and a medium with high sound speed to do it in), but loses a great deal of its energy lifting the envelope out of its deep potential well. Thus, there is less energy left to be radiated. Initial luminosity must briefly have touched 10^{44} ergs/s, most of which came out at $T\gtrsim10^5$ K and so in the ultraviolet, ionizing surrounding material (Raga, 1987) and fading in hours (Dopita *et al.*, 1987; Woosley, 1988a). The thinnest outer surface layers received expansion velocities in excess of 20 000 km/s, but, owing to the very steep density profile [$\rho\propto R^{-10}$ or so (Höflich, 1988, Lucy, 1988; Wheeler, Harkness, and Barkat, 1988)], we soon saw down to much slower-moving material, already cooled by adiabatic expansion. Hydrogen-line velocities, for instance, fell to 2000 km/s by days 25 to 40, and then no further (indicating that gas still deeper in the star consists of processed material).

Figures 2 and 3 [from Arnett (1988a) and Woosley (1988a)] are model light curves based on these ideas. We will return shortly to what happens after the first month. Figure 4 [from Wheeler, Harkness, and Barkat (1988a), but with slightly improved calibration] shows the observed optical and UV spectrum at the bottom, and three synthetic spectra, representing different total luminosities, above (shifted vertically from the data for visibility). It is intended that you be convinced that these are good fits.

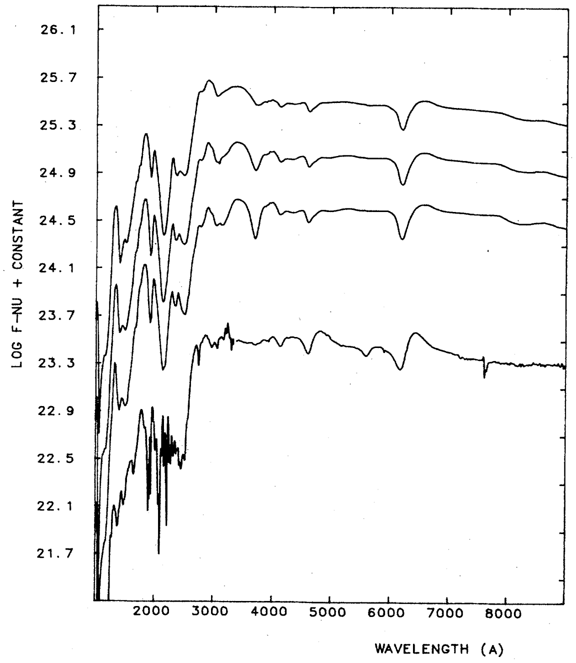

FIG. 4. Observed (bottom curve) and modeled (upper three curves) optical and ultraviolet spectra of 1987A, two days after turn-on. The models adopt a density varying as r^{-11}, with 1.5×10^{-14} g/cm^3 at the position corresponding to a velocity of 20 000 km/s (about the largest hydrogen-line velocity seen). The three curves from top to bottom have total luminosities of 4.9, 3.9, and 3.2×10^{41} ergs/s, bracketing the observed value. Several features, including the extreme UV deficit, are well modeled. [Slightly recalibrated from Wheeler, Harkness, and Barkat (1988, 1988a); courtesy J. Craig Wheeler.]

B. Near peak luminosity

Monitoring of SN 1987A has continued on a reasonably regular basis and with a range of resolutions at optical, infrared, and ultraviolet wavelengths (Ashoka *et al.*, 1987; Oliva, Moorwood, and Danziger, 1987; Tyson and Boeshaar, 1987; Williams, 1987; Aitken *et al.*, 1988; Catchpole *et al.*, 1988; Harvey *et al.*, 1988; Phillips, 1988a, 1988b; Whitelock *et al.*, 1988). So has the modeling.

The first feature to be noticed is the broad hump in the light curve at days 10–130, which is the equivalent of the plateau phase in normal Type II's—that is, it represents energy released as a recombination wave moves inward. The amount of energy radiated during this phase tells us that the hydrogen-rich envelope had not been eroded down to less than about $3M_\odot$ by mass loss before the explosion. The observed broadness and smoothness require that the recombining envelope have its helium and/or carbon-oxygen layers rather extensively mixed with the hydrogen (Arnett, 1988a; Woosley, 1988a). We will return repeatedly to the topic of mixing in the progenitor and the ejecta (enhanced, as Woosley notes, by the reverse shock propagating into the ejecta).

The second important point is that total brightness would have declined catastrophically after day 40 (the dashed line in Fig. 3) without an additional energy source. Such a source had, in any case, been eagerly awaited by proponents both of nucleosynthesis and of pulsar formation in Type-II SNe. The light curves shown in Figs. 2 and 3 have adopted $0.07-0.08M_\odot$ of Ni^{56} as the additional source. Weaver and Woosley (1980) had earlier postulated such a contribution in exponentially tailed SN II's, and Uomoto and Kirshner (1986) reported exponential decline in $H\alpha$ emission line intensities. It is worth noting (Fig. 5) that the light curve of 1987A eventually coincides with typical ones. We perhaps saw evidence for the first breakout of Ni^{56} decay energy at about day 25, in the form of kinks in the color curves (Phillips, 1988a, 1988b) and in the line excitation mechanism (Lucy, 1988). The actual energy source is gamma rays and positrons, released as Ni^{56} decays to Co^{56} (half-life 6 days) and in turn to Fe^{56} (half-life 77 days). In order for us to have seen material heated this way as early as the light curve indicated, even Ni^{56} (freshly synthesized at the base of the ejecta) must quickly have distributed itself through the envelope. Another, and perhaps better, way to describe this situation is to say that some portions of the envelope became optically thin very quickly (owing to filamentation or fragmentation), so that the effective photosphere included a portion of material from deep layers of the star.

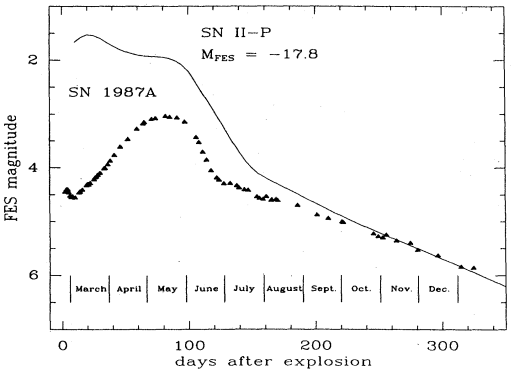

FIG. 5. Comparison of the light curve of 1987A (determined with the optical monitor on the IUE satellite) with the average of normal plateau-type SN II's. After about 200 days, when the light curve is largely dominated by Ni^{56} decay, 1987A ceases to be atypical. Courtesy Nino Panagia.

A third property of the light curve is that, once the Ni^{56} energy source has been included, then any pulsar contribution must be less than about 10^{40} ergs/s, setting a severe constraint $B^2P^{-4} \leq 2.6\times10^{-4}$, where B is in units of 10^{12} G and P is the rotation period in ms (Gunn and Ostriker, 1968). Light curves in which only a pulsar contributed would obviously be much less restrictive, but they have not yet been modeled in similar detail (McCray, Shull, and Sutherland, 1987; Ostriker, 1987; Shigeyama *et al.*, 1987).

