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Supernovae. Part II: the aftermath

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Part I [Rev. Mod. Phys. 54, 1183 (1982)] explored stellar evolution leading up to supernovae and observations and models of the events themselves. Part II addresses the aftermath: supernova remnants, products, and by-products, including nucleosynthesis, and the future of supernova research. Some of the important questions are: (1) How close is the association among supernova events, pulsar production, and remnant production? (2) Where does most of the energy from neutron star formation go? and (3) How do supernovae interact with the rest of the universe, for instance in heating and stirring the interstellar medium, accelerating cosmic rays, and triggering or inhibiting star formation?

CONTENTS

V. SUPERNOVA REMNANTS

Supernovae as a class were born with their remnants in place. By the time Baade and Zwicky (1934) separated them off from the classical novae, the work of Barnard (1917, 1919) on Nova Per 1901 and Nova Aql 1918 had established firmly within the astronomical folklore (Russell, Dugan, and Stewart, 1927) the idea that an old nova ought to be surrounded by an expanding gas cloud, with expansion time scale equal to the time since the outburst (Humason, 1935).

The lore of supernova remnants (SNR's) is an important subject in its own right. These objects are among the most conspicuous radio and x-ray sources in our own and other "normal" galaxies, and modeling them adequately probes the frontiers of plasma astrophysics and the techniques that must be used to understand the behavior of active galaxies and other exotics.

The standard reference has, for many years, been that by Woltjer (1972). More recent useful reviews include those of models by Chevalier (1982) and McKee (1982) and those of observations and their interpretations that will appear in the IAU Symposium edited by Gorenstein and Danziger (1983). The sections that follow, after a brief historical nod at the Crab Nebula, focus on those aspects of SNR's that help constrain models of supernova events and their interactions with the rest of the universe. These include the rates and types of supernovae in our own and other galaxies, the mechanism and energy of the ejection process, and the mass and composition of the material ejected.

A. The Crab Nebula

This pineapple-shaped enigma (Rosse, 1844) is the only single object to have rated its own IAU Symposium (Davies and Smith, 1971) without our living next to or inside of it. Its remarkable list of firsts and near-firsts includes genuinely diffuse emission as opposed to an unresolved star cluster (Lassell, 1854), high-velocity emission lines (Slipher, 1916), a radio source (Bolton and Stanley, 1948) with polarization (Mayer, McCullough, and Sloanaker, 1957) and a compact core (Hewish and Okoye, 1964), optical synchrotron radiation (Dombrovsky, 1954), an x-ray source (Bowyer *et al.*, 1964) also polarized (Weisskopf *et al.*, 1978), and an optical pulsar (Cocke, Disney, and Taylor, 1969) with a changing period (Richards and Comella, 1969) and glitches (Boynton *et al.*, 1969).

In the duodecade since IAU Symposium No. 46, the limelight has largely moved on to other objects. Nevertheless, an assortment of more recent observations has helped a bit to pin down what must be going on inside the volume of the nebula and provided evidence for appreciable mass and energy outside the familiar outline.

1. The inner nebula

The object which graces the covers of so many elementary astronomy texts emits both continuum synchrotron radiation from a power-law distribution of relativistic electrons (and positrons?) within an ambient magnetic field and emission lines from $\gtrsim 1\ M_\odot$ of gas near 10^4 K. The former is seen from very low radio frequencies well into the gamma-ray region, the latter largely in the optical, near-uv, and near-ir.

The synchrotron emission requires $\gtrsim 10^{49}$ ergs in field and relativistic particle energies, the minimum being achieved near equipartition. Clearly, it would be useful to know how much of each is present. The amount of inverse Compton scattering of the synchrotron photons by the electrons provides an approximate answer, subject to assumptions about homogeneity and so forth (Rieke and Weekes, 1969). These Compton-scattered photons have still probably not been seen. The unpulsed gamma-ray flux above 35 MeV fits smoothly on to an extrapolation of the x-ray (synchrotron) spectrum, and, above 100 MeV, virtually all the flux is pulsed at the period of NP 0532 (Thompson *et al.*, 1977a; Swanenburg *et al.*, 1981; Gupta *et al.*, 1978). If the measured photon fluxes (about 6×10^{-6} cm^{-2}s^{-1} above 35 MeV and 10^{-11} cm^{-2}s^{-1} above 500 GeV) are taken as upper limits to the inverse Compton flux, then the average magnetic field remains constrained to $\gtrsim 3\times10^{-4}$ G, essentially the equipartition value, as noted by Fazio *et al.* (1971) and others.

At the low-energy end, far-infrared and millimeter fluxes and upper limits have now been reported by several groups (Werner *et al.*, 1977; Harvey, Gatley, and Thronson, 1978; Wright *et al.*, 1979, Glaccum *et al.*, 1982). From 200 μm longward, these fit well onto an extrapolation of the radio spectrum, but the 60-, 100-, and 140-μm points (Glaccum *et al.*, 1982) imply a modest infrared excess, which the authors attribute to dust, behaving along the lines modeled by Dwek and Werner (1981). The dust temperature is about 40 K, reasonable for silicates exposed to the radiation field of the nebula. Fluxes measured in seven $40\times50''$ fields over the object show that the dust is not piled up around the edges like swept-up interstellar material. Rather, it is distributed more or less like the nonthermal radio emission. Given this distribution, the $2.6\times10^{-3}\ M_\odot$ needed to make the infrared excess in the central $60''$ implies $2.4\times10^{-2}\ M_\odot$ of dust for the nebula as a whole (Glaccum and Harper, 1982). This very nicely balances the modest heavy-element deficiency in the thermal gas, giving the inner nebula as a whole a quite ordinary Population I abundance pattern, apart from the excess helium.

The continuum ultraviolet spectrum shows up clearly in both ANS and IUE data (Wu, 1981; Davidson *et al.*, 1982). It confirmed earlier conclusions that line-of-sight reddening, $E(B-V)$, is about $0\overset{m}{.}5$ and helped to pin down the change in spectral index with frequency: $F(\nu)\propto\nu^{-\alpha}$, with $\alpha=0.25$ in the radio range, 0.43 in the optical, 0.5 in the uv, and 1.1 in the x-ray region.

The line-emitting gas, in comparison at least to that in other young SNR's, continues to be relatively unexciting. Both ultraviolet (Davidson *et al.*, 1982) and infrared (Dennefeld and Andrillat, 1981) lines of carbon show that the element is not significantly overabundant (C/O$\sim$1). Thus the only demonstrated abundance anomaly continues to be the enhancement of helium, which is, however, considerable. Helium probably makes up about 80% of the mass of line-emitting gas. He/H may be nonuniform over the nebula, with a relatively low value in the northwest sector (Henry and MacAlpine, 1982).

Individual filaments are presumably uniform in composition, but there is enormous stratification in temperature and ionization, Fe II, III, V, and VII managing to coexist within a single (spatial and velocity) feature (Fesen and Kirshner, 1982). The presence of the C I infrared line is a bit puzzling because the atom ionizes so easily. The problem disappears if the larger filaments have neutral cores, though one is then marginally puzzled by the absence of lines from neutral and singly ionized calcium, unless Ca is somehow locked up in dust grains, which also shield the neutral cores. The amount of dust required may, however, exceed the infrared continuum value. Inhomogeneities in the carbon distribution are also a possibility (Henry and MacAlpine, 1982).

2. The halo

Scargle (1970) seems to have been the first to report faint optical emission from outside the bright region marked off by the filaments of thermal gas. This extended a minute or two of arc beyond the sharp $4\times7'$ contour, and he suspected it was synchrotron emission from electrons leaking into the interstellar magnetic field. Soon after, van den Bergh (1970) also reported emission extending outward about $1'$, but this in the form of a relatively narrow jet sticking out of the northern edge of the nebula.

Both features now seem to belong to an emission line component, though not necessarily the one previously described. Interference filter photographs (Fig. 1) and spectroscopy of the jet (Davidson, 1979; Gull and Fesen, 1982) show that it is most conspicuous in [O III] and much less so in Hα + [N II] (meaning that it is warmer and/or more highly ionized than the nebular average). In addition, the jet has exceedingly sharp edges (width $45''$, length $75''$) and pronounced edge brightening, as if we were looking sideways at a hollow tube. The tube does not seem to project backward into the main body of the nebula at all; but if it did, it would miss both the pulsar and the center of nebular expansion by about twice its own width. It has not been ejected from the center in any straightforward way, tricky spiral geometries and such being largely excluded by the radial velocity, which is only about 150 km/s (Gull and Fesen, 1982). In fact, none of the early models (Bychkov, 1975; Chevalier and Gull, 1975) fit very well with the new data on the jet and on the medium into which it is apparently penetrating.

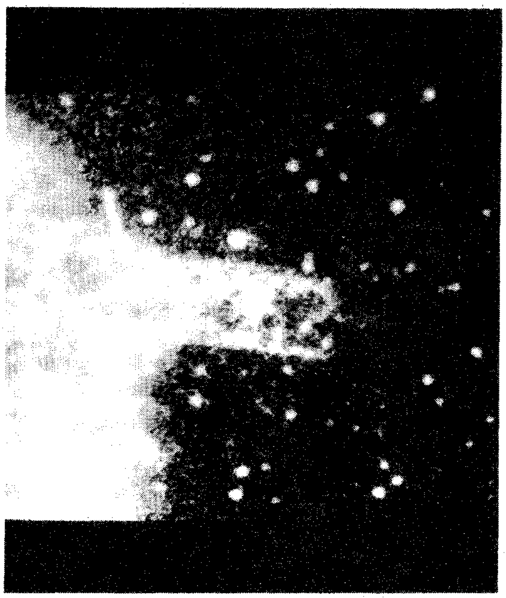

FIG. 1. The Crab Nebula jet, an emission-line feature extending out of the main body of the nebula into the faint Hα halo. It does not point back toward the pulsar or nebular expansion center, and neither its existence nor its sharp edges is understood. Photograph courtesy of Gull and Fesen (1982).

Blandford *et al.* (1982) suggest that the jet may be a trail of $\sim10^{-6}\ M_\odot$ of stellar wind material left by the parent red giant moving away from the galactic plane at about 30 km/s. The part of the trail inside the nebula (and/or the extended halo) has then been erased, and the misalignment between jet axis and direction to the pulsar reflects drift with the surrounding interstellar gas. The trail gas has been reionized by uv from the main nebula, and its high degree of ionization reflects its small column depth in this model.

The halo has shown up most clearly so far in an Hα + [N II] interference filter photograph (Murdin and Clark, 1981). It extends fairly smoothly over a region $6\times14'$ and is not limb brightened. Gas in that region must be completely ionized by the nebular ultraviolet synchrotron, and, in the absence of clumping, 8 $M_\odot$ of solar-abundance gas is required to reproduce the observed emission measure (~7 pc cm^{-6}). There is a reasonable chance that the Hα halo is an instrumental artifact attributable to reflections within the interference filter used by Murdin and Clark (Gull, 1982). The following paragraphs presuppose its reality.

The halo gas could, in principle, be relatively slow-moving material, ejected as a wind by the presupernova star. In this case, its outer edge should interact peacefully with the surroundings and remain cool, but one might expect fireworks where the main nebula is plowing into its inner edge. There is, indeed, apparently an x-ray halo, about $7'$ across (Toor *et al.*, 1976; Charles and Culhane, 1977) which might represent such an interaction. But, as the x-ray halo shows none of the emission lines one would expect from gas at any temperature between 2×10^6 and 10^8 K (Schattenburg *et al.*, 1980), it has, of late, generally been blamed on interstellar dust scattering x rays from the central source.

The mature reader may, at this point, be suffering mild twinges of *deja vu* related to something once called "the Slysh mechanism" (Slysh, 1969)—this being a case nearly unique in the annals of astronomical history in that the American astronomer (Overbeck, 1965) actually did the calculation before the Soviet astronomer who got the credit. The physical difference between that case and this is that the larger x-ray halo does actually show the dependences of intensity and size on energy that would be expected for dust scattering (Toor *et al.*, 1976), in a way that the central, polarized, extended x-ray source does not. The scattering cannot, however, be blamed for the disappearance of the pulsar x-ray flux at low energies, as this drops off much more rapidly than the halo flux comes up (Toor *et al.*, 1976).

The more interesting interpretation of the Murdin and Clark (1981) Hα halo is that it represents the outer layers of a massive star, ejected during a reasonably normal Type II supernova event. The size, mass, and emission measure are remarkably close to those predicted by Chevalier (1977a) on the basis of such a hypothesis. The outer edges should be moving at about 5000 km/s, and the absence of both optical and x-ray limb brightening there must indicate a very low density for the local interstellar medium. Such a halo carries a kinetic energy of about 2×10^{51} ergs and will have swept up about $10n_{\mathrm{H}}$ $M_{\odot}$ of interstellar material, where n_{H} is the local hydrogen number density.

The Hα halo and its interpretation have not, so far, been confirmed by other sorts of data. There is, for instance, no extended radio source of the sort that would be expected from a 5000–10 000 km/s shock wave plowing into the amount of interstellar medium normally found 200 pc from the galactic plane, according to a 610-MHz Westerbork map made by Wilson and Weiler (1982). Their upper limits require either an expansion speed in excess of 12 000 km/s or a very-low-density, hot, ionized interstellar medium. The latter, at least, is by no means impossible.

3. Models

Not surprisingly, the 1982 data have not yet been incorporated into models for the expansion of the nebula, energy injection by the pulsar, and so forth. Not that the models were in wildly good shape before (Michel, 1982; Benford, Ferrari, and Massaglia, 1982), neither winds nor waves being very effective at transporting magnetic field through the nebula. The halo may actually help by providing another relatively well-defined set of boundary conditions to match. A first attempt in this direction (Kennel and Coroniti, 1983) leads to a model in which the x-ray halo is real and thermal; an MHD wind evaporating from the pulsar evacuated the region out to the innermost wisp; beyond is a high-pressure confined flow that compresses and leaves behind thermal gas (the filaments) as it goes; there is much more energy in particles than in the weak toroidal magnetic field which accumulates in the nebula, much as argued by Rees and Gunn (1974). All of these things are basically good and in agreement with the observations except possibly the last, which may violate the gamma-ray upper limits. Temporal changes in the wisp structure, which have gone largely unstudied since the work of Scargle (1969), could provide additional constraints on the nature of the transition between zones.

Models for the evolution of the object before 1054 have, on the other hand, been much clarified by the discovery of the outer halo, and several workers (Nomoto in NATO81; Davidson *et al.*, 1982; Hillebrandt, 1982) have now joined Woosley *et al.* (1980) in favoring an 8–10 $M_{\odot}$ star undergoing core collapse in more or less the usual way (Sec. IV.B of Part I) and helping to define the lower boundary of the mass range that can give rise to supernovae (of Type II?).

B. Rates and types

Observations of light curves and spectra of extragalactic supernovae (Secs. III.B and III.C of Part I) require that a typical event expel $\gtrsim 1\ M_{\odot}$ at a velocity near 10^4 km/s, Type II's normally involving more mass but smaller velocities than Type I's. The associated kinetic energy, $\sim 10^{51}$ ergs, when followed via any of the standard models of SNR evolution (Gull, 1973; Rosenberg and Scheuer, 1973; Mansfield and Salpeter, 1974; McKee 1974; Chevalier, 1975; and many recent ones discussed in NATO81), results in a remnant that should remain visible for $\sim 10^5$ yr.

We thus expect *a priori* that the SNR formation rate should equal the SN rate in each galaxy where both can be determined. Table I shows that this is not entirely the case. Neither of the columns of numbers is free of uncertainties. The expected rates are scaled by galaxy type and luminosity from the statistical results compiled by Tammann (in NATO81 and elsewhere). The chief difficulties here are the correction factors for incompleteness in the surveys and the very small numbers of events in each box when different types of galaxies are considered separately (cf. Sec. III.A.1 of Part I).