Finally, we note another piece of evidence from this period for mixing in the progenitor. Strong barium and strontium lines (Williams, 1987) indicated the presence of *s*-processed material in the envelope (by no means uncommon in red giants and supergiants). A moderate excess (e.g., factor 2.5) of the full range of *s*-process nuclides (Sc, Ti, Ba, V, Cr, Sr) improves the fit of synthetic spectra to the continuum as well as to the lines (Höflich, 1988). Both the synthesis of these nuclei, and their transport to the stellar surface, require convection to have mixed several layers extensively.

C. Decline and fall

The fall from peak luminosity joined at about day 130 onto an exponential tail. Since astronomers plot everything in log-log coordinates, this phase looks like a straight line in Figs. 2, 3, and 5, and is often called the linear part of the light curve. Depending on precisely how observed wave length bands are dereddened and summed (Catchpole *et al.*, 1988), this linear phase has an *e*-folding time of 103–115 days, in good accord with the 111-day *e*-folding life of Co^{56}. The summing is tricky, because lines comprise more than half the total flux by day 350 and (a) available photometry misses some important ones (like Paschen alpha) and (b) one wants to include only the flux currently driven from the central energy source and not light echoes and the like. For instance, what looked for a while like an infrared excess due to heated dust (Danziger *et al.*, 1987) turns out to be line and band emission (especially CO at 4.8μ) and powered from the center (Catchpole *et al.*, 1988). In fact, so far, we have no evidence for any emission from dust heated by the event at any phase (Aitken *et al.*, 1988; Harvey *et al.*, 1988; Oliva *et al.*, 1988). Another infrared line at 17.93μ (Moseley, Dwek, *et al.*, 1988) implies, first, that we are seeing a significant amount of iron made in the progenitor star, and, second, that the radioactive mantle has been mixed with the hydrogen envelope (because the line extends blueward to velocities larger than the 2000 km/s hydrogen minimum). The implications of some other infrared lines are addressed in Secs. V and VI.

The ultraviolet emission from 1987A has also continued to do interesting things. After the very rapid early drop, UV flux began to recover in May 1987 (Wamsteker, Gilmozzi, Cassatella, and Panagia, 1987; Kirshner, 1988). The emission is largely concentrated in lines, which were still brightening in February 1988 (Fransson *et al.*, 1988). The gas responsible is considerably enriched in nitrogen ($N/C = 8\pm4$; $N/O = 1.6\pm0.8$). The lines are narrow (FWHM $\approx$ 30 km/s), meaning that the gas is not part of the expanding ejecta. The most probable source is material shed by the progenitor when it was a red supergiant, compressed into a shell by the later fast blue giant wind (Chevalier, 1988), and ionized by the UV burst which marked shock breakout on 23 February (Fransson *et al.*, 1988). The continued increase in line flux indicates that the emitting material is about 10^{18} cm out, thus the star must have become blue again 10 000–20 000 yr ago. A prediction of this picture of the emitting gas is that strong soft-x-ray emission should turn on in about 10 yr, when the outermost ejecta reach the shell (Itoh, Hayakawa, *et al.*, 1987).

Several other predictions are possible. First, the IR to UV flux should begin to drop below a linear extrapolation of Figs. 2, 3, and 5 when the ejecta become optically thin to gamma rays. This effect has probably been seen, the deficit amounting to about 8% at day 385, according to Whitelock *et al.* (1988), reporting data from SAAO (South African Astronomical Observatory). This drop is not fully supported by CTIO (Cerro Tololo Inter-American Observatory) data, according to Hamuy and Phillips (1988). Notice in the figures that the two observatories have never precisely agreed, the SAAO points being brighter at all phases.

Next, as the energizing flux continues to decline and leak out more directly, the object should experience an onset of strong infrared line cooling, in which the luminosity drops below 10^{39} ergs/s (Fransson and Chevalier, 1988), and is energized by the less powerful, but longer-lived nuclide Co^{57} [half-life = 272 days (Pinto, Woosley, and Ensman, 1988)].

Finally, if core collapse left a neutron star, we ought eventually to see it, either as an energizing pulsar that prevents the decline just described (Michel, Kennel, and Fowler, 1987; Bandiera, Pacini, and Solvati, 1988; Fransson and Chevalier, 1988), or at least in the form of thermal x rays from its hot surface. These should remain above the detection limits of the x-ray satellites ROSAT and AXAF for about 100 yr (Nomoto and Tsuruta, 1988), though one hopes for launches somewhat sooner.

V. NUCLEOSYNTHESIS, X RAYS, AND γ RAYS

Invoking $0.07-0.08M_{\odot}$ of Ni^{56} to explain the optical light curve of SN 1987A led immediately to the prediction that photons from the decaying excited product nuclides should become directly visible as the optical depth of the expanding ejecta dropped. The expectation (Chan and Lingenfelter, 1987; Gehrels *et al.*, 1987) was that γ-ray lines at 0.847 MeV and 1.238 MeV should turn up sometime in 1988, with a three-month warning signal consisting of a hard-x-ray continuum of nuclear decay photons degraded by multiple Compton scatterings (Grebenev and Sunyaev, 1987; McCray, Shull, and Sutherland, 1987; Xu *et al.*, 1988).

Even as the preprints were being mailed out, the x-rays had already turned on in August 1987 and were being recorded by experiments carried by the Ginga and MIR satellites (Dotani *et al.*, 1987; Makino *et al.*, 1987; Sunyaev *et al.*, 1987). These x rays were much earlier than expected, considerably fainter than expected, and showed no signs of the rapid rise and exponential fall anticipated. If they were the Compton-scattered γ's, then the early onset could only mean that some Ni and Co were in zones of quite small optical depth, yet another piece of evidence for mixing (Itoh, Kunagai, *et al.*, 1987; Ebisuzaki and Shibazaki, 1988), of a more thorough kind than that required for γ-ray heating to contribute to the light curve at and beyond maximum light (Woosley, 1988a).

How did these very deep layers find their way out so quickly? The energy released in the decays is comparable with the kinetic energy density of the local gas. Thus the surroundings are heated, expand, and push against the denser, cooler overlying layers. Such situations are Rayleigh-Taylor unstable and should lead to bubbles or plumes of Ni-Co rich material popping out (Arnett, 1988b; Woosley, 1988b). The early turn-on then marked the epoch when the first nickel bubbles reached moderate optical depth. The faintness and absence of rapid rise and fall mean that a few percent of Co^{56} was uncovered initially, and that more was being revealed over the next year or more. Under these circumstances, γ rays should also have started coming straight out earlier than expected (Shibazaki and Ebisuzaki, 1988).

Once again, observations overtook predictions, with the announcement by Matz *et al.* (1987, 1988) that their NaI spectrometer on the Solar Maximum Mission (SMM) satellite had been seeing a modest excess of γ rays peaked around 847 keV (though with very poor energy resolution) also since August 1987. As with the x rays, the photons were early and faint (representing a few percent of the total Co^{56} implied by the optical light curve), and the flux was neither rising nor falling rapidly.