In the case of the remnants, at least we know we are looking at the right kind of galaxy. But completeness of the surveys (optical, radio, and x ray) remains a problem, both for the most extended (old) remnants, which are generally faint, and for the most compact ones, which are easily confused with other kinds of objects. Evolutionary changes in remnant spectra in particular will cause older objects to be missed (Reich, 1982). There is direct evidence that any one sort of survey can miss objects in the size range to which it is supposedly sensitive that would be caught by another sort of survey from the x-ray detection of several previously unknown SNR's in the Milky Way (Markert *et al.*, 1981) and of many new ones in the Large Magellanic Cloud (LMC) (Long, Helfand, and Grabelsky, 1981; Helfand and Long in NATO81). The soft x-ray spectra and low radio luminosities of many of the LMC objects mean that similar ones would have been missed by both radio and x-ray counts in the Milky Way.

In addition to incomplete counting, we must worry about how to determine ages of supernova remnants if

TABLE I. Rates of supernovae and supernova remnant formation in nearby galaxies.

Galaxy	Predicted SN rate	Measured SNR formation rate
Milky Way	$\frac{1}{30}$ yr[a]	$\frac{1}{80}$ yr[b]
M31	$\frac{1}{36}$ yr[c]	$\frac{1}{200}$ yr[c]
LMC	$\frac{1}{300}$ yr[d]	$\frac{1}{110}-\frac{1}{340}$ yr[d]
M33	$\frac{1}{65}$ yr[c]	$\frac{1}{30}$ yr[c]
SMC	$\frac{1}{2400}$ yr[e]	$\frac{1}{1000}$ yr[f]

[a] Tammann, in NATO81.

[b] Caswell and Lerche, 1979.

[c] Dennefeld and Kunth, 1981.

[d] Long, Helfand, and Grabelsky, 1981.

[e] Scaled from LMC value by ratio of their luminosities.

[f] Mills, Little, Durdin, and Kesteven, 1982.

their formation rate is to be measured. The custom is to fit a Sedov (1959; adiabatic) solution, which says that the number of remnants with diameter less than D is given by

$$N(\leq D)=\frac{9.88D_{\rm pc}^{5/2}}{t(E_0/n_0)^{1/2}}$$

where t is the mean interval between supernovae exploding with energy E_0 (in units of 10^{50} ergs) into a medium with hydrogen number density n_0/cm^3. E_0 and n_0 can be found from x-ray data (total luminosity and temperature) and also from optical data, if it is safe to assume thermal pressure equilibrium between the optical and x-ray gas. Unfortunately, (a) when this latter assumption is made, the implied value of E_0 scales roughly as D^3 (Blair in NATO81), which is too steep to reflect merely the fact that energetic remnants expand faster than puny ones, and (b) a plot of $N(\leq D)$ for the LMC remnants does not in fact show a slope of $\frac{5}{2}$, at least for the smaller remnants, whether optical, radio, or x-ray data are used (Dopita in NATO81; Long, Helfand, and Grabelsky, 1981). The former, according to Blair (in NATO81), means that there is nonthermal (probably magnetic) pressure in the thermal gas filaments, so that the energies are not accurately estimated. And the latter means that we cannot put faith in SNR formation rates until the data are fitted by a more suitable model than a pure Sedov solution (Helfand *et al.*, 1982).

Ignoring all these caveats, one can nevertheless make some sense out of the numbers in Table I. Remnants seem to match events in the three gas-rich galaxies, M33 and MC's, but to be deficient in the Milky Way and Andromeda. This is just as it should be if long-term detectability of remnants requires events that go off in regions with enough neutral interstellar gas (e.g., $n_{\rm H}\gtrsim 0.1$) for the shocks to have something to shock (Kafatos *et al.*, 1981; Higdon and Longenfelter, 1981). There is, on this basis, at least no inconsistency among the rates given in Table I.

Types of a few galactic SNR's and their parent events were addressed in Sec. III.A.2 of Part I, with a tentative endorsement of Weiler and Panagia's (1980) conclusion that filled-center, flat-spectrum, young remnants come from Type II events and shell-like, steep-spectrum ones from Type I's. The combination filled center with steep ($\alpha\sim0.5$) spectral index also occurs (Caswell *et al.*, 1982). By an age of 10^4 yr, all SNR's will be dominated by interactions with the surrounding medium and the event type no longer be discernable (Lozinskaya, 1980) unless a radio pulsar or compact x-ray source can be detected. G93.3 + 6.9, which displays both a radio shell and enhanced emission near the center (but no point source with more than 1% of the total flux at 2700 MHz; Haslam, Paules, and Slater, 1980), is presumably an example of an object in transition to domination by its surroundings. N 157B in the Large Magellanic Cloud is the first Crab-like remnant seen outside the galaxy. It shows a filled center and nonthermal spectrum at both radio and x-ray wavelengths (Clark *et al.*, 1982). Of the several other Crab-like SNR's found recently in the MC's, a couple show jetlike structures, possibly analogous to that seen in the Crab (Sec. V.A.3). Another LMC remnant whose x-ray spectrum looks nonthermal and lineless, 0540−69.3 (Clark *et al.*, 1982), has oxygen-rich optical filaments and so seems to have no close analogs among galactic remnants. Two of the radio-weak LMC remnants display only hydrogen lines in their optical spectra and so somewhat resemble the Tycho and SN 1006 remnants (Long, Helfand, and Grabelsky, 1981; Helfand and Long in NATO81).

Among other weird objects, W50 (the home of SS 433) has at least a sibling if not a twin in G109.1−1.0 (Fahlman and Gregory, 1981; Blair and Kirshner, 1981) with its 3.5-s x-ray pulsar in the middle and optical emission lines typical of an oldish remnant (like the Cygnus Loop). Thus supernova remnants, like supernova events, can plausibly be classified as Type I, Type II, and anomalous or other.

Statistically, the populations of remnants in other galaxies may or may not differ significantly from that in the Milky Way. The standard things to plot are number versus diameter, called $N(\leq D)$, surface brightness versus diameter, called $\Sigma-D$, and input energy versus diameter, called $E_0(D)$. In $N(\leq D)$, M31 and M33 share the galactic slope of $\frac{5}{2}$ for small remnants, at least approximately (implying adiabatic evolution; Dennefeld and Kunth, 1981). The LMC (Dopita in NATO81) clearly does not. The slope is about $\frac{3}{2}$, implying that the remnants expand more freely than expected. This can be achieved if much of the mass is initially ejected in dense clumps, which later evaporate and thermalize. The $\Sigma-D$ diagram should also be the same for all remnants with the same value of E_0/n_0. Within the Milky Way, we must allow the slope of the relation to vary with the shape of the radio spectrum (Göbel, Hirth, and Fürst, 1981), though in a comprehensible way, to fit the data. And, outside, the M33 remnants apparently fit onto the Milky Way relation (D'Odorico, Goss, and Dopita, 1982), but the M31 ones do not (Dickel *et al.*, 1982), being on average fainter at a given diameter. Given adiabatic expansion, this could mean either smaller average initial energy (interesting) or denser average surroundings (not so interesting). Finally, the plot of E_0 vs D (Blair in NATO81) shows remnants from the Milky Way, M31, M33, and the LMC thoroughly intermingled, with E_0 proportional to D^3 on average, implying that a simple Sedov solution is wrong in the same way for all of them.

The chief implications of this and the two following sections are (a) that there is no strong reason to think the Milky Way population of SNR's (and so by implication, supernovae) is not typical of the rest of the universe, and (b) that it is going to be very difficult to decide what we mean by a "typical" remnant of any particular type, especially a young one.

C. Ejection mechanics and energy

The vast majority of models for supernova explosions and remnant evolution assume spherical symmetry. As neither core bounce nor neutrino transport (Sec. IV.B of

Part I) has really succeeded in producing ejection, and even nuclear detonation or deflagration may not (Sec. IV.D of Part I), it is perhaps time to look seriously at nonspherical ejection mechanisms in which rotation and/or magnetic fields are important (Ardelyan, Bisnovatyi-Kogan, and Popov, 1977 and references therein; Bodenheimer and Woosley, 1980; Hillebrandt and Müller, 1981; Woosley and Weaver, 1982a). If such an explosion expands into a homogeneous medium, the resulting remnant will eventually become sphericized. But this takes some hundreds of years (Bisnovatyi-Kogan and Blinnikov, 1981). Thus we might plausibly look for evidence of asymmetric explosions in young supernova remnants. The filled-center (plerion) remnants are no help; all are elongated more or less parallel to the galactic plane, suggesting the influence of local magnetic field structures (Caswell, 1979; disputed by Weiler and Panagia, 1980). Among other young SNR's, N 132D in the Large Magellanic Cloud shows a radial velocity field that is well fit by an expanding ring (Lasker, 1980). The optical velocity field of Cas A looks chaotic (Chevalier and Kirshner, 1978), though it is consistent with the models of Bisnovatyi-Kogan and Blinnikov (1981). But the x-ray emission, which samples 10 or more times as much mass, shows a 2000-km/s systematic velocity difference between the northwest and southeast sides of the remnant (Winkler *et al.*, 1982; Markert *et al.*, 1983). This and the observed shape are consistent with an expanding ring, provided it is tilted at least 30° to the line of sight (about 70° if the largest optical filament velocities represent the edge of the ring). The x-ray morphology of the oxygen-rich (hence young) SMR 292.0 + 1.8 may also imply ejection in a ring, superimposed upon a spherical component caused by blast-wave heating of interstellar or circumstellar material (Tuohy, Clark, and Burton, 1982).

Older remnants show no sign of this asymmetry. A reasonably uniform sample of 89 radio-emitting SNR's studied by Shaver (1982) shows no evidence for toroidal expansion, which can be responsible for at most 10% of the emitting structure seen.

The total energy carried by a supernova remnant tells us, on the one hand, how much our explosion models must be able to produce, and, on the other hand, how much we have to play with for stirring up the interstellar medium and accelerating cosmic rays (Secs. VI.C and VI.F below). Analyses so far have assumed that at least the younger remnants are still in an adiabatic (energy-conserving) phase, so that what we see is what we get (though some of the data mentioned in the previous section do not entirely support this). Even with this assumption, life is not entirely simple. We need to know both the large-scale kinetic energy, $\frac{1}{2}mv^2$, and the internal heat energy, $\frac{3}{2}nkT$, each suitably averaged and summed over all components of the remnant. And there is no single supernova remnant for which we can claim to know m, v, n, and T unambiguously for even one component (optical-line-emitting x-ray-emitting, whatever else there be), let alone all of them, except, just possibly, the Crab Nebula (Sec. V.A), which, given the massive halo, has energy near 2×10^{51} ergs, of which only about 1% is in the nebula as usually defined.

How, then, can we estimate the total injected energy E_0? Early work naturally concentrated on temperatures, densities, masses, and velocities derived from optical emission lines. For typical old remnants like IC 443 and the Cygnus Loop, the lines are coming from gas at a temperature near 2×10^4 K and densities of 10^{2-3} cm^{-3}. The measured expansion velocities are around 100 km/s, and the amount of matter in the luminous filaments at most 1–2 $M_\odot$ (e.g., Lozinskaya, 1969; Parker, 1969). In these respects, the SNR's in M31 (Blair in NATO81) are very similar to the galactic ones. The directly observed kinetic and thermal energy is then only about 2×10^{47} ergs each. But there had to be a good deal of material hiding, as any reasonable guess at interstellar densities in the vicinity of these older remnants (whose diameters are tens of parsecs) yields estimates for the swept-up mass of tens to hundreds of $M_\odot$. Since this hidden material can hardly help getting pushed along with the luminous gas, typical kinetic energies then come to $\sim10^{49}$ ergs, probably not enough to take care of heating the interstellar medium and accelerating cosmic rays.

Consternation and relief were therefore widely intermingled when x-ray observations of these old remnants (e.g., Grader, Hill, and Stoering, 1970, and Gorenstein *et al.*, 1971, on the Cygnus Loop; Palmieri *et al.*, 1971, on Pup A; and Winkler and Clark, 1974, on IC 443) began to reveal thermal emission with luminosities and temperatures that could only be explained by material heated by shocks moving at velocities exceeding the optically measured ones by factors of 2 to 10, raising a typical kinetic energy to 10^{50-51} ergs. (Winkler and Clark, 1974, give the equations in particularly clear and succinct form.) The difference in velocity between the optical and x-ray gas quickly found explanation (Bychkov and Pikelner, 1975; McKee and Cowie, 1975) in terms of SNR shocks moving into a two-phase interstellar medium, the slow, dense optical gas having come from small interstellar clouds and the fast, tenuous x-ray gas from an intercloud medium.

The models have evolved rapidly and now often involve expansion into a three-phase interstellar medium (McKee in NATO81; Sec. VI.F below), gradual evaporation of engulfed clouds, and much more elegant treatment of the outgoing and reverse shocks. Typical injection energies remain 10^{50-51} ergs. Similar numbers can be extracted from radio data, provided one is able to estimate the particle and field energy content of the radio-emitting shell and to derive how that is related to the expansion energy (Gull, 1973). Optical data also yield estimates for E_0 and n_0, provided one accepts a standard model of a Sedov shock encountering clouds and intercloud gas that were initially in pressure equilibrium (McKee and Cowie, 1975) and isobaric cooling of the shocked clouds (Cantó, 1977; Blair in NATO81).

Modest support for the view that the Sedov solutions are at least approximately right comes from measured expansion rates of objects of known age. The 1006 and

1572 remnants, for instance, show the $\frac{2}{5}$ ratio of present expansion rate to average expansion rate that follows from $R(t) \propto t^{2/5}$ (Hesser and van den Bergh, 1981; Kamper and van den Bergh, 1978).

Some problems remain. It is clear, for instance, from Fig. 2, that a spherical SNR expanding into a homogeneous interstellar medium is, at best, an approximation! In addition, the injection energies found (particularly from optical data) depend more strongly on remnant size than one would expect (Blair in NATO81). And some of the energies are very large, e.g., $\sim 10^{52}$ ergs for G65.2 + 5.7 (Reich, Berkhuijsen, and Sofue, 1979) and a shell near Per OB1 (Phillips and Gundhalekar, 1981). Possibly these should be moved from the class supernova remnant to the class superbubble (Sec. VI.F.3 below) and attributed to several supernovae or winds from many OB stars acting collectively. Such objects are apparently quite common, a thorough 21-cm search of the vicinity of 3C10 (Tycho's remnant) having yielded four. Two are likely to be due to OB stars and two to supernovae (Albinson *et al.*, 1982).