Given our anxiety to see the nuclear decay γ ray lines, and the rather poor angular and energetic resolution of the SMM detector, skepticism was briefly permissible. But three balloon flights have confirmed an 847-keV flux near 10^{-3} $\gamma\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and seen the 1.238-MeV line as well. The detectors were a low-resolution spectrometer launched from Alice Springs, Australia in November (Cook *et al.*, 1987), and two higher-resolution germanium spectrometers, launched from Alice Springs in October (Sandie *et al.*, 1988) and from Williams Field, Antarctica in January (Rester *et al.*, 1988). These also confirm that the γ's are coming from the direction of 1987A.

The relative steadiness of the flux over several months has permitted (or required, depending on your point of view) refinements of the mixing models (Arnett and Fu, 1988; Fu and Arnett, 1988; Pinto and Woosley, 1988). Sandie *et al.* (1988) also report a continuum flux between 50 and 200 keV, presumably representing another portion of the Compton-degraded spectrum seen by Ginga and MIR. According to 1988.3 models, the γ-ray flux should change rather little over the next year or so, before entering into exponential decline once there is no more buried Co to be revealed.

Additional balloon flights have occurred or are planned through the spring and summer of 1988. According to rumor (Lingenfelter, 1988), these can be expected to confirm the gradually increasing fraction of expected Co being seen [from 1.3% at first detection (Leising, 1988) to 10% in March], and the preliminary report (Rester *et al.*, 1988) that the lines are (a) double peaked, (b) redshifted by 1000 km/s or so more than expected from the + 270 km/s velocity of the LMC (cf. Pinto and Woosley, 1988), and (c) absorbed by 20–30 g/cm^2 each for the 0.847-, 1.238-, and 2.60-MeV lines (when one requires that their deabsorbed flux ratios match their branching ratios). The line splitting is at least qualitatively consistent with a remnant whose center has been cleared out by a reverse shock. The redshifting appears perhaps also in other spectral regions, and we return to it in Sec. VI. The absorption should decline with time and provide a test of the basic mixing model.

Much puzzlement resulted from the report that the hard-x-ray flux was varying suddenly and erratically (Makino *et al.*, 1988a, 1988b). It can, however, be argued that the Compton-degraded flux is, in fact, steady or slowly rising (Sunyaev *et al.*, 1988; Ubertini *et al.*, 1988), while a softer, thermal component changes both intensity and temperature in complicated ways (Tanaka, 1988a). This at least shoves all the rotten eggs into one basket, since no aspect of the soft-x-ray component is very well understood (Sec. VII). The proximity to SN 1987A of other bright x-ray sources, including the variable LMC X-1, has somewhat complicated the determination of fluxes and variability.

Finally, optical depths are much smaller in the infrared, permitting us to probe the entire remnant for nucleosynthesis products. Preliminary data have appeared at $8-13\mu$ from the European Southern Observatory (Bouchet and Danziger, 1988) and extending to longer wavelengths from the Kuiper Airborne Observatory (Moseley *et al.*, 1987, 1988; Haas *et al.*, 1988; Moseley, Dwek, *et al.*, 1988a; Rank *et al.*, 1988; Witteborn *et al.*, 1988). Line identifications were initially disputed, but it now seems at least probable (a) that a line near 10.5μ is due to Co II; (b) that it faded by about a factor of 2 between November and March, corresponding to the residual Co^{56} declining from 0.044 to $0.0023M_{\odot}$ as expected; (c) that another possible Co II line near 18.8μ disappeared between November and March; and (d) that the stable product iron made its appearance in a 17.9μ line, attributable to Fe II, whose width is large enough to suggest partial mixing into the hydrogen-rich envelope.

VI. ASYMMETRIES AND EXTENDED STRUCTURES

Many different kinds of data tell us that SN 1987A is not and never was a point or spherically symmetric source. The assorted data do not, however, add up to demonstrate any single asphericity or extension. Some items, in fact, seem to be mutually inconsistent. Thus, the ordering of topics is largely arbitrary, and the following paragraphs can be read in any order (or not read, as you prefer, though in that case the order matters less).

Small-scale lumpiness is suggested by the structure which began to appear in the $H\alpha$ emission line in October (Couch, 1988). The ragged appearance of known supernova remnants (and of nova remnants, which are much younger) indicates that filamentation and fragmentation are common phenomena. It is interesting that the breaking-up begins very early. A critical question is when filamentation progresses far enough to let us see a central pulsar or pulsar-driven nebula, and is this by any chance within the first year (Bandiera *et al.*, 1988)?

At least two observations indicate that something interesting and asymmetric (on the scale of the total ejecta) was going on as the light curve began to rise and (perhaps) the first radiogenic flux appeared at 25–40 days. First, the optical polarization changed in intensity, position angle, and wavelength dependence (Schwarz and Mundt, 1987; Barrett, 1988; Couch, 1988; Feast, 1988). Several interpretations have been offered, including an overall spheroidal structure with axial ratio about 0.7 (Jeffery, 1987) and a fast-moving jet, presumably driven by Rayleigh-Taylor instabilities of hot underlying gas (Barrett, 1988). This latter would imply a causal as well as a temporal connection with radiogenic break out. Couch (1988) and Cropper *et al.* (1988) have suggested and Barrett (1988) denied that the dominant polarization angle (after correction for interstellar contributions) is close to the 194° position angle of possible larger structure (below).

Second, between days 25 and 60, the hydrogen-line profiles, both optical and infrared, showed triple peaks, with extra emission at 4000 km/s on either side of the central maximum (Ashoka *et al.*, 1987; Hanuschik and

Dachs, 1987; Hanuschik, Theim, and Dachs, 1988; Larson, 1988; Phillips, 1988a, 1988b). This transient emission (most thoroughly studied by the Bochum group, though the Kavalur data were published first) must have come from some asymmetric structure—a rotating ring or ellipsoid or oppositely directed jets—that formed or was uncovered at a fairly definite epoch, and then dispersed or became optically thin. Lucy (1988) suggests excess emission energized by asymmetric first emergence of radiogenic x rays. If this is the right interpretation, then there may be some connection with the redshifted infrared and γ-ray lines (Haas *et al.*, 1988; Rester *et al.*, 1988; Witteborn *et al.*, 1988) which probe the present distribution and motion of material that was originally in the innermost ejecta. The event perhaps needs some descriptive name, referee Robert P. Kirshner suggesting "April split." Given the visual impact of the data shown by Hanuschik, Theim, and Dachs (1988) and Phillips (1988a, 1988b), I am inclined toward "April banana split."

These spectroscopic and polarimetric data seem to pertain to things happening within the main expanding remnant. In contrast, an assortment of results from speckle interferometry and direct imaging pertain to larger volumes. Much the most famous of these is an apparent companion, seen in March and April by two groups (Meikle, Matcher, and Morgan, 1987; Nisenson *et al.*, 1987) and not heard from since (Matcher *et al.*, 1988; Papaliolios *et al.*, 1988). The image was 3–4 magnitudes fainter than the main supernova image (brightest in the red), and about $0\rlap{.}''06$ away in position angle 194° (all numbers having fairly large error bars attached). Called the mystery spot, son of supernova, and even worse things, the companion requires information, energy, or matter to have traveled at $\gtrsim 0.4c$ if it was energized from the central event. This is not necessarily impossible, and might even be expected for a jet driven by a central neutron star (Rees, 1987) or merging pair (Goldman, 1987), which must then have hit previously existing material. The large luminosity of the companion presents problems for any model in which the triggering energy goes out spherically, as one would expect for the initial ultraviolet burst (Hillebrandt, Höflich, Schmidt, and Truran, 1987; Phinney, 1987).