The injection energy found from optical data and the assorted assumptions sometimes exceeds by factors of 2—4 that found from x-ray data and rather fewer assumptions (Blair and Kirshner, 1981; Blair, Kirshner, and Chevalier, 1981). The optically derived energy may have been distorted by nonthermal (magnetic) pressure in the filaments that produce the optical lines. The estimated energy is, as a result, really a lower limit (Blair, Kirshner, and Chevalier 1981), increasing the discrepancy with the x-ray result. The latter cannot be unequivocally accepted either, however, until the effects of nonequilibrium ionization and nonsolar composition have been properly included, simply because much of the cooling of the x-ray gas comes from ionized states of metals. Pravdo and Smith (1979) present evidence for nonequilibrium ionization in observed remnants, neglect of which results in the x-ray temperature and kinetic energy coming out too low (Gronenschild and Mewe, 1982; Shull, 1982). It is also worth remembering that both measured values and estimates of velocities, densities, and the rest scale as assorted powers of the distances assumed for galactic remnants. For instance, bringing the Tycho remnant in from 6 to 2.5—3 kpc, in accordance with the most recent H I absorption measurements (Albinson *et al.*, 1982), results in

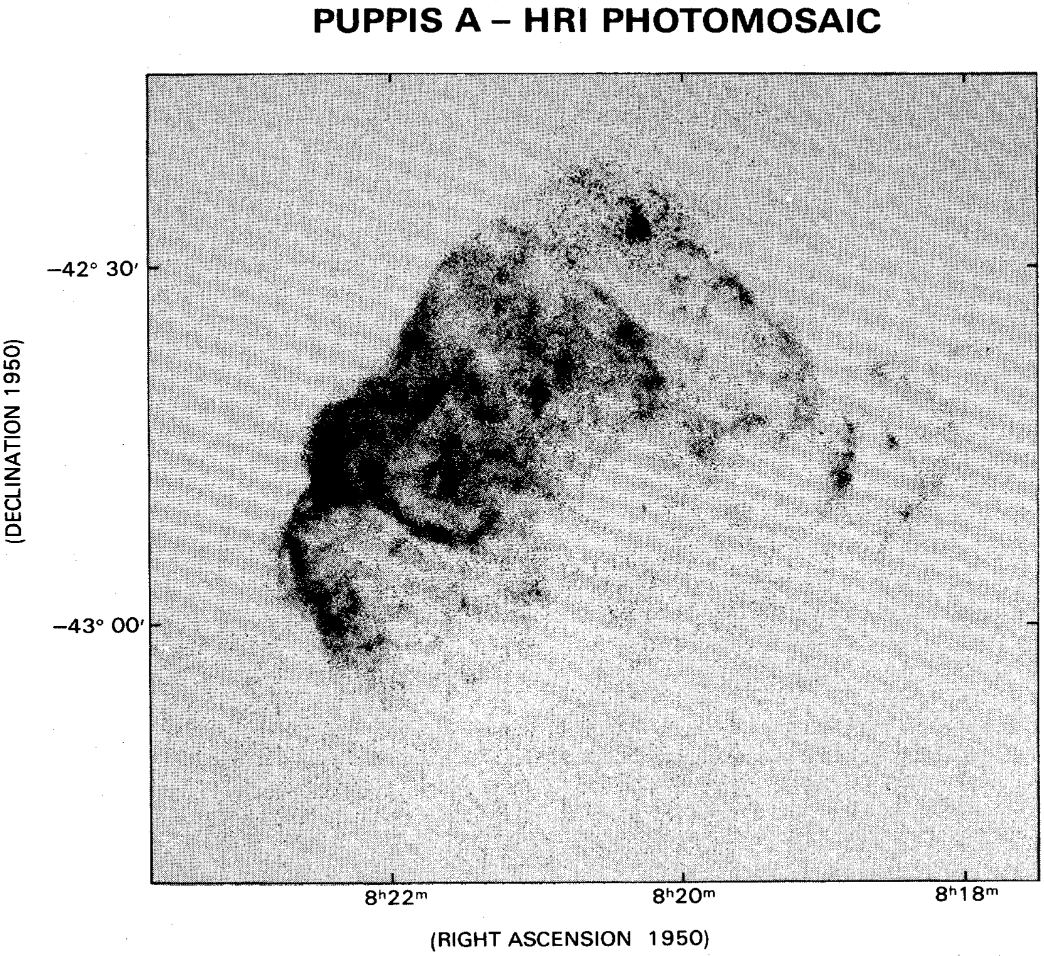

FIG. 2. An x-ray picture of the intermediate-age supernova remnant Pup A (from Petre *et al.*, 1982). Clearly, a spherical shock wave expanding into a homogeneous medium is, at best, an approximation to what is really going on!

velocity and energy estimates from the x-ray data and optical proper motions that are at least consistent (Seward *et al.*, 1982).

It seems safe to conclude from galactic SNR's that many or most supernovae eject material that initially carries about 10^{51} ergs of kinetic energy, in reasonable accord with the number deduced from spectra of extragalactic objects, and that there is weak evidence that the ejection has toroidal rather than spherical symmetry, at least some of the time.

D. Mass and composition of ejecta

The ejecta from Type I and Type II supernova explosions should have quite definite signatures, according to the "best buy" models advertised in Sec. IV of Part I. A Type I should eject about 1 $M_\odot$ of Ni^{56} (which decays to Fe^{56} in months) plus modest amounts of hydrogen-deficient, but otherwise solar-composition, material from the unburned envelope of the deflagrating star. And a Type I should eject all but the inner 1.5 $M_\odot$ of the onion structure achieved by a highly evolved, massive star, which is to say $\gtrsim 8\ M_\odot$, about half in relatively unprocessed envelope, and the other half divided among new He, CONe, MgSiSAr, and Fe in proportions depending upon the mass of the progenitor star (roughly, more massive stars yield higher proportions of massive nuclide products).

Each sort of ejecta may get gradually tangled up with a circumstellar envelope lost during hydrostatic evolution of the parent star, and each will surely in due course be diluted beyond recognition by swept-up interstellar material of normal composition. But, at least among the youngest remnants, we ought to be able to see these signatures of the events that made them. Do we? Yes and no.

First, and perhaps foremost, we have not seen large iron excesses in the emission lines of any remnant studied to date. This includes those of the events of 1006, 1572, and 1604, generally advertised as having been of Type I. Assorted fancy footwork, involving inhomogeneities and special temperature and density distributions (Arnett, 1980; Fabian, Stewart, and Brinkmann, 1982; Chevalier, 1982a), can keep lines from $\sim 1\ M_\odot$ of iron below detectability. Such models have an additional virtue: The total ejected mass needed in a remnant to make the x-ray continuum emission drops from the 5—15 $M_\odot$ found for solar composition (Sec. III.A.3 of Part I) to something closer to 1 $M_\odot$ (Fabian, Stewart, and Brinkmann, 1982), as would be expected for the canonical model SN I. Sarazin *et al.* (1982) have reported absorption lines in the spectrum of the ultraviolet star near the center of SNR 1006 (Schweizer and Middleditch, 1980), which, if attributed to Fe II broadened by $\sim$5000 km/s expansion, imply $\gtrsim 0.05\ M_\odot$ of iron too cool to emit x rays in the remnant. But we have not seen very much anyplace!

Even some of the youngest known remnants show emission from gas of essentially normal composition. The high-velocity gas (3000—5000 km/s) in the Tycho and 1006 remnants (Kamper and van den Bergh, 1978; Hesser and van den Bergh, 1981) emits only hydrogen lines. Three similar cases are known from the Magellanic Clouds (Dopita in NATO81) and are presumed also to be young Type I remnants. They share with their galactic counterparts relatively low radio surface brightness for their sizes. Such remnants have been modeled with high-velocity, collisionless shocks propagating into partially ionized gas (Chevalier and Raymond, 1978; Chevalier, Kirshner, and Raymond, 1980). The low-velocity (200—300 km/s) gas seen in the Kepler remnant (van den Bergh and Kamper, 1977) and Cas A [where it makes up the quasistationary flocculi (QSF's)], on the other hand, shows standard H II region lines of [S II], [N II], [O II], and the like. It is apparently part of a circumstellar envelope shed by the evolving presupernova star and overtaken by the expanding remnant. Support for this interpretation comes from the order-of-magnitude excess abundances of He and N (made by hydrogen burning and mixed outward in the envelopes of evolved massive stars) in the Cas A QSF's (Chevalier and Kirshner, 1978) and a modest N excess in the Kepler low-velocity gas (Dennefeld, 1982). An entire interstellar cloud may occasionally be noticeably polluted for a few thousand years by a single supernova event (Laurent, Paul, and Fettini, 1982, on the Carina star-formation region).

Among older remnants, not surprisingly, there are no conspicuous abundance anomalies (e.g., Raymond *et al.*, 1981, on Vela and the Cygnus Loop; Dopita in NATO81, Blair in NATO81, and Dennefeld and Kunth, 1981, on extragalactic objects; Leibowitz and Danziger, 1982, on [N/H] versus age), except ones also seen in H II regions that reflect gradients within their parent galaxies. These belong to the subject matter of Sec. VII below.

Amidst all this normality, there are two clear classes of interesting nonstandard abundances in young supernova remnants. First, there is optical line evidence for remnants and pieces of remnants with large excesses of oxygen and smaller ones of its burning products, Ne, Mg, Si, S, and Ar. The fast-moving knots of Cas A (Chevalier and Kirshner, 1978) were the first members of this class identified. There are oxygen-rich remnants in each of the Magellanic Clouds (Mathewson *et al.*, 1980; Dopita, Tuohy, and Mathewson, 1981), an anonymous one in NGC 4449 (Balick and Heckman, 1978), and another in the Milky Way (MSH 11-54; Murdin and Clark, 1979) which shares with Cas A the correlation of high gas velocity with excess oxygen and low gas velocity with relatively normal composition. In accordance with the astronomical custom that one object is a discovery, two is a confirmation, and three is a well-known class of objects, oxygen-rich supernova remnants now constitute a well-known class of objects.

The Cas A fast-moving knots (Chevalier and Kirshner, 1978) include at least 50% oxygen by mass, at most 22% helium (cf. Itoh, 1981, for indirect evidence that there is indeed some helium), and the rest mostly Mg, Si, and S. Fe and Ni are there, but not significantly enhanced, and [C/O] is low by a factor of 100 or more (Dennefeld and Andrillat, 1981). This is so extreme that we must be seeing essentially pure ejecta from the oxygen-burning shell of the parent star. Thus, until other data provide separate estimates of the masses ejected in other elements, we learn nothing about the parent star, except that it must have been massive enough to make and burn oxygen hydrostatically and eject the products, which is not very informative. The ratio of oxygen to its products varies among the knots (Chevalier and Kirshner, 1979).

Among older remnants, Pup A shows x-ray emission lines of O, Ne, and Fe that can be interpreted (Canizares and Winkler, 1981) as reflecting about 3 $M_\odot$ of O and Ne from the parent star mixed with about 100 $M_\odot$ of swept-up interstellar matter. To make this much O and Ne would require a progenitor of at least 25 $M_\odot$. Alternative interpretations of the data include iron depletion on grains and assorted disequilibria. The optical observations of Pup A (Dopita, Mathewson, and Ford, 1977) are also somewhat difficult to interpret, but seem to require modest enhancements of O and S and $[\mathrm{N/H}] \geq 1.0$. Perhaps the progenitor was a WN (nitrogen-rich Wolf-Rayet) star (van den Bergh, 1982).

The second main class of nonsolar abundances in young remnants turns up in x-ray line intensity measurements from the Einstein Observatory. The remnants concerned are Cas A (Becker *et al.*, 1979), Tycho (Becker *et al.*, 1980a), and Kepler (Becker *et al.*, 1980b). All these show strong lines of Si, S, and Ar. Calculations of their abundances assuming collisional ionization equilibrium produced rather peculiar results. These have now been superseded by nonequilibrium ones (Shull, 1982, etc.) which give factors of 2—8 enhancements in the mix of ejecta and sweepings as we see it; and thus, presumably, larger enhancements in the ejecta alone. The nonequilibrium calculations still presuppose that elements from H to O are present in solar ratios. Masses derived for the several components are exceedingly sensitive to this assumption.

If light elements are present in normal proportions, then Tycho, for instance, turns out to have about 2 $M_\odot$ of ejecta and 2 $M_\odot$ of sweepings (Seward, Gorenstein, and Tucker, 1982, and Strom, Goss, and Shaver, 1982, on the ratio of ejected to swept-up material). Thus the enhancements seen amount to only about 0.02 $M_\odot$ newly synthesized Si, S, and Ar, and again we learn only that the progenitor star burned oxygen and ejected its products. There is, perhaps, a modest iron enhancement in the Tycho remnant (Shull, 1982), but for the nominally Type I remnants, it remains puzzling that we should see more evidence for Si, S, and Ar, of which the models are supposed to produce at most about 0.1 $M_\odot$, than for Fe, of which the models make about 1 $M_\odot$ (Sec. IV.C.2 of Part I).

Finally, the large masses found for young x-ray-emitting SNR's (Cas A$=$15 $M_\odot$, 1006$=$5—15 $M_\odot$, Tycho$=$15 $M_\odot$, and Kepler$=$7 $M_\odot$; Sec. III.A.3 of Part I) should also be regarded as exceedingly suspect. Both ionization disequilibrium (Shull, 1982) and heavy-element excesses (Fabian, Stewart, and Brinkmann, 1982) will reduce them a great deal, and the resulting values of Tycho, Kepler, and 1006 are then all 1—2 $M_\odot$ (Long, Dopita, and Tuohy, 1982). The new round of models and observations presented at IAU Symposium No. 101 (Gorenstein and Danziger, 1983) tended to support these modifications, and it will surely all eventually be sorted out.

Meanwhile, it is undoubtedly safe to say that at least some supernova events do contribute to the galactic budget of intermediate-weight elements. But the young remnants do not tell us much about the size of the contribution, its ratio to contributions of other elements (C, Fe, He, and so forth), or the differences between Type I and Type II events.

VI. SUPERNOVA BY-PRODUCTS

The gravitational binding energy of a neutron star is about 10% of Mc^2 or $\sim 10^{53}$ ergs (Cameron, 1970). If, as we now generally suppose, a Type II supernova involves the formation of a neutron star by collapse of matter previously in the next-highest stable density regime (Sec. IV.B. of Part I), then this much energy must be got rid of in fairly short order.

Where does it go? Electromagnetic radiation carries off not much more than 10^{50} ergs, largely in the visible and adjacent bands, in the first year (Sec. III.C.2 of Part I). The expanding remnant has a kinetic energy of 10^{51} ergs (for 10 $M_\odot$ moving at 3000 km/s) or less (Sec. VI.F below). Acceleration of cosmic rays accounts for 10^{49-51} ergs, depending on the supernova rate and the galactic cosmic-ray confinement volume (Sec. VI.C below). The newly formed neutron star stores another $\sim 10^{51}$ ergs in rotational and magnetic field energy, given the likely properties of young pulsars (Ruderman, 1972; Sec. VI.I below). A bit is absorbed by the endoergic reactions of explosive nucleosynthesis (Sec. VII below), and so forth.

But no matter how you do the sum, $\gtrsim 90\%$ of the energy remains unaccounted for. What becomes of it? Baade and Zwicky did not provide any prescient suggestions on this one. Because of their low estimated supernova rate, neglect of cosmic-ray confinement in the galaxy, and very high deduced SN photospheric temperatures, they needed all the available energy to make light and cosmic rays (Sec. I.A. of Part I). We don't. And about the only remaining known physical processes that can be invoked to carry off the excess are gravitational radiation (Sec. VI.A) and neutrino emission (Sec. VI.B). The following sections discuss those rather ghostly byproducts, as well as some more tangible ones.

A. Gravitational radiation

Any oscillating mass quadrupole will emit gravitational radiation at a characteristic frequency twice that of the oscillation. Astronomical objects can be oscillating mass quadrupoles by virtue of nonradial collapse or pulsation, asymmetric rotation, or orbital motion. Unfortunately, the expressions for the intensity of the radiation from these various configurations tend to have in front of them a factor like $(v/c)^5$ or $(R/R_{\rm Sch})^{-5}$, where $R_{\rm Sch}$ is the Schwarzschild radius, $2GM/c^2$, about $4\times10^{-6}\ R_\odot$ for the sun (Misner, Thorne, and Wheeler, 1973; Ostriker, 1979). This sobering weakness would seem to make gravitational radiation an unlikely candidate for getting rid of anybody's excess energy.

1. Binaries and asymmetric rotators

Dyson (1963), however, pointed out that a pair of neutron stars in grazing orbit would radiate away their orbital energy in a $\sim$1-s burst of 10^{52-53} ergs. He did not regard such binaries as very likely objects. But the discovery of one probable binary neutron star (the shortest-period binary pulsar; Hulse and Taylor, 1975) and of x-ray-emitting systems consisting of a neutron star (NS) in orbit around a normal state massive enough to form another NS (Blumenthal and Tucker, 1974) has made NS pairs seem less improbable.

Clark, van den Heuvel, and Suntantyo (1979) have calculated that pairs like the known ones should evolve to contact configurations in less than the age of the galaxy, and thus estimated a rate of one per 3000 yr for NS binaries dying in an unglorious burst of gravitational radiation throughout the Milky Way. These are the most intense sources unambiguously predictable from known objects.

The Dyson scheme may be directly applicable to supernovae if massive stellar cores rotate so rapidly that they fission during collapse. This leads to a short-lived binary neutron star, which rapidly coalesces to a single one, after emitting some 6×10^{52} ergs (Clark and Eardley, 1977). Since fission occurs when an object attempts to reach rotational kinetic energy greater than gravitational binding energy, this mechanism can clearly get rid of essentially all the excess energy. The arguments for slow rotation in evolved stellar cores (Hardorp, 1974, etc.) are not so strong as to eliminate this possibility.

A core rotating a bit more slowly will collapse to a single, triaxial (Jacobi-like) ellipsoid (Endal and Sofia, 1977). This also constitutes an oscillating mass quadrupole. There are no models for triaxial neutron stars incorporating realistic equations of state, but the predictions of liquid-drop models (Miller, 1974; Fedosov and Tsvetkov, 1974) presumably give the right order of magnitude. Again, most of the stored $\sim10^{53}$ ergs radiates away in a fraction of a second. And, again, we cannot reject these models out of hand.

2. Core collapse and pulsation

Still slower rotation will lead to an axial symmetric (Maclaurin-type) spheroid as the figure of equilibrium for the neutron star and thus not produce an oscillating quadrupole. The transition value of angular momentum has not been calculated for a realistic NS equation of state, but the liquid-drop value, $J=.3(GM^3\bar{a})^{1/2}$, where $\bar{a}$ is the radius of a sphere with the same volume (Chandrasekhar, 1969), cannot be enormously wrong.

The energy stored in rotation in this case cannot be directly radiated away. Two possibilities remain, however. First, the real figure of equilibrium might be a rotating tesseral, in which shape changes would release a few $\sim$1-s pulses of kilohertz gravitational radiation (Tsygan, 1971). Second, and rather more likely sounding, rotation couples radial motion to nonradial modes. Thus the collapse and subsequent core bounce(s) involved in NS formation will have quadrupole terms (Chau, 1967; Thorne, 1969). If there is differential rotation, then there are also octupole radiation terms which may dominate (Turner and Wagoner, 1979). In all models thus far studied, the two-dimensional nature of the calculations has kept the configuration axially symmetric, though in a few of them, angular momentum slightly exceeds the critical value. The axial ratio of the collapsing object changes as the collapse proceeds, however, hence the possibility of radiation.

The amount of gravitational radiation produced by such axisymmetric collapses can be quite large if there are no competing processes. Wheeler (1966) got 3×10^{50} ergs in 1.7 s from the pulsation of a newly formed NS. Thuan and Ostriker (1974) and Novikov (1975) found $10^{50.5-53}$ ergs radiated from the collapse of a sphere to an infinitely thin pancake. Detweiler (1975), allowing for somewhat more realistic collapse followed by pulsation (damped only by gravitational radiation), got the same sort of total energy, but released over many pulsation periods, in up to 25 s. Epstein and Wagoner (1975) provided an improved $\frac{3}{2}$ post-Newtonian formalism for handling the calculations that has been widely used since. Thus the general relativistic part of the problem is reasonably well under control.

But it now appears that neutrinos rather than gravitational radiation are the dominant damping force in such pulsations (Kazanas and Schramm, 1976, 1977). The v/GR ratio drops in successive bounces of the core, if these occur (Saenz and Shapiro, 1978, 1979), but the latest word is that critical damping occurs very nearly in a single bounce (Saenz and Shapiro, 1981).

The result is a considerable reduction in the estimated fluxes of gravitational radiation from neutron star collapse and pulsation. Chia, Chau, and Henricksen (1977), Arnett (1979), Wilson (1979), Kazanas and Schramm (1979), and Saenz and Shapiro (1979) all found $<10^{-2}$, down to $10^{-6}Mc^2$, using a wide variety of models. Some treat the nonspherical shape carefully, but the thermodynamics of the collapse in a one-zone model; others start with state-of-the-art spherical collapse models and treat nonsphericity as a perturbation. Turner and Wagoner (1979) got only about $10^{-10}Mc^2$ in radiation, but considered only slowly rotating models. The emission is always concentrated in the kilohertz region and lasts $\sim$0.1 s. Quite generally, quadrupole terms can yield a fraction of Mc^2 which is at most $(R_{\rm Sch}/R)^5(cJ/Mc^2)^4$ and octupole terms a fraction of at most $(R_{\rm Sch}/R)^3(cJ/Mc^2)^2$, where J is the total angular momentum.

A hybrid model (Müller in NATO81) treats the relevant microphysics, shock propagation, and the axisymmetric configuration all on more or less equal footing. It yields 10^{-7}—$(4\times10^{-6})Mc^2$ in gravitational radiation, starting with the rotating collapse models of Müller and Hillebrandt (1981). The answer depends very much on total angular momentum and its distribution in the core as collapse begins. These are really completely unknown for real cores, as no one has ever evolved a rotating star all the way from the main sequence to core collapse, using realistic prescriptions for internal transport of angular momentum. Nor is anyone likely to do so in the immediate future! But the efficiency of radiation is low even in the most favorable case—differential rotation and angular momentum somewhat in excess of the Maclaurin-Jacobi bifurcation value after core bounce.

If these calculations are based on the right premises, that the core neither fragments nor becomes triaxial, then gravitational radiation is not a major energy sink for supernovae. The effects of neutrino damping on binary fragment motion and triaxial rotation inside a stellar envelope have not been explored. Endal and Sofia (1977) expect them to be small, but this is not quite self-evident. Lindblom and Detweiler (1979) find that ν's do not damp differential rotation. Thus, right now, we cannot honestly say whether a "typical" core collapse should emit 10^{47} or 10^{53} ergs in gravitational radiation.

Still less is known about gravitational radiation emission if a stellar core collapse continues down to black hole densities. Both analytic and numerical calculations suggest that the amount of radiation is heavily dependent on the amount of departure from spherical symmetry, with slowly rotating configurations giving $\leq 10^{-2}Mc^2$ (Moncrief, Cunningham, and Price, 1979). As in the neutron star case, the proper initial conditions are not known. A numerical study of collapse of a cylindrical configuration (Piran, 1979, 1982) indicates the limits for extreme asymmetry—65% of Mc^2 was liberated as gravitational radiation. Damping by neutrino emission or other processes would presumably reduce this.

At least one experiment capable of detecting a $\sim 10^{53}$-erg burst of kHz gravitational radiation, emitted anywhere in the Milky Way, has been in operation somewhere in the world more or less continuously since 1969 (not always the same experiment!). Supernova statistics suggest a 10—30% chance of a core collapse having occurred in the interim. Unfortunately, the blips recorded by such experiments do not come labeled with distance, direction, or nature of the interaction producing them. Thus this is probably not the best way to look for the next galactic supernova. Experiments capable of seeing comparable bursts from as far away as the Virgo Cluster are in various states of completion various places. These, by recording or not recording events in coincidence with supernovae caught in optical searches at a rate of a few a year (Sec. VIII.B), could rule out some of the possibilities discussed above.

3. Pulsars

The ink was scarcely dry on the paper announcing the discovery of pulsars (Hewish, Bell, *et al.*, 1968) when the first calculation of their potential for emitting gravitational radiation appeared (Weber, 1968). This was so large for a binary neutron star or white dwarf as to rule out the model as having an inadequate lifetime (Ostriker, 1968), but much smaller for typical pulsation modes. Once these were ruled out by the measured sign of the period derivatives, model builders focused on rotating neutron stars with assorted magnetic field configurations and the gravitational radiation to be expected from them (Ostriker and Gunn, 1969; Shklovskii, 1970a; Ferrari and Ruffini, 1969; Melosh, 1969; Chau, 1970).

Although the calculation requires, in principle, the full apparatus of general relativity, once again that is not the hard part of the problem (Ipser, 1971). The hard part is deciding what value to assign to the mass quadrupole moment of the rotating neutron star. If it is zero, you get no gravitational radiation; and an equatorial eccentricity of 10^{-3} for NP 0532 already produces more gravitational than electromagnetic radiation ($\sim 10^{38}$ ergs/s), and so disagrees with the measured second derivative of the period (Ruderman, 1972, Press and Thorne, 1972).

Zimmermann (1978) suggests that we can set a minimum eccentricity from the deformations due to the magnetic field needed to explain pulsars by one of the standard models; a maximum from the likely strength of NS crustal materials or the slowdown rate; and a "most likely" value by attributing the restlessness of pulsar periods to imperfect alignment of the rotation axis and principle moment of inertia (Pines and Shaham, 1972, 1974). Additional uncertainty comes from the choice of equation of state for dense matter. Although NP 0532 (the Crab) rotates fastest, 0833 (Vela) has a stronger crust, and the gravitational luminosities for the two are comparable according to these considerations, $10^{34\pm3}$ ergs/s for Vela and $10^{34\pm4}$ ergs/s for the Crab. The error bars are not exactly small. A semi-independent estimate comes from the remark by Ostriker and Gunn (1969) that if 0532 started with zero period, has not changed its eccentricity or magnetic field, and is slowed only by electromagnetic and gravitational radiation, then $L_{GR}/L_{EM}=\frac{1}{6}$ to make the age come out right. Rather small changes in the assumptions introduce error bars on this argument as wide as the previous ones. For other pulsars, the uncertainties are just as large, but the fluxes, which scale as (rotation period)$^{-6}$, will surely be much smaller.

Experiments are still rather far away from helping much to pin things down. Gravitational radiation in the $\sim$1-Hz band can excite oscillations in the earth (Weber, 1968; Dyson, 1969) as well as in deliberately constructed laboratory apparatus (Hirakawa, Tsubono, and Fujimoto, 1978). The one reported positive result, for earth modes excited by CP 1133 (Sadeh and Meidav, 1972), proved unrepeatable (Mast *et al.*, 1972), and, in light of the total flux possible, would have implied an exceedingly elaborate triggering mechanism for its explication (perhaps invoking an alignment of the pulsar with Jupiter?). The most sensitive upper limits to detected gravitational radiation from pulsars (Hirakawa, Tsubono, and Fujimoto, 1978) are still about 10 orders of magnitude above optimistic predictions, but nearly 5 orders better than earlier limits. Recent developments in technology of detectors for both bursts and narrow-band radiation are reviewed by Weber and Hirakawa (1982).

B. Neutrinos

Supernovae and their products should radiate neutrinos (meaning particles and antiparticles of the electron-, muon-, and tau-neutrino species) at four stages: (1) during the deleptonization ($p+e \rightarrow n+\nu_e$) needed to turn ordinary matter into neutrons, (2) during core collapse, when rapid heating facilitates exotic radiation mechanisms, (3) after cosmic rays have been accelerated and can interact with their surroundings, and (4) when the young neutron star cools.

The contributing processes (Barkat, 1975; Kolb and Mazurek, 1979; Friman and Maxwell, 1979; Soyeur and Brown, 1979) are an impressive array, including: (1) Electron and positron capture and emission by nuclei and nucleons. (2) Urca cycling by protons ($p+e \rightarrow n = \nu_e$; $n \rightarrow p+e+\bar{\nu}_e$) and pions. The process was named by Gamow and Schoenberg (1941) for a Rio casino whose patrons, including we fear Gamow and Schoenberg, gradually lost money through similar recycling. When pions are present they are much more effective croupiers, owing to their smaller rest masses (Bahcall and Wolf, 1965a). (3) Pair annihilation ($e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e$). (4) Photoneutrino emission (Compton scattering with outgoing photon replaced by neutrino pair). (5) Brehmsstrahlung ($n+n$, $n+p$, or $e+$ ion$\rightarrow$original particles plus neutrino pair). (6) Plasma neutrinos (plasmon deexcites with emission of neutrino pair). (7) Decay of highly excited nuclear states by emission of neutrino pair. (8) Neutrino synchrotron emission. Process (1) radiates only ν_e. Process (2) makes ν_e and $\bar{\nu}_e$ in pairs. And the others can produce all three species, always in pairs.

Deleptonization (Zeldovich and Guseinov, 1965) and emission during core collapse (Colgate and White, 1966) are unavoidable. The predicted electron neutrino fluxes have held quite constant at 10^{51-52} ergs for the former and $\sim 10^{53}$ ergs for the latter through several changes of physics. Neutral-current effects make rather little difference (Freedman, Schramm, and Tubbs, 1977); and mu and tau neutrinos carry off only about half the flux when they are properly included (Bethe, Applegate, and Brown, 1980). Even coalescence of a binary neutron star (or of fragments of a single fissioned one) puts more energy into neutrinos than into gravitational radiation (Clark and Eardley, 1977).

What has changed is the time scale expected for the emission. Early work supposed that the neutrinos would stream freely out of the collapsing core, yielding a burst within the free-fall time (~ 1 ms). But it seems this doesn't happen. Neutrinos are trapped inside the collapsing core (cf. Sec. IV.B.1 of Part I) by effects of degeneracy and neutral currents. Their pressure retards the collapse, and the burst is thus spread out over most of a second (Mazurek, 1976; Lichtenstadt *et al.*, 1980; Bethe, Applegate, and Brown, 1980; Burrows, Mazurek, and Lattimer, 1981). This feature is common to all the recent collapse models mentioned in Sec. VI.A above. The burst tapers off gradually to $\sim 5 \times 10^{51}$ ergs/s at ~ 10 s (Salpeter and Shapiro, 1981). The change in time scale is of some importance to the design of experiments to look for neutrinos from collapsing stars.

There is still some dispute about whether enough of the momentum of the outgoing neutrinos is deposited in the envelope of the star to eject it (Sec. IV.B.1 of Part I). But 1% of the energy would be enough, so this issue in no way affects the intensity or time scale predicted for the neutrino burst.

If collapse continues past neutron star densities, many of the neutrinos emitted will have geodesics that get swallowed by the black hole (Dhurandkar and Vishveshwara, 1981), reducing the predicted neutrino burst intensity, at least for a spherically symmetric collapse. As in the gravitational radiation case, asymmetries in the collapse are likely to let more energy escape.

The observational status of these predicted neutrino bursts is not very different from that of the predicted gravitational radiation bursts. Existing detectors (Lande, 1979; Hampel, 1981) should see an event anywhere in our galaxy, but with no information on distance or direction to identify a particular burst as coming from stellar collapse. One possible $\bar{\nu}_e$ burst turned up on 4 January 1974 (Lande *et al.*, 1974), but there was no corresponding ν_e burst (Evans, Davis, and Bahcall, 1974), implying a ratio $L(\bar{\nu}_e)/L(\nu_e) \geq 4$. This is very difficult to explain with any combination of processes. Extending the range of the detectors to external galaxies will require either $\gtrsim 10^9$ tons of (water) detector or a fundamentally new idea.

Deleptonization and collapse produce mostly low-energy (~ 10-MeV) neutrinos. Much higher energies (to 10^{14-15} eV) are possible if cosmic rays accelerated by a supernova explosion or a young pulsar interact with gas having $n_{\rm H} \gtrsim 10^3$ cm^{-3}, as might be expected in a dense molecular cloud or in a circumstellar shell ejected by the presupernova star (Berezinsky and Prilutsky, 1978; Eichler and Schramm, 1978). The dominant process is decay of pions made by *p*-*p* collisions (Eichler, 1978), and about 10^{43} ergs should be radiated in the first month. The resulting flux will exceed the threshold of DUMAND (100 eV/cm^{2}s in $\bar{\nu}_e$ above 3×10^{11} eV) only for events in the Milky Way.

Finally, a newly formed neutron star will shine more brightly in neutrinos than in photons for the first 10^5 yr or so. The early calculations (Finzi, 1964; Bahcall and Wolf, 1965b) already made it clear that the neutrino luminosities would not be directly detectable in the foreseeable future. At a plausible starting temperature of 10^9 K, Urca processes dominate the emission, yielding 10^{38}

ergs/s if the core is mostly neutrons or 10^{46} ergs/s if it is mostly pions or quarks (Burrows, 1980; Iwamoto, 1980), the emission dropping as T^8 or T^6 in the two cases. Thus a newborn object, even as close as 1 kpc, would cause ≤ 1 count in Davis's tank (Evans, Davis, and Bahcall, 1974) in a month.

Recent work (e.g., Yakovlev and Urpin, 1981) has focused on comparing the predictions of neutrino-cooled neutron stars to surface temperatures deduced from x-ray observations. The data for the Vela and Crab pulsars are consistent with their being cooled by *n-p* Urca alone, while upper limits for the 1006, 1572, 1604, and Cas A remnants imply either pion-Urca cooling or no neutron star remnant, the latter being perhaps the more likely. This neutrino emission makes a modest contribution to the slowing down of pulsar rotation (Mikaelian, 1977).

Turner (1978) and Epstein (1978) point out that neutrinos emitted from a sufficiently asymmetric collapsing core will produce their own gravitational radiation. The intensity will be, at most, comparable with that made directly by quadrupole oscillations of the core. Thus this process could increase the predicted fluxes of gravitational radiation by a factor of 2 or so without noticeably diminishing the neutrino flux.