One of the groups reporting the companion has also found the supernova itself to be resolved from late March 1987 onward (Karovska *et al.*, 1987, 1988; Papaliolios *et al.*, 1988) at several wavelengths. The measurements through their $H\alpha$ filter give radii of $0\rlap{.}''008$ in June 1987, $0\rlap{.}''020$ in February–March 1988, and $0\rlap{.}''027$ in April 1988, corresponding to average outflow of 4000–6000 km/s, a reasonably representative velocity for the hydrogen-rich ejecta. The later images are moderately elliptical ($a/b \sim 1.2$). Strangely, the simultaneously measured sizes at blue continuum wavelengths are all as large as, or larger than, the $H\alpha$ images: $0\rlap{.}''011$ in April 1987, $0\rlap{.}''018$ in June 1987, and $0\rlap{.}''026$ in April 1988. This is much harder to interpret, and does not seem to correspond to any velocity or feature seen in other ways.

An L-band speckle observation, reported by Chalabaev, Perrier, and Mariotti (1987), found still larger-scale structure in the form of spots or a ring providing 3–4% of the flux and $0\rlap{.}''4$ across in August 1987. This requires $v \gtrsim 0.4c$, and so ought, presumably, to be interpreted as some sort of light echo (or as a last appearance by son of supernova, if it was the tip of a relativistic jet).

Such echoes are expected—in the infrared if dust is heated and reradiates (Dwek, 1988), or in visible light if dust and gas merely reflect and scatter. The latter effect has been seen (Crotts, 1988; Gouiffes *et al.*, 1988; Heathcote and Suntzeff, 1988; Rosa, 1988) in the form of two arcs or rings, about 30″ and 50″ from the supernova (in early 1988), and 5–10″ wide. The inner one, at least, is moving out at about $1\rlap{.}''8$/month [$v \approx 19c$ (Heathcote and Suntzeff, 1988)], as was predicted from the geometry when they were first seen (Crotts, 1988). In early 1988, the arc spectra resembled that of the supernova at maximum light (April–May 1987), not that of the contemporaneous supernova. One could hardly ask for clearer evidence of the light echo phenomenon, first seen in Nova Persei 1901 (Couderc, 1939). The echo is somewhat fainter and faster-moving than predicted by Schaefer (1987), who thought it would remain at binocular visibility for some years, rather than requiring a coronagraph.

VII. RESIDUAL PUZZLES

Reference has already been made to several unexpected and perhaps unexplained aspects of 1987A. These include (a) the hows and whys and wherefores of the extensive and rather fine-tuned mixing required to account simultaneously for the optical light curve, the hard x-rays, γ rays, and infrared Co II lines if they are all results of the same decaying Co^{56} (Secs. IV and V), and (b) the short-lived speckle companion and unexpectedly large disc size at continuum wavelengths (Sec. VI). This section addresses two more incompletely solved problems: the origin of the soft-x-ray flux and the absence of evidence for a central pulsar.

One previous Type-II supernova, 1980K, was seen as a soft-x-ray source by Einstein in its dying days (Canizares, Kriss, and Feigelson, 1982). The progenitor presumably had a standard red supergiant structure (since it displayed a typical SN II light curve) and had shed a dense wind late in life, thus accounting for both the x rays and strong radio emission (Weiler *et al.*, 1982) as coming from the shocked region where ejecta encountered wind material (Chevalier, 1982). Such x rays were not expected from 1987A, given its blue progenitor and faint, brief radio emission, indicative of only tenuous circumstellar material. Behavior of the narrow UV lines mentioned in Sec. IV.C suggests that denser stuff is some 10^{18} cm out and should not be shocked for several years.

Nevertheless, the Ginga satellite saw x rays below 10 keV, beginning in August at the same time as the harder ones, addressed in Sec. VI. Eight months of monitoring (Makino *et al.*, 1987, 1988a, 1988b; Tanaka, 1988a, 1988b) have revealed complex, and seemingly correlated, variability in the hard and soft channels. Tanaka (1988b) suggests, however, a deconvolution into two components, first the degraded nuclear gamma rays, with constant flux between days 190 and 390, adsorbed by about 10^{25} atoms/cm^2 or 5 g/cm^2 (assuming cosmic abundances, which may well be wrong) and, second, thermal bremsstrahlung, whose flux and temperature varied between 8×10^{36} ergs/s at $kT=4-10$ keV, and 10^{38} ergs/s at $kT\approx60$ keV. No absorption is evident in their energy band, but there must be a sharp cutoff below 2–3 keV to avoid conflict with simultaneous rocket upper limits (Aschenbach, 1987; Briel *et al.*, 1987; Burrows, Nousek, and Gamire, 1987) of about 1.5×10^{36} ergs/s at 0.2–2 keV. The thermal nature of the emission is demonstrated by the presence (at least at high flux levels) of a 6.7–6.9 keV iron line. The measured energy means that the line is coming from iron atoms with only one or two electrons and is not fluorescence of neutral iron excited by initially nonthermal radiation.

The temporal history of the soft-x-ray component is complex, but can perhaps be summarized (Tanaka, 1988b) as a baseline low, cool flux with a couple of moderate flares in September and November 1987 and a strong, hot one in January 1988. The rise time was about 10 days, and the return to baseline took about 25 days but with a 30% drop occurring in one or two days about 23 January. Peak flux reached 10^{38} ergs/s, and the total energy in the event was at least 10^{44} ergs.

The January flare was, in a sense, predicted by Hillebrandt, Höflich, Schmidt, and Trurau, 1987, who said that soft x-rays should turn on when the outermost ejecta hit a nearby cloud they had postulated to account for son of supernova. Detailed models along these lines are not, however, terribly satisfactory (Masai *et al.*, 1987; Masai, 1988). First, a normal thermal spectrum would extrapolate to a violation of the rocket upper limits at 0.2–2 keV. Second, we have not seen the expected associated radio emission. If 1987A produced the same ratio of 6-cm flux to 4-keV flux that 1980K did, then the baseline level would correspond to a 0.4-Jy source, and the January flare to 5 Jy. But the limits (like the flux briefly seen) are at mJy levels. Masai (1988) suggests that these objections are less severe if the collision is indeed with an isolated cloud rather than with a uniform circumstellar shell. But, third, the rapid fading on 23 January requires either a cloud with $n_H\geq10^{11}$ cm^{-3}, if the time scale is set by radiative cooling, or expansion at $v\geq10^9$ cm/s, if cooling is adiabatic. Neither seems terribly likely.

Bandiera *et al.* (1988) have suggested as an alternative that the entire x-ray spectrum is being radiated by a central, pulsar-driven nebula, whose radiation we see through a rapidly varying screen of fragmented ejecta, accounting for the changes in both flux and spectrum. Such a pulsar and nebula will inevitably contribute flux at other wavelengths as well, and more detailed modeling is required to decide whether it can also fit with the observed light curve, the independent (γ-ray) evidence for radiogenic energy input, and so forth.

We are left with the puzzle, if this is not the pulsar, then where is it, and how and when can we expect to see it? The expected luminosity is

$$L=\frac{32\pi^4B^2R^6}{3c^3P^4}\ \text{ergs/s}\ ,$$

where B, R, and P are surface dipole field, radius, and rotation period, all in cgs units. This is anything from 4×10^{44} ergs/s on down.

The observations give only upper limits, mostly much lower than the maximum possible. TeV γ rays are expected from the highest-energy particles accelerated in the magnetosphere, but have not so far risen above 5×10^{38} ergs/s (Bond *et al.*, 1988; Ciampa *et al.*, 1988), considerably less than the predictions (Berezinsky and Ginzberg, 1987; Honda and Mori, 1987a, 1987b; Protheroe, 1987). There is at most very marginal evidence for a TeV flux of about 3×10^{38} ergs/s at the time of the January soft-x-ray flare (Kifune, 1988). Once the radiogenic components in IR to UV, hard x rays, and MeV γ rays are allowed for, limits of 10^{39-40} ergs/s from the pulsar obtain at those wavelengths.

Apparently, then, the current rotation period (for $B=3\times10^{12}$ G) is longer than 10–15 ms, or the dipole field strength is less than $(1-3)\times10^{10}$ G (for $P=1$ ms), or collapse on 23 February 1987 continued past neutron-star densities. Statistics of young pulsars suggest that the combination of rapid rotation and strong dipole field is, in fact, rare (Srinivasan, 1985).

Even if B^2P^{-4} is currently small, the relict neutron star could be producing up to 2×10^{38} ergs/s in x rays fueled by accretion. In the absence of exotic cooling mechanisms like pion condensates or strange quark matter, thermal x rays should persist until satellites sensitive enough to see them to have been launched (Nomoto and Tsuruta, 1988).

To decide among the alternatives—pulsar, pulsar-driven nebula, inert neutron star with or without accretion, or black hole—we will have to wait either for emission from the relic to dominate or for the ejecta to become optically thin at some wavelength where emission is unambiguously expected. When this happens depends somewhat upon composition and dust formation, but mostly upon the degree of filamentation. For $10M_\odot$ of ejecta, moving at an average speed V_{4000} (in units of 4000 km/s) for a time t years, the overburden is $10V_{4000}^{-2}t^{-2}$ g/cm^2 for a thin spherical shell, or $30V_{4000}^{-2}t^{-2}$ g/cm^2 for a uniform density sphere. This does not mean that we will never detect a central object without filamentation—on a clear day you look up through about 1000 g/cm^2, and 1987A is already nearly transparent at optical and infrared wavelengths. But it does mean that filamentation decides whether the time scale for visability will be one, ten, or a hundred years at the more readily absorbed and scattered ratio and x-ray wavelengths. If asked to bet, I would say that the time scale will turn out to be just about that on which most astronomers lose interest in a particular problem or object.

Note added in proof

Predictably, both the fluxes coming from SN 1987A and our perceptions of what they mean have continued to evolve through the summer of 1988. Some of the more important points, labeled by the sections to which they pertain, follow.

Section IV.A. The VLBI (very long baseline interferometry) results appear in D. Jauncey *et al.*, Nature (London) **334**, 412 (1988).

Section IV.C. Turn-on of emission from dust perhaps finally occurred in July 1988, when the $10-13\mu$ flux brightened by about a factor 2 (C. Smith *et al.*, IAU Circular 4645, 1988).

The total electromagnetic flux has continued to follow the exponential light curve expected from Co^{56} decay through July, although its distribution among the wavebands has gradually changed (R. M. Catchpole, in IAU, 1988).

Section V. The two main gamma-ray lines remained essentially constant through May 1988 (W. A. Mahoney *et al.*, IAU Circular 4584; W. R. Cook *et al.*, IAU Circular 4584; S. Barthelmy *et al.*, IAU Circular 4593; S. M. Matz *et al.*, IAU Circular 4618; all 1988). The details of the mixing of the various layers of ejecta are thus still further constrained.

On issues of nucleosynthesis, J. Spyromilio [Nature (London) **334**, 327 (1988)], among others, has noted that the CO bands imply $C^{12}/C^{13} \geq 10$. The carbon must, therefore, have come from a region in the progenitor that experienced triple-alpha processing, not from the zone further out dominated by CNO cycle reactions. M. A. Dopita *et al.* [Astron. J. **95**, 1717 (1988)] have noted that the ejecta have $[O/Fe] = +0.65$. Thus, if nucleosynthesis in 1987A is typical of that in SN II's, the oldest stars should be similarly iron poor, as indeed they are.

The soft x rays continue to inspire a range of models, including accretion on a central neutron star from a hypothetical binary companion [A. C. Fabian and M. J. Rees, Nature (London) **335**, 50 (1988)].

Section VI. The arc of the light echo is eccentric in a direction suggesting that the dust involved may be a shell around the 30 Doradus region (D. Allen, W. Couch, and D. Malin, IAU Circular 4633, 1988). The dust involved in producing the echo is most of what the reddening indicates must exist along the line of sight [R. Chevalier and R. T. Emmering, Astrophys. J. **331**, L105 (1988)].

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REFERENCES

Aglietta, M., *et al.*, 1987, Europhys. Lett. **3**, 1315; 1321.

Aitken, D. K., C. H. Smith, S. D. James, P. I. Roche, H. R. Hyland, and P. J. McGregor, 1988, Mon. Not. R. Astron. Soc. **231**, 7P.

Alexeyev, E. N., L. N. Alexeyava, I. V. Krivusheina, and V. I. Polchenko, 1987, Pis'ma Zh. Eksp. Teor. Fiz. **45**, 461 [JETP Lett. **45**, 589 (1987)].

Amaldi, E., P. Bonifazi, S. Frasca, M. Gabellieri, D. Gretz, G. V. Pallotino, G. Pizzella, J. Weber, and G. Wilmot, 1988, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 453.

Arafune, J., and M. Fukugita, 1987, Phys. Rev. Lett. **59**, 367.

Arafune, J., M. Fukugita, T. Yanagida, and M. Yoshimura, 1987, Phys. Rev. Lett. **59**, 1865.

Arnett, W. D., 1987, Astrophys. J. **319**, 136.

Arnett, W. D., 1988a, Astrophys. J. **331**, 377.

Arnett, W. D., 1988b, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 301.

Arnett, W. D., and A. Fu, 1988, Astrophys. J. (in press).

Aschenbach, B., 1987, Nature (London) **330**, 232.

Ashoka, B. N., G. C. Anupama, T. P. Prabhu, S. Giridhar, K. K. Ghosh, S. K. Jain, A. K. Pati, and N. Kameswara Rao, 1987, J. Astrophys. Astron. **8**, 195.

Bahcall, J. N., T. Piran, W. H. Press, and D. N. Spergel, 1987, Nature (London) **327**, 682.

Bahcall, J. N., D. N. Spergel, and W. H. Press, 1988, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 172.

Bandiera, R., F. Pacini, and M. Salvati, 1988, Nature (London) **332**, 418.

Barbiallini, G. B., and G. Cocconi, 1987, Nature (London) **329**, 21.

Barkat, Z., and J. C. Wheeler, 1988, Astrophys. J. **332**, 247.