The implication of the preceding two sections is that gravitational radiation and neutrino emission are exceedingly convincing in the role of the culprits that carry away the missing 90—99 % of a neutron star's binding energy. It would, on the other hand, probably be a tactical error to hold ones' breath until there is complete observational verification of the preceding sentence.

C. Cosmic rays

Baade and Zwicky (1934) told us that supernovae make cosmic rays. Unfortunately, they neglect to mention just how the trick was done. And, although the basic idea has been rediscovered many times (Cernuschi, 1939; Hoyle, 1947; ter Haar, 1950; Ginzburg 1953, 1958, etc.), the details continue to elude us. Four basic schemes exist: (1) acceleration in the supernova explosion itself (Colgate and Johnson, 1960; Colgate and White, 1966), (2) acceleration (by shocks) in and around young supernova remnants (Scott and Chevalier, 1975; Chevalier, Robertson, and Scott, 1976; Reynolds and Chevalier, 1981; Cavallo, 1982), (3) acceleration by pulsar remnants of (presumably Type II) supernovae (Gunn and Ostriker, 1969; Kulsrud, Ostriker, and Gunn, 1972), and (4) acceleration by shock waves in the general interstellar medium (Parker, 1955, 1958, Bell, 1978; Axford, Leer, and Skadron, 1977; Axford, Leer, and McKenzie, 1982; Axford, 1981, 1982; Blandford and Ostriker, 1980), keeping in mind that the shock waves must, in turn, be driven by something else (presumably and predominantly expanding SNR's) or lose most of their energy to particles in about one galactic rotation period.

These supernova-related mechanisms in fact comprise a large majority of suggested origins for positively charged cosmic rays, excepting only the very local theories that draw on the energy of the sun or nearby OB stars (Menzel and Salisbury, 1948; Alfvén, 1949; Richtmeyer and Teller, 1949; McMillan, 1950; Cassé and Paul, 1980), and the metagalactic theories that draw on energy of radio galaxies, quasars, etc. (Gold and Hoyle, 1959; Burbidge and Hoyle, 1964; Brecher and Burbidge, 1972; Burbidge, 1975). These classes of models cannot perhaps entirely be ruled out, but they have fallen slowly into disfavor (Ginzburg and Alfvén, 1967; Burbidge, and Ginzburg, 1967; Schmidt and Burbidge, 1967; Parker, 1968; Meyer, 1969; Cesarsky, 1980; Setti, Spada, and Wolfendale, 1981), at least partially through the aging and attrition of their proponents. Such models are, in any case, not logically part of our supernova story. The Fib cosmology model for the origin of cosmic rays (Barnothy and Forro, 1943; Barnothy and Barnothy, 1963, 1967) is very much *sui generis* and cannot logically be placed in any of the above classes. It draws cosmic-ray energy ultimately from all sources of light (entropy) in the universe; thus the cosmic rays will be most numerous where the light is most intense, in galaxies. This model is, therefore, also not really part of our story, though it does propose an alternative mechanism for creating supernova explosions. Rosen (1969) has collected many of the early papers on origins of cosmic rays, some of them proposing mechanisms still more wildly original and unrelated to supernovae.

Historically, the outstanding argument in favor of supernovae as the chief galactic accelerators of cosmic rays was the enormous energy requirement and lack of other adequately powerful candidates (Baade and Zwicky, 1934). The input required per event is about 1 eV cm^{-3} $\times$ (whatever you think is the galactic volume—disc or halo—within which cosmic rays are confined)$\times$(the confinement time)$^{-1}\times$(your favorite supernova rate)$^{-1}$. Disc confinement (Cesarsky, 1980) for 10^7 yr (Garcia-Muñoz, Mason, and Simpson, 1977) and an event rate 0.05 yr^{-1} (Sec. III.A.1 of Part I) yields 10^{49} ergs. Halo confinement and/or a lower SN rate could raise this to 10^{51} ergs, but surely not much beyond.

The case for acceleration by supernovae was much strengthened (Ginzburg, 1953; Ginzburg and Syrovatskii, 1964) with the realization that young SNR's must contain some 10^{49} ergs in relativistic electrons to produce their observed radio emission (as well as optical and x ray in the Crab Nebula) via the synchrotron process. Honesty, however, compels the admission that there is no evidence for relativistic protons in any SNR. There is actually evidence against them in the Crab Nebula. If, as Burbidge (1958) once suggested, the object had the average galactic ratio of relativistic proton to electron energy (~ 100), then outward pressure would be accelerating the nebular expansion a good deal faster than the observed rate.

More recently, the cosmic rays have revealed an assortment of elemental and isotopic abundance differences from normal solar system material. Many of these are attributable to the vicissitudes of high-speed, long-distance travel. But corrections for spallation in the interstellar medium are now fairly well understood (Ormes and

Freier, 1978) and do not quite account for everything. The implied anomalies in source composition (meaning after acceleration but before propagation) include a general excess of heavy elements relative to hydrogen and helium, excess Ne^{22} and $Mg^{25,26}$ (Mewaldt *et al.*, 1980; Webber, 1982), low nitrogen and perhaps neon (Mewaldt *et al.*, 1980, 1981; Webber 1982), and an excess of neutron-rich ("*r*-process") isotopes among the elements above iron (Fowler *et al.*, 1981) and perhaps below (Young *et al.*, 1981). Each anomaly can be correlated with one or another of the nucleosynthesis processes normally attributed to supernovae and their parent stars (Hayakawa, 1956; Talbot and Arnett, 1974; Audouze, Chieze, and Vangioni-Flam, 1980; Woosley and Weaver, 1981; Wefel, 1981), possibly via an intermediary of supernova-accelerated dust grains (Spitzer, 1949; Tarafdar and Apparao, 1981). Many of the anomalies correlate equally well with ionization potential, suggesting that the composition at the source is dominated by the acceleration mechanism rather than the synthesis mechanism (Blake and Margolis, 1982).

It will become clear in the next few paragraphs that all the various supernova-related mechanisms for the acceleration of cosmic rays present difficulties of one sort or another. It would, however, be premature to excise this section until somebody thinks of something better.

1. Acceleration in the supernova explosion

Supernova explosions of both types inevitably have outgoing shock waves. They are necessary to explain the observations (Rosseland, 1946; Schatzman, 1946, 1948) and are inherent in current models (Sec. IV of Part I). Colgate and Johnson (1960) pointed out that as such a shock moved to regions of lower and lower density in the star, it should accelerate a small fraction of the total shocked mass to exceedingly high energies. This has been confirmed by later, more detailed calculations (Colgate and White, 1966; Colgate, 1975b, 1979; Colgate and Petschek, 1979). There are three difficulties with the model: compositional, observational, and adiabatic.

First, the source ratio of Co:Ni:Fe says that at least several years of electron captures occur between synthesis and acceleration (Soutoul, Cassé, and Juliusson, 1978; Minagawa, 1981; Wefel, 1981). The problem disappears if material is accelerated largely from the unprocessed, hydrogen-rich envelope of the star, or if the relativistic particles are able to recombine after accelerating, getting restripped in the interstellar medium (Colgate and Petschek, 1978).

Second, there is some observational evidence against large numbers of relativistic particles being present in supernovae immediately after the event. Beall (1979) pointed out that the relativistic electron content initially must be less than 10% of the 10^{49} ergs eventually needed in the remnant or else inverse Compton production of x rays would exceed the observed values and upper limits. This constraint is particularly tight for SN 1979*c* (Palumbo and Cavallo, 1981). Rather similarly, if some galactic supernovae go off in dense molecular clouds, then the known gamma-ray fluxes from point sources limit prompt production of relativistic protons to 10^{48} ergs (Morfill and Drury, 1981; Zweibel and Shull, 1982). Berezinsky and Prilutsky (1978) present similar arguments for events occurring in the general interstellar medium. Moving the particles rapidly away from the supernova can help only if the surrounding region is rather freer of particles, photons, and magnetic field than one would expect. In particular, the electrons cannot evade the SN photons—but we do know other ways to accelerate electrons (Secs. VI.C.2 and VI.C.3).

Finally, the newly accelerated particles will almost certainly be trapped in and around the expanding shock wave, breaking loose from the supernova remnant gradually as it expands. The details of the escape are complex (Morfill and Scholer, 1979), but one inevitably worries about the enormous adiabatic losses. If these are to be compensated by initially making more than the canonical 10^{49-51} ergs in relativistic protons, then the problems of the previous paragraph are much the worse for it.

None of these objections apply so strongly to having supernova events serve as the injectors which raise particles to mildly relativistic energies, so that the mechanisms of Secs. VI.C.2 and VI.C.4 can act on them. ter Haar (1950) seems to have been first to cast supernovae in this modified role. It has subsequently been invoked from time to time (cf. Fransson and Epstein, 1980; Blandford and Ostriker, 1980) and retains the virtue of tying cosmic-ray abundance anomalies to nucleosynthesis in a straightforward way.

2. Acceleration in and around young supernova remnants

Shklovskii (1953) noted that relativistic particles would have an easier time getting way from supernovae into the general interstellar medium if acceleration occurred well after maximum light. He suggested strong, irregular magnetic fields in young remnants as a probable intermediary.

Scott and Chevalier (1975) and Chevalier, Robertson, and Scott (1976) have looked in detail at what Cas A should be doing. They find that fast-moving knots in the SNR cause turbulence in the immediately adjacent interstellar medium, whose elements can act as randomly moving, magnetic scattering centers, causing second-order Fermi (1949, 1954) acceleration of both protons and electrons. The electrons suffice to maintain the observed synchrotron radiation from the remnant, and the protons (etc.) have the right spectral index and time-integrated energy ($\sim 10^{51}$ ergs) to be the dominant component of cosmic rays, supposing all SNR's to behave similarly. Abundance anomalies in the GCR's reflect, in this model, the peculiar composition of the knots (Chevalier and Kirshner, 1979) diluted by material from the interstellar medium. Acceleration occurs outside the main body of the nebula, but inside the large-scale shock wave; thus the problem of adiabatic losses is somewhat reduced, though not entirely eliminated (cf. Morfill and Scholer, 1979).

Unfortunately, other SNR's may not be similar. The analogous process in the 1006 remnant suffices to keep up an adequate electron supply (Reynolds and Chevalier, 1981). But shocks in it and the 1572 remnant can be shown to be exceedingly inefficient particle accelerators, only 2×10^{-5} of the available shock energy appearing as relativistic electrons (Reynolds and Chevalier, 1981). The difficulty should be taken the more seriously as it has been raised by one of the proponents of the mechanism. As in Sec. VI.C.1, the problem is somewhat ameliorated if we require only injection at moderately relativistic energies and not complete acceleration from the process. As the rather similar interplanetary bow shocks are efficient particle accelerators (Hoppe and Russell, 1982), despair would be premature.

3. Acceleration by pulsars

Pulsars must continuously accelerate relativistic electrons in order to pulse. In addition, NP 0532 is required by ancient custom to make enough extras to keep the Crab Nebula radiating. The required end might be achieved by several different mechanisms (Smith, 1976; Manchester and Taylor, 1977; Sieber and Wielebinski, 1981), some of which also accelerate positively charged particles. Two possibilities have been explored in some detail.

First, if pulsar magnetic dipole moments are obliquely aligned to the rotation axes, intense low-frequency electromagnetic radiation is generated. It can, in turn, transfer energy efficiently to a small number of particles. Roughly equal amounts should be given to electrons and protons, the former radiating near the pulsar and in the surrounding SNR, and the latter becoming cosmic rays (Gunn and Ostriker, 1969; Kulsrud, Ostriker, and Gunn, 1972). The spectrum and total energy ($\sim10^{49}$ ergs) are OK. Most of the acceleration must occur in the first few years, when the pulsar is spinning most rapidly. As a result, this mechanism faces an aggravated form of the difficulties inherent in mechanism (1). That is, if the newborn cosmic rays encounter photons, magnetic fields, or high-density (interstellar or circumstellar) gas, they are likely to make things we don't see; and, as they are generated well inside the young SNR, adiabatic losses will be severe.

The other standard sort of electron acceleration can occur for either parallel or oblique alignment of magnetic and rotation axes. The spinning magnetic field induces an electric field of sufficient strength that breakdown and pair creation occur. Pair annihilation makes gamma rays, which create further pairs and a cascade of relativistic electrons and positrons (Goldreich and Julian, 1969; Sturrock, 1971; Roberts and Sturrock, 1973; Ruderman and Sutherland, 1975; Cheng and Ruderman, 1977, 1980; Arons and Scharlemann, 1979; Dougherty and Harding, 1982; Barnard and Arons, 1982; etc.). Under these circumstances, relatively little energy goes into accelerating positively charged nuclei (essentially none, if the polar caps are negatively charged; Arons, 1981), and pulsars cannot be important cosmic-ray sources except perhaps for electrons.

It is worth noting that no strong, low-frequency electromagnetic wave is generated by any pulsar which has appreciable pair production (Kennel, Fujimara, and Pellat, 1979). Thus the mechanisms of the two preceding paragraphs are mutually exclusive.

4. Acceleration in the general interstellar medium

Fermi (1949) showed that a population of moderately relativistic protons, repeatedly colliding with moving magnetic field structures in the interstellar medium, would gradually gain energy and evolve to the observed power-law spectrum, as a natural consequence of stochastically distributed accelerating events. The mechanism also gradually evolved with time and encounters with many authors (Fermi, 1954; Morrison, Olbert, and Rossi, 1954; Fan, 1956; Davis, 1956; etc.) to include betatron processes, induction, hydromagnetic waves, and the realization that the turbulence of the interstellar medium must be replenished if the thing is to keep working for long. This last is where supernovae come in (Sec. VI.F below).

The primordial Fermi mechanism has quite low efficiency ($\lesssim1\%$ under normal interstellar conditions; Parker, 1955). This increases usefully, however, in the presence of interstellar hydromagnetic shocks (Parker, 1955, 1958). And it is probably fair to say that some form of acceleration in interstellar hydromagnetic shocks is the current favorite among models of cosmic-ray origins (Axford, Leer, and Skadron, 1977; Bell 1978, Eichler, 1979; Blandford and Ostriker, 1978, 1980; Axford, 1981, 1982; Axford, Leer, and McKenzie, 1982). Blandford and Ostriker (1980) specifically consider shock waves around supernova remnants expanding into an interstellar medium dominated by fossil remnants of older events. But in any case, much of the shock energy that is drained in accelerating cosmic rays must be replenished by SNR's (and/or expanding H II regions around OB stars; cf. Sec. VI.F).

Eichler (1979) has suggested that, under some circumstances, a shock can act on a purely thermal distribution of particle energies—the general interstellar medium— and put about half the available energy into a tiny fraction of the particles, thus solving the injection problem. If that is what is going on, it is perhaps surprising that cosmic-ray source abundances should show traces of recent nucleosynthesis, although some of the composition anomalies can be explained by preferential acceleration (Eichler, 1980, 1982).

Most modern versions of the shocked Fermi mechanism imply stochastic acceleration, that is, a particular cosmic ray has changed its energy many times, gaining only gradually and on average. This means that the highest-energy particles have (also on average) been kicked most often, and so must have been around longest. A consequent prediction is that the ratio of secondary nuclei (those produced by spallation in the interstellar medium, like Li, Be, B, and N) to primary nuclei (those accelerated to begin with, like C and O) should increase with energy. It doesn't. It falls, resulting in a severe constraint on stochastic acceleration models (Fransson and Epstein, 1980; Cowsik, 1980), even when proper account is taken of confinement time versus energy (which tends to make the lowest-energy particles stay around longest). Crudely, the bulk of the total power must come from the sources in one step, though it can be gradually redistributed among the particles without causing problems. The parameters of the Blandford and Ostriker (1980) model just fall within the constraints, provided the injection energy is already quite high. Injection and acceleration by a single shock (Eichler, 1980) is apparently also OK. Truly stochastic acceleration is not. A few authors find shock acceleration in any form fairly unacceptable, except perhaps for electrons (Prishchep and Ptuskin, 1982; Fedorenko, 1982).

It does not seem possible at the present time to provide a tidy conclusion to this section.