Baron, E., H. Bethe, G. E. Brown, J. Cooperstein, and S. H. Kahana, 1987, Brookhaven National Laboratory Preprint No. 39814.

Barrett, P., 1988, SAAO Preprint.

Bartel, N., *et al.*, 1988, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 81.

Berezinsky, V. S., and V. I. Ginzberg, 1987, Nature (London) **329**, 807.

Bionta, R. M., *et al.*, 1987, Phys. Rev. Lett. **58**, 1494.

Blanco, V. M., *et al.*, 1987, Astrophys. J. **320**, 589.

Bludman, S., and P. J. Schinder, 1988, Astrophys. J. **326**, 256.

Bond, I. A., *et al.*, 1988, Phys. Rev. Lett. **60**, 1110.

Bouchet, P., and I. J. Danziger, 1988, IAU Circular 4575.

Bouchet, P., R. Stanga, T. Le Bertre, N. Epchtein, W. R. Hamann, and D. Lorenzetti, 1987, Astron. Astrophys. **177**, L9.

Branch, D., 1987, Astrophys. J. **320**, 421.

Briel, U. G., E. Pfeffermann, B. Aschenbach, H. Bräuninger, and J. Trümper, 1987, IAU Circular 4452.

Bruenn, S. W., 1987, Phys. Rev. Lett. **59**, 938.

Brunish, W. M., and J. W. Truran, 1982, Astrophys. J. Suppl. Ser. **49**, 447.

Burrows, D., J. Nousek, and G. Garmire, 1987, IAU Circular 4494.

Canizares, C. R., G. A. Kriss, and E. D. Feigelson, 1982, Astrophys. J. **253**, L17.

Cannon, R. D., 1988, Organizer, Supernova 1987A in the Large Magellanic Cloud (Canberra, Australia, June, 1988).

Catchpole, R. M., *et al.*, 1987, Mon. Not. R. Astron. Soc. **229**, 15P.

Catchpole, R. M., *et al.*, 1988, Mon. Not. R. Astron. Soc. **231**, 75P.

Chalabaev, A., C. Perrier, and J. M. Mariotti, 1987, IAU Circular 4481.

Chan, K. W., and R. E. Lingenfelter, 1987, Astrophys. J. **318**, L51.

Chevalier, R. A., 1982, Astrophys. J. **259**, 302.

Chevalier, R. A., 1988, Nature (London) **332**, 514.

Chevalier, R. A., and C. Fransson, 1987, Nature (London) **328**, 44.

Ciampa, D., *et al.*, 1988, Astrophys. J. **326**, L9.

Cook, W. R., D. Palmer, T. Prince, C. Schindler, C. Starr, and E. Stone, 1987, IAU Circular 4527.

Couch, W. J., 1988, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 60.

Couderc, P., 1939, Ann. Astrophys. **2**, 271.

Cristiani, S., *et al.*, 1987, Astron. Astrophys. **177**, L5.

Cropper, M., J. Bailey, J. McCowage, R. D. Cannon, W. J. Couch, J. R. Walsh, J. O. Straede, and F. Freeman, 1988, Mon. Not. R. Astron. Soc. **231**, 695.

Crotts, A., 1988, IAU Circular 4561.

Danziger, I. J., 1987, Ed., *Supernova 1987A* (European Southern Observatory, Munich).

Danziger, I. J., P. Bouchet, R. A. E. Fosbury, C. Gouiffes, L. B. Lucy, A. F. M. Moorwood, E. Oliva, and F. Rufener, 1988, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 37.

Danziger, I. J., R. A. E. Fosbury, D. Alloin, S. Cristiani, J. Dachs, C. Gouiffes, B. Jarvis, and K. C. Sahu, 1987, Astron. Astrophys. **177**, L13.

Dar, A., and S. Dado, 1987, Phys. Rev. Lett. **59**, 2768.

De Rújula, A., 1987, Phys. Lett. B **193**, 514.

Dopita, M., S. J. Meatheringham, P. Nulsen, and P. R. Wood, 1987, Astrophys. J. **322**, L85.

Dotani, T., *et al.*, 1987, Nature (London) **330**, 230.

Dwek, E., 1988, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 240, and Astrophys. J. **329**, 814.

Ebisuzaki, T., and N. Shibazaki, 1988a, Astrophys. J. **327**, L5.

Ebisuzaki, T., and N. Shibazaki, 1988b, Astrophys. J. **328**, 699.

Ellis, J., and K. A. Olive, 1987, CERN Preprint No. TH 4701/87.

Evans. D., R. Fong, and P. D. B. Collins, 1988, Astron. Astrophys. **189**, 210.

Fabian, A. C., M. J. Rees, E. P. J. van den Heuvel, and J. van Paradijs, 1987, Nature (London) **328**, 323.

Feast, M. W., 1988, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 51.

Fransson, C., A. Cassetella, R. Gilmozzi, R. Kirshner, N. Panagia, G. Sonneborn, and W. Wamsteker, 1988, Astrophys. J. (in press).

Fransson, C., and R. A. Chevalier, 1988, Astrophys. J. (in press).

Fu, A., and W. D. Arnett, 1988, Astrophys. J. (in press).

Gehrels, N., E. J. MacCallum, and M. Leventhal, 1987, Astrophys. J. **320**, L19.

Gilmozzi, R., *et al.*, 1987, Nature (London) **328**, 318.

Girard, T., W. F. van Altena, and C. E. Lopez, 1988, Astron. J. **95**, 58.

Goldman, I., 1987, Astron. Astrophys. **186**, L3.

Gouiffes, C., M. Rosa, J. Melnick, I. J. Danziger, M. Remy, C. Santini, J. L. Sauvageot, P. Jakobsen, and M. T. Ruiz, 1988, Astron. Astrophys. **198**, L9.

Grasberg, É. K., V. S. Imshennik, D. K. Nadezhin, and V. P. Utrobin, 1987, Sov. Astron. Lett. **13**, 227.

Grebenev, S. A., and R. A. Sunyaev, 1987a, Pis'ma Astron. Zh. **13**, 945 [Sov. Astron. Lett. **13**, 397 (1987)].

Grebenev, S. A., and R. A. Sunyaev, 1987b, Pis'ma Astron. Zh. **13**, 1042 [Sov. Astron. Lett. **13**, 438 (1987)].

Gunn, J. E., and J. P. Ostriker, 1968, Nature (London) **221**, 454.

Haas, M. R., S. W. J. Colgan, E. F. Erickson, S. D. Lord, and M. G. Burton, 1988, IAU Circular 4578.

Hamuy, M., and M. Phillips, 1988, IAU Circular 4534.

Hamuy, M., N. R. Suntzeff, R. Gonzalez, and G. Martin, 1988, Astron. J. **95**, 62.

Hanuschik, R. W., and J. Dachs, 1987, Astron. Astrophys. **182**, L29.

Hanuschik, R. W., G. Theim, and J. Dachs, 1988, Mon. Not. R. Astron. Soc. (in press).

Hari Dass, N. D., *et al.*, 1987, Curr. Sci. **56**, 575.

Harvey, P., *et al.*, 1988, IAU Circular 4518.

Hayakawa, S., and K. Sato, 1988, Eds., *Proceedings of the 20th Yamada Conference, Big Bang, Active Galactic Nuclei, and Supernovae,* edited by S. Hayakawa and K. Sato (Universal Academy Press, Tokyo).

Heap, S. R., and D. J. Lindley, 1987, Astron. Astrophys. **185**, L10.

Heathcote, S., and N. R. Suntzeff, 1988, IAU Circular 4567.

Hillebrandt, W., P. Höflich, P. Kafka, E. Müller, H. U. Schmidt, and J. W. Truran, 1987a, Astron. Astrophys. **177**, L41.

Hillebrandt, W., P. Höflich, P. Kafka, E. Müller, H. U. Schmidt, and J. W. Truran, 1987b, Astron. Astrophys. **180**, L20.

Hillebrandt, W., P. Höflich, H. U. Schmidt, and J. W. Truran, 1987, Astron. Astrophys. **186**, L9.

Hillebrandt, W., P. Höflich, J. W. Truran, and A. Weiss, 1987, Nature (London) **327**, 597.

Hirata, K., *et al.*, 1987, Phys. Rev. Lett. **58**, 1490.

Hodge, P., and F. Wright, 1967, The Large Magellanic Cloud (V chart 54; B chart 53).

Höflich, P., 1988, in *Atmospheric Diagnostics of Stellar Evolution,* IAU Colloquium No. 108, edited by K. Nomoto, Lecture Series in Physics (Springer, Berlin) (in press).

Honda, M., and M. Mori, 1987a, Prog. Theor. Phys. **78**, 63.

Honda, M., and M. Mori, 1987b, Prog. Theor. Phys. **78**, 1065.

IAU, 1988, Joint Discussion on SN 1987A at 20th General Assembly of International Astronomical Union, in Vol. 8 of

Highlights of Astronomy, edited by D. McNally (in press).

Itoh, M., S. Hayagawa, K. Masai, and K. Nomoto, 1987, Publ. Astron. Soc. Jpn. **39**, 529.

Itoh, M., S. Kunagai, T. Shigeyama,and K. Nomoto, and J. Nishimura, 1987, Nature (London) **330**, 233.

Jeffery, D. T., 1987, Nature (London) **329**, 419.

Joss, P. L., P. Podsiadlowskii, J. J. L. Hsu, and S. Rappaport, 1988, Nature (London) **331**, 237.

Kafatos, M., and A. G. Michalitsianos, 1988, Eds., *Supernova 1987A in the Large Magellanic Cloud* (Cambridge University Press, Cambridge, England).

Kahana, S. H., J. Cooperstein, and E. Baron, 1987, Brookhaven National Laboratory Preprint No. 40012.

Karovska, M., L. Koechlin, P. Nisenson, C. Papaliolios, and C. Standley, 1987, IAU Circular 4521.

Karovska, M., L. Koechlin, P. Nisenson, C. Papaliolios, and C. Standley, 1988, IAU Circular 4604.

Kifune, T., 1988, in *Proceedings of the 20th Yamada Conference, Big Bang, Active Galactic Nuclei and Supernovae,* edited by S. Hayakawa and K. Sato (Universal Academy Press, Tokyo).

Kirshner, R. P., 1988, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 87.

Kirshner, R. P., G. Sonneborn, D. M. Crenshaw, and G. E. Nassiopoulos, 1987, Astrophys. J. **320**, 620.

Koshiba, M., 1988, private communication.

Krauss, L. M., 1987, Nature (London) **329**, 689.

Larson, H. P., 1988, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 74.

Lattimer, J. M., and J. Cooperstein, 1988, Phys. Rev. Lett. **61**, 23.

Leising, M. D., 1988, Nature (London) **332**, 516.

Lingenfelter, R. E., 1988, private communication.

Long, M. J., 1988, Phys. Rev. Lett. **60**, 127.

Lucke, P. B., and P. Hodge, 1970, Astron. J. **75**, 171.

Lucy, L. B., 1987, Astron. Astrophys. **182**, L31.

Lucy, L. B., 1988, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 323.

Maeder, A., 1987, Astron. Astrophys. **173**, 247.

Makino, F., and the Ginga Team, 1987, IAU Circular 4447.

Makino, F., and the Ginga Team, 1988a, IAU Circular 4530.

Makino, F., and the Ginga Team, 1988b, IAU Circular 4532.

Masai, K., 1988, in *Proceedings of the 20th Yamada Conference, Big Bang, Active Galactic Nuclei, and Supernovae,* edited by S. Hayakawa and K. Sato (Universal Academy Press, Tokyo).

Masai, K., S. Hayakawa, H. Itoh, and K. Nomoto, 1987, Nature (London) **330**, 235.

Matcher, S., *et al.*, 1988, IAU Circular 4543.

Matz, S. M., *et al.*, 1987, IAU Circular 4510.

Matz, S. M., *et al.*, 1988, IAU Circular 4568.

Mayle, R., J. R. Wilson, and D. N. Schramm, 1987, Astrophys. J. **318**, 288.

McCray, R., J. M. Shull, and P. Sutherland, 1987, Astrophys. J. **317**, L73.

McNaught, R. H., 1987a, IAU Circular 4316.

McNaught, R. H., 1987b, IAU Circular 4317.

McNaught, R. H., 1987c, IAU Circular 4389.

Meikle, W. P. S., S. S. Matcher, and B. L. Morgan, 1987, Nature (London) **329**, 608.

Menzies, J. W., *et al.*, 1987, Mon. Not. R. Astron. Soc. **227**, 39P.

Michel, F. C., C. F. Kennel, and W. A. Fowler, 1987, Science **238**, 938.

Moseley, H., E. Dwek, W. Glaccum, J. Graham, R. Loewenstein, and R. Silverberg, 1988, IAU Circular 4576.

Moseley, H., E. Dwek, W. Glaccum, J. Graham, R. Loewenstein, and R. Silverberg, 1988a, IAU Circular 4574.

Moseley, H., W. Glaccum, R. Loewenstein, R. Silverberg, E. Dwek, and J. Graham 1987, IAU Circular 4500.

Nisenson, P., C. Papaliolios, M. Karovska, and R. Noyes, 1987, Astron. J. **320**, L15.

Nomoto, K., and S. Tsuruta, 1988, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 421.

Oliva, E., A. F. M. Moorwood, and I. J. Danziger, 1988, ESO Messenger **50**, 18.

Ostriker, J. P., 1987, Nature (London) **327**, 287.

Pacini, F., 1988, in *Proceedings of the 20th Yamada Conference, Big Bang, Active Galactic Nuclei, and Supernovae,* edited by S. Hayakawa and K. Sato (Universal Academy Press, Tokyo).

Paczyński, B., 1970, Acta Astron. **20**, 195.

Paczyński, B., 1971, Acta Astron. **22**, 163.

Panagia, N., R. Gilmozzi, A. Cassatella, W. Wamsteker, R. P. Kirshner, and G. Sonneborn, 1987, IAU Circular 4514.

Papaliolios, C., *et al.*, 1988, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 225.

Phillips, M. M., 1988a, Astron. J. **95**, 1087.

Phillips, M. M., 1988a, in *Supernova 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 16.

Phinney, E. S., 1987, Nature (London) **329**, 698.

Pinto, P. A., and S. E. Woosley, 1988, Nature (London) **333**, 534.