D. Gamma rays

Gamma rays comprise all photons too energetic to be called anything else, particularly when emitted by nuclear rather than atomic processes. Gamma-ray astronomy (first suggested as a useful endeavor by Morrison, 1958) thus spans nearly 9 orders of magnitude in photon energy, from the 0.07-MeV lines of Ti^{44} sought by Schwartz, Lin, and Pelling (1980) to the $\gtrsim 10^{12}$-eV range searched by Fegan *et al.* (1980). Virtually all the extrasolar gamma rays seen or thought of to date can be blamed on supernovae and their products directly or indirectly, if these are presumed to include cosmic rays (Sec. VI.C) and neutron stars (Sec. VI.I). We will here narrow our sights to (1) bursts ($\lesssim 1$ s) and (2) transients ($\lesssim 1$ yr) produced by supernova explosions, (3) prolonged emission from SNR's, and (4) everything else in inadequate summary. Both continuum and line emission are possible in most categories. Cowsik and Wills (1980) include a number of useful summaries of observations and explanations thereof.

1. Bursts

Supernovae should make gamma-ray bursts (Colgate, 1968). Gamma-ray bursts have been seen (Klebesadel, Strong, and Olson, 1973). Unfortunately, the ones that were predicted have not been seen (Fegan *et al.*, 1980), and the ones that have been seen were not predicted (Colgate, 1975).

The predicted bursts arise as a shock wave (produced by core bounce, or thermonuclear detonation; Sec. III.C of Part I) penetrates the surface of the exploding star. Contributions can come from thermalization of the shock via brehmsstrahlung (Colgate, 1974) and from nonthermal processes including internuclear and π^0 production, yielding both lines and continuum emission (Khlopov, Chechetkin, and Éhranzhyan, 1981). Each contribution is of order 10^{47-48} ergs. The time scale and average energy are exceedingly sensitive to model details, and not independent—more gradual emission goes with lower energies when photons are degraded by scattering. Energies of 1—100 MeV and time scales of 0.1—100 s cover at least the middle of the predicted range. The present upper limits on such emission don't significantly constrain the models, and improved sensitivity will not easily be achieved, either from the ground (Fegan *et al.*, 1980) or from space, since we don't know *a priori* where to look.

And what about the observed bursts? There still seems to be some connection with supernovae: The most intense burst yet seen, that of 5 March 1979, occurred near the center of a supernova remnant, N49, in the Large Magellanic Cloud (at least in two dimensions). Cline *et al.* (1980) and Evans *et al.* (1980) give the data, which have been interpreted by Ramaty *et al.* (1980, 1981) in terms of a vibrating neutron star.

The commoner class of less intense bursts has elicited explanations of truly enormous creativity (reviewed, e.g., by Puget, 1981). A rapporteur speaker at the 1974 Texas Symposium presented a list of noted theorists who had *not* advanced a model for gamma-ray bursts. It contained exactly one name (cf. Ruderman, 1975). Recently, there has been some convergence around the idea of thermonuclear flashes on the surfaces of accreting neutron stars with strong magnetic fields (Woosley and Wallace, 1982; Fryxell and Woosley, 1982; Jones and Ramaty, 1982). Supernovae are thus involved only indirectly, and we can abandon the bursters here with a clear conscience.

Supernova models that predict gamma-ray bursts should also give rise to $\sim$1-s pulses of microwaves. The expected total energy and peak wavelength of the pulse depend very much on plasma densities near the SN, but at least 3×10^{34} ergs ought to escape at centimeter-to-meter wavelengths (Colgate, 1975a). Meikle and Colgate (1978), reviewing the half-dozen experiments that had some sensitivity to such bursts, conclude that the present upper limits do not usefully constrain the models, but that one could do much better with existing technology.

2. Transients and lines

Supernovae should emit gamma rays at (perhaps) detectable levels in both continuum and lines for some months after the explosion. Berezinsky and Prilutsky (1978) pointed out that cosmic rays accelerated by a newborn pulsar will interact with a surrounding supernova shell to make a π^0 gamma-ray continuum, a search for which would constitute a fairly definitive test of whether or not young supernovae/pulsars accelerate cosmic rays. They thought not, incidentally. More recent calculations (Cavallo and Pacini, 1981) lead to a predicted flux of $\sim10^{-6}$ photons/cm^{2}s for the first year or so from an event 10—20 Mpc away. Thus SN 1979*c* in NGC 4321 might have been just above the threshold of COS-B, but was not, in fact, seen. A similar event in the late 1980s should be conspicuous to the Gamma-Ray Observatory (GRO).

Supernova gamma-ray line emission arises from the decay of radioactive nuclides made in the explosions. Credit both for many of the early calculations and for much of the spadework that convinced the astronomical community that gamma-ray lines are the way to look at nucleosynthesis in progress belongs to Clayton (Clayton, 1971, 1973a, 1973b; Clayton, Colgate, and Fishman, 1969; Clayton and Craddock, 1965; Clayton and Fowler, 1969).

Once upon a time, when SN I light curves were blamed on the decay of Cf^{254} (Burbidge *et al.*, 1957), the predicted fluxes were as high as 10^{-4} photons/cm^2 s in the Cf^{254} line at 390 keV from a fresh event at 1 Mpc (Clayton and Craddock, 1965) and 10^{-2} $cm^{-2}s^{-1}$ in a Ra^{226} line from the Crab Nebula even now (Morrison, 1958).

Explosive nucleosynthesis in current SN models produces lower fluxes but a wider variety of isotopes (Clayton, 1973a, 1973b). Table II lists the likely nuclides, their half-lives, processes and sites that make them, and the length of time after a SN explosion the strongest line from each should remain detectable by GRO (flux$=2\times10^{-5}$ photons/$cm^{-2}s^{-1}$) for galactic and extragalactic events. The data come from Woosley, Axelrod, and Weaver (1981) and Weaver and Woosley (in NATO81). There are two major uncertainties in the predicted fluxes. First, the amounts of each thing made vary with mass of the parent star and details of its modeled evolution. Second, it takes a while for the expanding SN shell to become transparent to gammas coming from nuclides near the center—about a year for the massive envelopes of SN II's. The time for SN I's should be much shorter as their envelopes are much thinner. Spectroscopic evidence for excess Co and Fe in the atmospheres of SN I's a month or two after maximum light (Sec. III.B.3 of Part I; Axelrod in NATO81) indicates that interior gas may reach the photosphere quite quickly.

As we cannot expect a galactic supernova in the two year lifetime of GRO, the best bets seem to be the steady fluxes of Al^{26} and Fe^{60} lines, concentrated in the spiral arms of our galaxy where SN II's occur, Ti^{44} from the historical remnants, and Co^{56} from extragalactic SN I's. This last is perhaps the most exciting, both because it would reveal the synthesis of a major nuclide nearly in real time and because it will probe directly the nuclear explosion that we now think makes SN I's (Sec. IV.C of Part I). Detecting it will require concurrent operation of a ground-based optical supernova search. Statistics strongly favor there being several SN I's within 10—20 Mpc in a 2-yr period, but it is essential to locate them promptly, so that the Oriented Scintillation Spectrometer Experiment can be aimed in the right direction. Several relevant searches are under construction (Sec. VIII.B).

3. Long-lived sources

The processes that make both lines and continua in a supernova explosion will continue at diminishing intensity through the life of the remnant. Schwartz, Lin, and Pelling (1980) looked with a balloon-borne experiment for the 78.4- and 67.9-keV lines of Ti^{44} from Cas A and set an upper limit of 10^{-3} photons/cm^2 s. This is about 100 times larger than the predicted flux (Woosley *et al.*, 1981), which lies very close to the GRO threshold.

Relativistic particles (cosmic rays) in the SNR or a shock front at its edge can excite additional nuclear gamma-ray lines from stable nuclides. Lines expected to be strongest in the historical supernova remnants include C^{12} at 4.44 MeV (Meneguzzi and Reeves, 1975; Bussard, Ramati, and Omidvar, 1978) and Fe^{56} at 0.845 MeV. The predicted fluxes are a few $\times10^{-5}$ $cm^{-2}s^{-1}$ on the assumption that young SNR's contain $\sim10^{51}$ ergs in GCR's. Bussard, Ramati, and Omidvar (1978) normalized their prediction to the observed 6.8-keV atomic line of iron, on the assumption that it is produced by cosmic-ray collisional excitation in Cas A. If other mechanisms contribute to the x-ray lines, then the predicted gamma-ray intensity is an upper limit.

Finally, positrons from the decays of Ni^{56} and Co^{56} will not all necessarily annihilate immediately. Colgate (1970) and later Woosley, Axelrod, and Weaver (1981) suggested that they might get out of their SNR's and make an important contribution to the 0.5-MeV flux coming from the vicinity of the galactic center (Leventhal *et al.*, 1980). The 1981 decrease in that line flux (Jacobson, 1982) has made this seem less likely.

As long as an expanding SNR contains particles with energy $\gg1$ MeV, then it is capable of emitting some

TABLE II. Properties of nuclear decays expected in supernova ejecta and their detectability by the Gamma Ray Observatory.

Decay	Half-life	Sources	Years visible to GRO	
			at 10 kpc	at 10 Mpc
$Co^{56}\rightarrow Fe^{56}$	77 days	SN II explosive Si burning	<5	
		SN I CO detonation or deflagration	4	0.2
$Co^{57}\rightarrow Fe^{57}$	271 days	SN II explosive Si burning	≤10	
$Na^{22}\rightarrow Ne^{22}$	2.6 yr	SN II explosive C burning	15	
$Ti^{44}\rightarrow Ca^{44}$	47 yr	SN I and SN II, nuclear statistical equilibrium	~100	
$Fe^{60}\rightarrow Co^{60}$	3×10^5 yr	SN II explosive He burning	longer than time between galactic supernovae	
$Al^{26}\rightarrow Mg^{26}$	7.2×10^5 yr	SN II explosive He burning	longer than time between galactic supernovae	

gamma rays via pion and pair production, nuclear excitation, and various other processes. Lamb (1978) proposed that the interaction of old supernova shocks with the interstellar medium was responsible for a large fraction of the COS-B unresolved sources. van den Bergh (1979) found that there are, indeed, optical SNR's at positions of many of the sources, and Panagia and Zamorani (1979) showed that the general spatial distribution is similar. A further refinement, in which only SNR's associated with large OB associations, having lots of gas and dust for the SNR's to smash into, should be sources, also produced a number of promising identifications (Montmerle, 1979). X-ray sources are associated with, or at least close to, some of them (Lamb and Markert, 1981). The region where the North Polar Spur encounters the ρ Oph molecular cloud is particularly promising (Morfill *et al.*, 1981), and the general idea continues to have considerable support (Vladimirsky, 1980).

The previous argument supposes that gas is fairly uniformly distributed in space, and that it is extra cosmic rays that make a "point" gamma-ray source. The alternative (proposed by Black and Fazio, 1973, and supported by Bignami and Morfill, 1980) is that the cosmic rays are fairly uniformly distributed and the gas that is lumpy. Thus gamma-ray sources are to be identified with giant molecular clouds. This is perhaps marginally the more popular hypothesis (Swanenburg, 1982).

4. Everything else (Pooh-Bah models)

Our galaxy radiates a diffuse gamma-ray background, concentrated toward the plane and the galactic center. Many things undoubtedly contribute to it (Salvati and Massaro, 1982). Most of them are, directly or indirectly, supernova products, including pulsars (Harding and Stecker, 1981), cosmic rays interacting with interstellar gas in one (Stecker *et al.*, 1975) or more (Morfill, 1982; Schlickeiser, 1982) stages, warm interstellar medium compressed by SN shocks (Blandford and Cowie, 1982), and weaker versions of the unresolved sources, whatever they may be.

The diffuse extragalactic background also has an impressive number of contributors (Silk, 1973), whose relative importance is not very well known. Some, like Ni^{56} and Co^{56} decays to make the $\sim$1-MeV feature (Clayton and Silk, 1969) and cosmic rays hitting intergalactic gas, invoke supernovae one way or another. Others, like annihilation at matter-antimatter interfaces (Stecker *et al.*, 1971), do not.

Finally, the most convincingly identified point gamma sources are still pulsars, largely because the pulse period helps a lot in singling out one object in a 2° error box. The Crab (Albats *et al.*, 1972), Vela (Thompson *et al.*, 1975, 1977), and others (Ögelman *et al.*, 1976) have been seen in the balloon-and-satellite energy range, the Crab and Vela (Bhat *et al.*, 1980) probably also at air shower energies, >500 GeV. Models abound (Thompson, 1975; Salvati and Massaro, 1978; Schlickeiser, 1980; Ayasli and Ögelman, 1980; Ochelkov and Usov, 1981). On a one-paper—one-vote basis, the correct answer is curvature radiation and pair production in a shower near the pulsar.

The 0.5-MeV line source near the galactic center is variable, thus also compact. The requisite production of positrons can be attributed to supernovae or to a variety of other things (Ramaty and Lingenfelter, 1982).

E. X rays

For x rays, as for gamma rays, a very large fraction of the sources, backgrounds, and models involve supernovae and their by-products, one way or another. The following sections address (1) the (predicted) precursor pulse, (2) the (observed) emission near maximum light, and (3) everything else, greatly condensed.

1. The precursor pulse

Models for both types of supernovae (Sec. IV of Part I) invoke outgoing shock waves, initiated either by core bounce or by nuclear deflagration, which heat and expand the envelopes of the progenitor stars, thereby producing many of the observed light-curve and spectral phenomena. As the shock reaches a point having optical depth one below the surface of the envelope, a burst of photons will emerge with considerably shorter wavelengths than those radiated later at maximum light. The precise wavelengths, as well as the total energy and time scale of the burst, will depend (a) on whether the pre-shock envelope was compact or extended and (b) on whether or not the shock continues to steepen as it moves through the tenuous material above optical depth one.

In all cases, the pulse precedes by some days ($\sim$10—20) the rise to optical maximum, which occurs as the shocked envelope expands. In no case is there an observed event corresponding to the predicted one. This is not very surprising. Though at least some of the modeled pulses should have fallen within the sensitivity limits of Uhuru, OSO-7, or Einstein for supernovae within about 10 Mpc, only by the greatest good fortune might one of the satellite detectors have been pointing in the right direction at the right moment, weeks before an optical event could have been spotted (cf. Sprott *et al.*, 1974, and Arnett, 1977, for a near miss). Even then, the pulse might well have looked like the sort of thing that normally causes one to throw out that bit of data. The properties of the precursor pulses, therefore, constitute genuine Popperian predictions of and tests for the several models as outlined below.

An initially compact envelope yields a short, sharp shock. Thus Type I supernovae should be preceded by a short burst of relatively hard x rays, first calculated approximately by Colgate (1968). At one time, it looked as if the pulses might have some of the properties of the observed gamma-ray bursts (Colgate, 1974; Bisnovatyi-Kogan *et al.*, 1975), that is, total energies from 10^{42} up to as much as 10^{48} ergs, time scales of 0.02—0.2 s, and spectra peaked well above 10 KeV, with appreciable flux out to and beyond 0.1 MeV. More recent calculations (Colgate and Petschek, 1979; Imshennik, Nadyozhin, and Utrobin, 1981) yield predicted bursts in the 1—10-keV range, with peak outputs near 10^{42} ergs/s, lasting 0.01—1 s.

An initially extended (supergiant sized) envelope moderates but by no means eliminates the shock and its photon burst, as remarked by Chevalier (1976) and Falk and Arnett (1977). These and more recent calculations (Arnett, 1977; Klein and Chevalier, 1978; Falk, 1978; Chevalier and Klein, 1979; Lasher and Chan, 1979) more or less agree on a spectral peak in the ultraviolet or soft x-ray region, corresponding to a photospheric temperature of $(1-2)\times 10^5$ K, but with appreciable amounts of non-Planckian flux in the 0.1—0.5-keV range due to bremsstrahlung and inverse Compton scattering. The time scale is $10^{4\pm0.5}$ s and the total pulse energy $10^{48\pm1}$ erg. The flux received at the Earth from such an event will depend very much on the amount of intervening interstellar and (especially) circumstellar material.

Finally, several of the extended-envelope models (Chevalier, 1976; Falk, 1978; Chevalier and Klein, 1979) showed a transition to a harder, hotter, ion-viscous shock in the extreme surface layers of the envelope. This would radiate a roughly concurrent hard x-ray (10—100-keV) pulse, with perhaps 1% as much energy as the soft one. Absorption should not influence this much, so that it might be the more detectable effect. Epstein (1981) has, however, suggested that radiation from the erupting shock will accelerate matter in front of it, smoothing out the velocity discontinuity, so that little or no shock steepening or hard x-ray emission should occur.

2. Emission near maximum light

The light emission from most supernovae near maximum looks quite Planckian, with characteristic temperatures near 10^4 K (Sec. III.C of Part I). One would not, therefore, necessarily expect any significant hard photon flux. Some of the models (particularly those involving pulsars) did, however predict an x-ray luminosity comparable with the optical one for some months after maximum (Bahcall, Rees, and Salpeter, 1970; Shklovskii, 1973). These were largely ruled out on the basis of upper limits or marginal detections from early satellite work (Canizares, Nabors, and Matilsky, 1974, and references therein).

The Einstein Observatory, in its dying days, finally detected x-rays from one extragalactic supernova, the Type II 1980*k* in NGC 6946 (Canizares, Kriss, and Feigelson, 1982), whose radio emission was also seen (Weiler *et al.*, 1982). The luminosity, 35 days after light maximum, was about 2×10^{39} ergs/s in the 0.2—4-keV band (for a distance of 10 Mpc), or $\frac{1}{3500}$ of the light output at the same time. Six weeks later, L_x had fallen by a factor of about 2. No further observations were possible. The x-ray spectrum could be fitted either by a Planck distribution with $kT \gtrsim 0.5$ keV or by a power law with index $\gtrsim -3$ in frequency units. Nothing was seen from the locations of the four previous supernovae in that galaxy.

Because the x-ray emission is a tiny fraction of the total and its properties not very well known, many models are possible (Canizares, Kriss, and Feigelson, 1982; Chevalier, 1981a, 1982b, and in NATO81; Fransson, 1982).

Possibilities include (a) synchrotron radiation from an extension of the spectrum of electrons that make the radio emission, (b) inverse Compton scattering of the supernova optical photons by the radio electrons, (c) thermal emission from an encounter between the expanding envelope and a circumstellar shell, and (d) processes in newly synthesized Ni^{56}, Co^{56}, and Fe^{46} (*K*-shell emission and degraded nuclear gamma rays). Of these, (b) must surely occur, and the flux will be interestingly large unless the radio emission is coming from well outside the optical photosphere; (a) and (c) may or may not occur, depending on whether electrons are being accelerated up to γ's near 10^6 and on whether there is a dense circumstellar shell; and (d) is perhaps rather unlikely for a Type II SN, since peak-light optical spectra show no evidence of excess iron, etc. (though the post-peak-light curve may; Weaver and Woosley, 1980). Canizares, Neighbors, and Matilski (1974) did, however, predict an x-ray luminosity of 2×10^{39} ergs/s for Type I supernovae shortly after maximum light on the basis of these processes.

Data on even one or two more events would undoubtedly much clarify the situation, but do not try to hold your breath while waiting for them.

3. Everything else

The preceding sections suggest that supernovae do not themselves contribute much in the way of x-ray sources or backgrounds. Their products undoubtedly do, supernova remnants turning up both as discrete extended sources and as contributors to the galactic background, and neutron stars contributing x-rays fed by thermal, rotational (pulsar), and gravitational (accretion) energy stores. Convenient entree to recent ideas and literature can be found in the reviews by Holt and McCray (1982) and Bradt and McClintock (1982) and in the conference proceedings edited by Andresen (1981) and Lewin and van den Heuvel (1982).

a. Supernova remnants

The first x-ray source definitely identified with an object outside the solar system was the Crab Nebula (Bowyer *et al.*, 1964). A few other SNR's gradually revealed themselves to rocket-borne detectors and Uhuru (e.g., Pounds, 1973). And the Einstein Observatory recorded 0.2—4-keV x rays from some 40 galactic supernova remnants (Seward in NATO81) and another 26 or so in the Large Magellanic Cloud (Helfand and Long in NATO81) before closing up shop. The Crab identification quickly inspired discussion of likely production mechanisms, Shklovskii (1965) calling attention to the probable extension of the radio and optical synchrotron spectrum into the x-ray region, and Heiles (1964) calculating the bremsstrahlung x rays to be expected when a Sedov-like SN blast wave plows into the interstellar medium. Shklovskii was right about the Crab, as we now know from the polarization of the x rays (Weisskopf *et al.*, 1978), and Heiles about nearly all the others, as confirmed by emission lines of iron and other abundant elements (Tucker, 1970; Holt, 1980; Shull, 1981, etc.). The expected emission from a shock wave around the Crab Nebula has still not been seen (Gorenstein *et al.*, 1981). Not suprisingly, analysis of the x-ray data has made an enormous contribution to our understanding of SNR structure, composition, and dynamics (see Sec. V above, and Gorenstein and Danziger, 1983).

Diffuse soft (e.g., 0.25-keV) x-ray emission reaches us from all directions in the sky (Bowyer, Field, and Mack, 1968), much modified by absorption in the interstellar medium. Early theoretical work (reviewed by Silk, 1973) largely attempted to attribute this background to some combination of point sources within the galaxy and hot gas outside it. Shklovskii and Sheffer (1971) and Ilovaisky and Ryter (1971), however, blamed supernova remnants almost from the beginning. The discovery of O VI absorption lines in the ultraviolet spectra of stars (Rogerson *et al.*, 1973) demonstrated the existence of hot gas within the galactic disc and was closely followed by the suggestion (Kraushaar, 1973; Cox and Smith, 1974) that the x rays might be produced by more or less the same gas, which was in turn, probably, a component of the interstellar medium made up of interconnecting old supernova remnants. Refinements of this model followed (McKee and Ostriker, 1977; Cowie *et al.*, 1979; Paresce and Stern, 1981; Cox and Franco, 1981), leading to the conclusion that O VI, extreme ultraviolet, and soft x-ray emission probably probe gas at slightly different temperatures, though part of the same SNR-dominated structures. These cannot, however, be entirely in equilibrium or steady state.

b. Neutron stars

The x-ray detection of the Crab Nebula prompted a burst of calculations of the flux to be expected from a cooling neutron star (Chiu and Salpeter, 1964; Morton, 1964; Hayakawa and Matsuoka, 1964), which tapered off after the demonstration that the source was extended (Bowyer *et al.*, 1964). It is not entirely clear to this day that we have ever seen thermal x rays from a neutron star. Nonpulsed fluxes come from the Vela and (probably) Crab pulsar (Harnden, 1983) and from point or compact sources associated with RCW 103 (Tuohy and Garmire, 1980), 3C58, CTB 80 (Becker, Helfand, and Szymkowiak, 1982), MSH 15-5(2) (Seward and Murdin, 1981; Seward *et al.*, 1982), and several other supernova remnants (Sec. VI.I.3). MSH 15-5(2) pulsates, and the rest are faint enough that pulsation cannot be ruled out very strongly. Some of the observed fluxes are in reasonable agreement with what is expected from neutron stars cooling in accord with recent calculations (Yakovlev and Urpin, 1981; Van Horn, Ratcliff, and Malone, 1982; Gudmundsson, Pethick, and Epstein, 1982). Thus there is no contradiction in interpreting them as thermal emission from neutron stars with surface temperatures near 10^6 K; but a preponderance of the evidence favors nonthermal (synchrotron) emission (Sec. VI.I.3).

The fashion in models for strong, compact x-ray sources switched from single stars to binaries when the optical identifications of Sco X-1 and Cyg X-2 showed that the former had a spectrum rather like an old nova (Sandage *et al.*, 1966) and the latter a wildly variable radial velocity (Burbidge, Lynds, and Stockton, 1967). Cameron and Mock (1967) suggested accretion onto a white dwarf, Shklovskii (1967) accretion onto a neutron star, and Prendergast and Burbidge (1968) accretion via a disc which did most of the emitting. Models incorporating one or more of these components have now been attached to virtually all types of bright, compact galactic x-ray sources, including the steady, transient, bursting, pulsing, globular cluster, and cataclysmic variable varieties. For a representative sample of each, see Milgrom (1978) on steady sources, Rappaport *et al.* (1976) and Skinner *et al.* (1982) on transients, McCray (1982) on bursters, Ghosh and Lamb (1979) on pulsators, van Paradijs (1978) on the globular cluster sources, and Córdova and Mason (1982) on cataclysmic variables, which have some chance of being supernova precursors if not products. The 0.15-s pulsator in the supernova remnant MSH 15-5$\underline{2}$ (Seward and Harnden, 1982; Manchester, Tuohy, and D'Amico, 1983) is a "real" pulsar (further discussed in Sec. VI.I below). By adding a brief mention of Cyg X-1, in which the accreting object is likely to be a black hole (Bahcall, 1978) and so presumably also a supernova product, we can claim to have touched on all types of x-ray sources that are likely to be part of our story.

F. Heating and stirring of the interstellar medium (ISM)

The interstellar medium is turbulent, in the sense that individual gas clouds, like individual stars, have peculiar velocities (of order 10 km/s) distributed around the general galactic rotation (Beals, 1936; Adams, 1949; Blaauw, 1952). This turbulence is constantly being dissipated, perhaps by accelerating cosmic rays (Sec. VI.C above), and surely by inelastic cloud-cloud collisions on a time scale much shorter than the age of the galaxy (Parker, 1953), and so must be replenished. In addition, of course, thermal, ionization, and excitation energy is constantly drained from the gas by radiation, also on a time scale that requires constant replenishment (Dalgarno and McCray, 1972). The lore of how supernovae might contribute via cosmic rays, ionizing photons, and kinetic energy of expanding remnants is considerable. Useful reviews include those by Dalgarno and McCray (1972), Kaplan and Pikelner (1974), Chevalier (1977), McCray and Snow (1979), McKee and Hollenbach (1980), and McKee (in NATO81).

The chief competing energizer is OB stars and associations (Oort and Spitzer, 1955) and their associated H II regions (Kaplan, 1953), via both radiation and stellar winds. Crudely one expects comparable contributions from supernovae and OB stars simply because the total amount of kinetic energy a massive star puts into its surroundings over its lifespan is about equal to the 10^{51} ergs that ends up in the expanding supernova remnant (Tinsley, 1980c). The wind energy alone averages about 10% of that put into the SN (Abbott, 1982). The most significant difference is perhaps that the higher velocities of the SNR's ($\sim 10^4$ km/s initially) put in "higher-grade" energy than the $\sim$1000-km/s winds and $\sim$10-km/s expanding H II regions (Chevalier, 1977). Supernovae probably also put a larger fraction of their ionizing radiation into very hard photons than do OB stars, favoring partial ionization of a large region over complete ionization of a smaller one.

Generation of interstellar turbulence at the expense of galactic differential rotation (von Weizsäcker, 1951) is typically neglected in modern models and must be much smaller than the other two sources. The following sections explore some of the important, interesting, or controversial details of supernova interactions with the interstellar medium.

1. Total energy supplied to the ISM

Early estimators (Parker, 1957; Kaplan, 1953) concluded that supernovae were at most a 10% contributor of thermal and kinetic energy, most of which came from early-type stars. Later calculations (Kahn and Woltjer, 1967; Chevalier, 1977; and many others) have found that supernovae can plausibly contribute all or most of what is required. The requirements have not changed much—characteristic numbers are 10^{-26}—10^{-25} ergs $\mathrm{s}^{-1}\,\mathrm{cm}^{-3}$ each for kinetic, thermal, and ionization energies. But there have been increases both in our best guess at the galactic supernova rate (to $\frac{1}{30}$ yr; cf. Sec. III.A.1 of Part I) and in the expected energy available from each event (up to 10^{50} ergs in light for $H_0 = 50$ km/s Mpc^{-1} and about 10^{51} ergs in kinetic energy of the remnants given Sedov-solution models of their evolution; cf. Sec. V above).

This can take care of stirring and heating the ISM. We should not, however, go overboard the other side and conclude that stellar processes are unimportant. Their contributions are undoubtedly on par with those of supernovae and may be dominant in some contexts (Jaffe, Stier, and Fazio, 1982).

Ionization is slightly more complicated. Supernova events themselves apparently contribute at most 1% of the requisite ionizing radiation (cf. Sec. VI.E above; Chevalier, 1977; etc.). There may, however, be appreciable contributions from the blast waves as young supernova remnants expand (Silk, 1973a) and from the hot interiors of older SNR's (McKee and Ostriker, 1977).

2. Mechanism of energy input

The basic equations for the slowing down of expanding supernova remnants as they sweep up interstellar gas and so transfer momentum to it go back to Oort (1946) and were later elaborated by Shklovskii (1962) and, especially, Spitzer (1968). Modern treatments (Chevalier, 1977, 1982a; McKee, in NATO81, and references therein) divide the process into several phases: (a) free expansion, while the ejected mass exceeds the swept-up mass, (b) blast-wave, adiabatic, or Sedov (1959)-Taylor (1946) phase, in which the swept-up gas is no longer negligible, but has not yet had a chance to cool radiatively since being shock heated, (c) radiative phase, in which the expansion time scale has grown to exceed the cooling time behind the shock, which leads to conspicuous shell structure, and (d) equilibrium phase, in which the pressure inside the remnant no longer exceeds that of the ambient ISM, though the temperature may, so that expansion stops, though radiation need not.

Energy transfer to the ISM is largely mechanical in the first two phases and radiative in the latter two. But as the expanding remnant cools, it may also lose significant amounts of energy by conduction and by evaporation of dense cloudlets within the ISM. Calculations incorporating these processes (Cowie, McKee, and Ostriker, 1981; McKee, in NATO81) provide good matches to a number of observations, including the difference in expansion velocities of, e.g., the Cygnus Loop, as determined from optical and x-ray observations; the existence of very large SNR's like the North Polar Spur and the size distribution of the others; the optical spectra; the emission by cloudlets embedded in more tenuous material (Greve *et al.*, 1982); and the existence of dense H I shells inside the shock in some SNR's. The calculations nevertheless make a number of assumptions and approximations (including the neglect of magnetic fields, which can inhibit conduction and evaporation) and are thus still subject to improvement and modification of the conclusions.

3. Specific features attributable to supernova effects

Since expanding SNR's put in "high-grade" energy, we might expect to see their effects most clearly in features with high velocities, large size scales, and the like. High-velocity gas (30—300 km/s in the Local Standard of Rest, after allowing for galactic rotation effects) is widely distributed both in and out of the galactic plane (Adams, 1949; Münch and Zirin, 1961; Oort, 1966; Hobbs, 1974; Shull and York, 1977; etc.) and comes in hot and cold, ionized and neutral versions. Explanations for it are equally widely distributed and diverse (see, e.g., Burton, 1979, for a representative sampling). No one explanation fits all the cases. Some features probably have been accelerated by supernova blast waves (Cohen, 1981); for others, OB star winds are an equally likely (Welsh and Thomas, 1982) or more likely (Downes *et al.*, 1982; Walborn and Hesser, 1982) explanation. Still others are clearly associated with totally disjoint phenomena, like the Magellanic Stream (Mirabel, 1982) and other tidal debris of Magellanic Cloud interaction with the Milky Way (Cohen, 1982).

The largest coherently expanding features seen in 21-cm maps of the galaxy were dubbed superbubbles (or supershells) by their discoverer (Heiles, 1976, 1979). Similar features occur in other spiral galaxies, including the Magellanic Clouds, M55, and M31 (Graham and Lawrie, 1982; Brinks, 1981). Their kinetic energies can reach 10^{53} ergs, much too large to blame on a single supernova or OB star. But stars form in clusters. Thus their winds and/or remnants can merge and blow large collective bubbles. Öpik (1968) believed that Barnard's Loop, surrounding the Orion region, had been formed by a sequence of supernovae. Since then, Tomisaka, Habe, and Ikeuchi, (1981) and Cowie *et al.* (1982) have favored supernovae, and Dopita *et al.* (1981) and Abbott, Beiging, and Churchwell (1982) have favored OB stars as the dominant contributor. Some shells undoubtedly have contributions from both energy sources (Gaulet *et al.*, 1982) and some, perhaps, from neither (Beltrametti, Tenorio-Tagle, and Yorke, 1982). Other kinds of stars may occasionally be important (Rosa and D'Odorico, 1982), especially once the expansion is well underway (Elmegreen and Chiang, 1982). Such shells are clear candidates for the sites of supernova-induced star formation (Sec. VI.G), though they must overcome a magnetic pressure barrier due to enhanced field ($\sim 7\ \mu$G) before they can collapse further (Troland and Heiles, 1982).