Pinto, P. A., S. E. Woosley, and L. M. Ensman, 1988, Astrophys. J. **331**, L101.

Protheroe, R. J., 1987, Nature (London) **329**, 135.

Raffelt, G., and D. Seckel, 1988, Phys. Rev. Lett. **60**, 1793.

Raga, A. C., 1987, Astron. J. **94**, 1578.

Rank, D. M., P. A. Pinto, S. E. Woosley, J. D. Bregman, F. C. Witteborn, T. X. Axelrod, and M. Cohen, 1988, Nature (London) **331**, 505.

Rees, M. J., 1987, Nature (London) **328**, 207.

Rester, A. C., G. Eichborn, R. L. Coldwell, J. I. Trombka, R. Starr, and G. P. Lasche, 1988, IAU Circular 4535.

Rosa, M., 1988, IAU Circular 4564.

Rousseau, J., N. Marin, L. Prévot, E. Rebeirot, A. Robin, and J. P. Brunet, 1978, Astron. Astrophys. Suppl. Ser. **31**, 243.

Saavedra, O., *et al.*, 1988, in *Proceedings of the 20th Yamada Conference, Big Bang, Active Galactic Nuclei, and Supernovae,* edited by S. Hayakawa and K. Sato (University Academy Press, Tokyo).

Saio, H., M. Kato, and K. Nomoto, 1988, Astrophys. J. **331**, 388.

Sandie, W., G. Nakano, L. Chase, G. Fishman, C. Meegan, R. Wilson, W. Paciesas, and G. Lasche, 1988, IAU Circular 4526.

Sanduleak, N., 1970, CTIO Contr. 89.

Sato, K., and H. Suzuki, 1987a, Phys. Rev. Lett. **58**, 2722.

Sato, K., and H. Suzuki, 1987b, Phys. Lett. B **196**, 267.

Schaefer, B. E., 1987, Astrophys. J. **323**, L47.

Schaeffer, R., M. Casse, R. Mochkovitch, and S. Cahew, 1987, Astron. Astrophys. **184**, L1.

Schaeffer, R., Y. Declais, and S. Jullian, 1987, Nature (London) **330**, 142.

Schwarz, H. E., and R. Mundt, 1987, Astron. Astrophys. **177**, L4.

Shibazaki, N., and T. Ebisuzaki, 1988a, Astrophys. J. **327**, L9.

Shigeyama, T., K. Nomoto, and M. Hashimoto, 1988, Astron. Astrophys. **196**, 141.

Shigeyama, T., K. Nomoto, M. Hashimoto, and D. Sugimoto, 1987, Nature (London) **328**, 320.

Shklovskii, I. S., 1984, Sov. Astron. Lett. **10**, 302.

Sonneborn, G., B. Altner, and R. P. Kirshner, 1987, Astrophys. J. **323**, L35.

Spergel, D. N., and J. N. Bahcall, 1988, Phys. Lett. B **200**, 366.

Spergel, D. N., T. Piran, A. Loeb, J. Goodman, and J. N. Bahcall, 1987, Science **237**, 1471.

Srinivasan, G., 1985, in *Supernovae, Their Progenitors and Remnants,* edited by G. Srinivasan and V. Radhakrishnan (Indian Academy of Sciences, Bangalore), p. 105.

Storey, M. C., and R. N. Manchester, 1987, Nature (London) **329**, 421.

Sunyaev, R. A., *et al.*, 1987, Nature (London) **330**, 227.

Sunyaev, R. A., *et al.*, 1988, preprint (in Russian).

Suzuki, H., and K. Sato, 1987, Publ. Astron. Soc. Jpn. **39**, 521.

Takhara, M., and K. Sato, 1987, Mod. Phys. Lett. A **2**, 293.

Tanaka, Y., 1988a, in *Proceedings of the 20th Yamada Conference, Big Bang, Active Galactic Nuclei, and Supernovae,* edited by S. Hayakawa and K. Sato (Universal Academy Press, Tokyo).

Tanaka, Y., 1988b, in *Supernovae 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 349.

Testor, G., 1988, Astron. Astrophys. **190**, L1.

Trimble, V., 1982, Rev. Mod. Phys. **54**, 1183.

Trimble, V., B. Pacyński, and B. Zimmerman, 1973, Astron. Astrophys. **25**, 35.

Turtle, A. J., *et al.*, 1987, Nature (London) **327**, 38.

Tyson, J. A., and P. Boeshaar, 1987, Publ. Astron. Soc. Pac. **99**, 905.

Ubertini, P., *et al.*, 1988, IAU Circular 4590.

Uomoto, A., and R. P. Kirshner, 1986, Astrophys. J. **308**, 685.

Voskresensky, D. N., *et al.*, 1987, Astrophys. Space Sci. **138**, 421.

Walborn, N. R., B. M. Lasker, V. G. Laidler, and Y.-H. Chiu, 1987, Astrophys. J. **321**, L41.

Wampler, E. J., J. W. Truran, L. B. Lucy, P. Höflich, and W. Hillebrandt, 1987, Astron. Astrophys. **182**, L51.

Wamsteker, W., *et al.*, 1987, Astron. Astrophys. **177**, L21.

Wamsteker, W., R. Gilmozzi, A. Cassatella, and N. Panagia, 1987, IAU Circular 4410.

Weaver, T. A., and S. E. Woosley, 1980, Ann. N.Y. Acad. Sci. **336**, 335.

Weiler, K. W., R. A. Sramek, J. M. van der Hulst, and N. Panagia, 1982, in *Supernovae: A Survey of Current Research,* edited by M. J. Rees and R. J. Stoneham (Reidel, Dordrecht), p. 281.

Weiss, A., W. Hillebrandt, and J. W. Truran, 1988, Astron. Astrophys. Lett. **197**, L11.

West, R. M., A. Laubertz, H. E. Jurgensen, and H. E. Schuster, 1987, Astron. Astrophys. **177**, L1.

Wheeler, J. C., R. P. Harkness, and Z. Barkat, 1988, in *Supernovae 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England), p. 264.

Wheeler, J. C., R. P. Harkness, and Z. Barkat, 1988a, IAU Colloquium 108, edited by K. Nomoto (in press).

White, G. L., and D. F. Malin, 1987, Nature (London) **327**, 36.

Whitelock, P. A., *et al.*, 1988, Mon. Not. R. Astron. **234**, 5p.

Williams, R. E., 1987, Astrophys. J. **320**, L117.

Witteborn, F., J. Bregman, D. Wooden, P. Pinto, D. Rank, and M. Cohen, 1988, IAU Circular 4592.

Woosley, S. E., 1988a, Astrophys. J. **330**, 218.

Woosley, S. E., 1988b, in *Supernovae 1987A in the Large Magellanic Cloud,* edited by M. Kafatos and A. G. Michalitsianos (Cambridge University Press, Cambridge, England).

Woosley, S. E., P. A. Pinto, and L. Ensman, 1988, Astrophys. J. **324**, 466.

Woosley, S. E., P. A. Pinto, P. G. Martin, and T. A. Weaver, 1987, Astrophys. J. **318**, 664.

Xu, Y., P. Sutherland, R. McCray, and R. R. Ross, 1988, Astrophys. J. **327**, 197.