Finally, Altunin (1982) has suggested that the fluctuations in the interstellar medium responsible for scintillation may be magnetoacoustic turbulence produced by supernova shocks.

4. Large-scale structure of the ISM

Shklovskii (1962) pointed out that supernovae going off at the observed rate and making remnants that expand with the observed velocities and kinetic energies could not help but fill up a major fraction of interstellar space. He believed that the remnants would tend to rise buoyantly out of the galactic plane, giving rise to a hot, ionized galactic halo and a major portion of the observed galactic synchrotron radiation. Cox and Smith (1974) made the same point, with observational support from the detection of interstellar O VI and soft x-ray production. They predicted that a network of interconnecting tunnels of gas at $\sim 10^6$ K and density near 10^{-2} cm^{-3} should fill about half the galactic disc.

Some of the gas should indeed rise out of the plane, but perhaps also cool and fall back again as a galactic fountain (Shapiro and Field, 1976; Habe, Ikeuchi, and Tanaka, 1981; Hall, 1982), the infalling material showing up as high-velocity gas (Bregman, 1980). Alternatively, the outflow might continue as a hot galactic wind, in low-mass galaxies if not in ours (Mathews and Baker, 1971), and perhaps episodically in ellipticals (Sanders, 1981).

The interstellar medium that results from domination by supernova remnants then contains at least four phases which must be treated self-consistently (McKee and Ostriker, 1977; Cowie, McKee, and Ostriker, 1981; McKee, in NATO81). These are: (1) The old SNR's themselves, filling half to 90% of interstellar space with hot ($10^{5.5}$-K), tenuous ($10^{-2.5}$-cm^{-3}) ionized gas. (2) A dense ($n \sim 20$ cm^{-3}), neutral phase, responsible for typical optical interstellar absorption lines and H I emission, which takes up only a few percent of the available space, but much of the mass, and is characteristically divided into small cloudlets; it is replenished by the radiatively cooled dense shells that pile up around old SNR's. (3) A warm ($\sim 10^4$-K), partially ionized phase, using the remaining 10% or so of both volume and mass, and forming where host gas is evaporating cold clouds from their edges. (4) The giant molecular clouds, of much higher density (to 10^5 cm^{-3}) and lower temperature (~ 10 K), which do not interact enough with the rest of the system to require inclusion in the models. Their internal turbulence is probably replenished by violent mass loss from newly formed stars (Bally, 1982).

Such models adequately postdict a great many observed properties of the ISM (Sec. II.F.2 above), though fail to postdict some others, e.g., the small number of clouds along typical lines of sight near the sun (Bruhweiler and Kondo, 1981). The statistical significance of the disagreement is not currently very great.

A potentially serious objection to the three-phase, SNR-dominated ISM is that it is not readily shocked and compressed by a spiral density wave (Shu, 1978). This might seriously interfere with the preservation and encouragement of spiral galaxies. Perhaps the right way to look at the problem (Brand and Heathcote, 1982) is as a closed-loop feedback system, in which excessive massive star formation leads to so much hot ISM that density-wave triggering of cloud collapse and further star formation is inhibited until things calm down a bit (cf. Cowie, 1980, for a likely sounding mechanism in which the cloudlets themselves serve as the "atoms" of a gas undergoing shock). One is likely to get rather similar feedback and regulation of star formation rates from interstellar turbulence created by supernovae (Talbot and Arnett, 1975). Thus everything may yet be all right.

5. The local interstellar medium

If interstellar gas in our galaxy is divided among the four phases described in the previous section, then the region around the sun should fit the parameters of one of them. The question is which. Frisch (1982) says we are inside a supernova remnant, in fact the one seen as Loop I in radio maps. Meier (1980) describes our environs as warm (10^4 K), partially (60%) ionized, and of relatively low density ($n_{\rm H} = 0.04$ cm^{-3}), as do Schnopper *et al.* (1982) and Cox and Anderson (1982). Bruhweiler and Kondo (1981, 1982), on the other hand, report low ionization and $n_{\rm H} = 0.1$ cm^{-3} within a few parsecs and lower densities beyond that. And Crutcher (1982) describes evidence for both cool clouds and warm intercloud medium within a few parsecs, the whole assemblage having been shocked and accelerated by OB winds and SNR's coming from the Sco-Oph OB association.

Given the widely varying spatial resolutions and wavelength (hence temperature) coverage that has gone into the various determinations, there is probably no real inconsistency. Everything is neatly included by Bruston *et al.* (1981), who say that we are actually in a warm intercloud region, but with a cool cloud nearby, into which we are currently moving (Vidal-Madjar *et al.*, 1978); and the whole lot is inside a hot SNR zone, whose edges are a few parsecs from us.

At least no one seems to have proposed that we are inside a dense, dusty giant molecular cloud just at the moment, though we may have been at various times in the past, ice ages being one of the possible consequences (McCrea, 1975).

G. Supernova-induced star formation

Star formation is not very well understood (De Jong and Maeder, 1977). Perhaps the right question to ask, at least within the Milky Way now, is what prevents it, since the free-fall time of a typical giant molecular cloud is less than 10^7 yr. In the absence of inhibitors, therefore, the interstellar medium should either all long since have been turned into stars or all be in one of the tenuous phases discussed in Sec. VI.F, depending on whether giant molecular clouds (GMC's) reform on a time scale longer or shorter than the age of the galaxy. Not much is known about their formation either.

Toward the end of the previous section, it was suggested that supernovae, by feeding turbulent energy into the ISM, may inhibit star formation in the requisite fashion. We shall here inquire whether they may also cause star formation. Anyone who is bothered by the contradiction is invited to skip this section and read instead the entire platform of his favorite political party, or any book on economics.

1. Stars in general

Öpik (1953) pointed out that an old supernova remnant, by the time it stopped expanding, would have piled up around its edges enough interstellar gas to form a respectable star cluster. Bird (1964) further developed the idea that many or most young stellar associations form around exploding objects, which he tentatively identified with Type II supernovae (but believed to have masses $\gtrsim 10^3$ $M_\odot$).

The idea then lay more or less dormant until supernova triggering of the formation of the solar system (Sec. VI.G.2) caught on in 1976–1977. Observational evidence that particular groups of young stars are a consequence of, or at least closely associated with, particular old SNR's then accumulated rapidly. Berkhuijsen (1974) and Ögelman and Maran (1976) remarked upon H II regions in the shell of the old SNR the Origem Loop; Herbst and Assousa (1977) pointed to the CMa R1 and Ceph OB3 associations (though the latter does not apparently have an adjacent SNR after all; Rossano, Angerhofer, and Grayzeck, 1980); Wooten (1977, 1978, 1981) noted a young star at the edge of W44 and a dense molecular cloud seemingly compressed by W28, Angerhofer and Kundu (1981) a compact H II region near S147, Jenkins *et al.* (1981) a cloud compressed by the Vela SNR; and so forth (further discussion in Assousa and Herbst, 1980).

Theoretical support for the importance of supernova-induced star formation came from a new class of models of galactic evolution invoking stochastic self-propagating star formation (Gerola and Seiden, 1978; Seiden, Schulman, and Gerola, 1979; Seiden and Gerola, 1979; Gerola, Seiden, and Schulman, 1980). In these models, star formation begins at a few points, randomly distributed in space and time, in a differentially rotating gas disc, propagates away from each point for a while, and gradually dies away, only to begin somewhere else shortly. Such models, with assorted values of differential rotation, duration and separation of star-forming episodes, and so forth, produce spiral galaxies that look impressively like almost the full range of observed forms (including dwarf galaxies, in which star formation is intermittent because the time between star forming episodes is longer than the duration). The spiral arms are not permanent features, but grow and decay as star formation spreads from a point along curves determined by differential rotation. The models look still better if star formation episodes begin most often where gas is densest (Shore, 1981).

The propagation of star formation can be effected by expanding H II regions as well as by supernova remnants. Elmegreen and Moran (1979) have studied NGC 281 in which an H II shock is apparently functioning this way; and the two mechanisms are likely to make comparable contributions to star formation as well as to stirring the ISM.

Finally, of course, there is also undoubtedly star formation that results directly from the passage of spiral density waves (Toomre, 1977). It shows up, for instance, as a gradient of stellar luminosities (hence masses, hence ages) away from the edge of a spiral arm (Efremov and Ivanov, 1981, on arm S4 in M31). The ratio of density wave to stochastic star formation may be estimated from the distributions of large and small H II regions (Kaufman, 1981) and is apparently different in the Milky Way and M31.

Qualitatively, one expects galaxies dominated by density-wave star formation to show "grand design" two-arm spirals; while those with mostly stochastic star formation should appear less well organized—"flocculent" in the terminology of Meloy-Elmegreen (1981). It is not absolutely certain to which class our galaxy belongs (Bash, 1981), but there does seem to be evidence for all the advertised forms of star formation in the Milky Way.

2. The solar system

If nucleosynthesis occurs primarily in massive stars that end as Type II supernovae (Burbidge *et al.*, 1957 = B^{2}FH; Sec. VII below), then there was necessarily a last supernova that contributed heavy elements before the presolar nebula became isolated from the rest of the interstellar medium (Murthy, 1960). Considerations of lifetimes and abundances of radioactive nuclei permit an estimate of the length of time between this last supernova and solidification of material incorporated into meteorites. The time scale so derived is quite short (10^{6-7} yr) compared to the average time interval expected between supernovae in any given (e.g.) 10-pc box (Kohman, 1961; Murthy and Urey, 1962). This is (at least statistically) surprising, unless the last supernova was itself part of the cause of the cloud collapse that formed the solar system (Cameron, 1962).

The modern version of this argument (Cameron and Truran, 1977); Lattimer, Schramm, and Grossman, 1978) blossomed with the discovery of excess Mg^{26} in aluminum-rich inclusions in the Allende meteorite (Lee, Papanastassiou, and Wasserburg, 1976). This Mg^{26} presumably formed as Al^{26}, whose half-life is only about 700 000 yr. Thus the inclusions must have solidified within about 10^6 yr of the "last supernova." The Al^{26} decay then releases enough energy to melt portions of the meteorite parent bodies, accounting for much of their minerology and crystal structure. But, in addition, abundances of Xe isotopes produced by decay of I^{129} and fission of Pu^{244} imply larger contributions of heavy elements that ceased about 10^8 yr before solidification. Thus we are led to a picture in which the formation of the solar system was part of the development of a stellar association whose birth was triggered by a spiral density wave—the 10^8-yr time scale reflecting the time between successive passages through such shock waves. And our particular protostar in turn was triggered by some nearby supernova in the association, accounting for the 10^6-yr time scale.

This is probably the current "best-buy" model of solar system formation. Inevitably, it has not gone unchallenged. First, once a protostellar cloud begins to condense, it becomes rather impenetrable. The implication is that the meteorites bearing fossil radioactivities must have condensed near the edge of the cloud (Margolis, 1979). This is not impossible, but there is evidence for components of isotopically anomalous composition (excess O^{16}, etc.) in the Earth as well as in the meteorites (Clayton *et al.*, 1974). And we think we more or less know where the Earth is. Grains somewhat larger than the interstellar average may penetrate protostellar and protoplanetary clouds somewhat more readily (Elmegreen, 1982).

Second, the 10^6-yr time scale need not really imply a single last SN and trigger. If the solar system formed as part of a large association, then in the 10^7 yr it takes a $\sim 1\ M_\odot$ cloud to collapse, many more massive clouds will have had time to collapse and have their stars give rise to supernovae that collectively pollute the more slowly evolving parts of the association (Reeves, 1978). Under these circumstances, some of the "anomalous" meteorite inclusions might be more representative than the solar system average of the composition of the general interstellar medium (Olive and Schramm, 1982).

And finally, the radioactive decay time scales tell us only the interval from synthesis to final solidification. The interstellar medium is about 1% (by mass) dust grains, made almost entirely of heavy elements in poorly known proportions. These necessarily solidified somewhere—*in situ*, in giant molecular clouds, in atmospheres and winds of cool giant stars, in nova or supernova ejecta (Hoyle and Wickramasinge, 1970), or somewhere. The "best-buy" model supposes that all the interstellar grains incorporated into the solar system vaporized along the way and were resolidified, with chemical fractionation based on solidification temperatures, as the planets and meteorites formed. But we do not know this. The alternative is the incorporation of unmelted presolar grains (Black, 1972; Clayton, Grossman, and Mayeda, 1973). If this occurred wholesale, then the radioactive time scales tell us nothing about the formation of the solar system; and the evidence for a supernova trigger largely disappears. Many of the observed properties of meteorites and their anomalous inclusions (summarized, e.g., by Wasserburg and Papanastassiou, 1982) are equally well explained by this alternative hypothesis (Clayton, 1979, 1980, 1982, and in NATO81). It is the only rational explanation for components with excess Ne^{22} (Black, 1972; Clayton, 1975), as the progenitor (Na^{22}) half-life is 2.6 yr.

This scheme requires that solidification occur quite soon after nucleosynthesis in supernovae, at least for anomalous isotopes with short progenitor half-lives. There is, indeed, dust around some Type II supernovae within months after the explosion, for we see its infrared emission (Dwek *et al.*, 1982, and references therein). Unfortunately, the current "best-buy" model (Dwek, 1982) says that the dust is not formed in the outgoing supernova envelope gas, but is part of a circumstellar shell ejected earlier by the parent star. Thus the grains we see now cannot be locking up anomalies for future generations of meteorites!

We all have to vote on this one every time we teach planetary astronomy, stellar evolution, or geophysics. So far, I've always voted for supernova triggering for the formation of the solar system because it makes such a tidy picture, with first and last things closing on themselves in a loop. But it may not be right.

H. Supernova-triggered galaxy formation

Galaxy formation is, if anything, even less well understood than star formation, and so provides a still wider frame for speculative pictures. Ikeuchi (1981, and in NATO81) and Ostriker and Cowie (1981; Ostriker, in NATO81) have proposed that supernovae may be an important contributor. Normally, one supposes that expanding supernova remnants remain confined within their parent galaxies, so as to heat and stir the interstellar medium (Sec. VII.F) and enrich it in heavy elements (Sec.

VII). At early times, however, the supernova rate was large enough that the expanding remnants may have joined to form a blast wave moving out from the galaxy as a whole, carrying some 10^{60-62} ergs.

The outgoing blast wave blows a hole in the surrounding gaseous intergalactic medium, until it stagnates, leaving an annulus of dense, cooling gas that can collapse and fragment into new galaxies in considerably less than the Hubble time. The fragment masses are typically of galactic size ($10^{9-12}\ M_{\odot}$) for events occurring after a redshift of 6. In this way, a single, randomly arising, seed galaxy can trigger the formation of many others, which may themselves trigger another generation, so that the hole continues to grow. The model provides a good match to the observed correlations between the mass of a "daughter" galaxy and the velocity dispersion within it (Ostriker, in NATO81; Vishniac, Ostriker, and Bertschinger, 1982).

Galaxies produced by this mechanism will be distributed in space as shells around large, relatively vacant regions, whose size scale is set when the rate at which the hole is expanding ceases to be larger than the difference in Hubble velocity across its diameter. The result is $23(100/H_0)(\epsilon/10^{-4})^{1/2}$ Mpc, where ϵ is the efficiency with which rest-mass energy inside the hole gets turned into blast-wave energy. This is not a bad match to the largest-scale structures so far reported (Einasto, Joeveer, and Tago, 1978; Davis *et al.*, 1981; Kirshner *et al.*, 1981). The holes should not be completely empty, as they will contain the seed galaxy and daughters of all generations but the last.

There is at least one obvious objection to the model. The energy required for the blast wave corresponds to all that is available from supernovae that made the heavy elements in the inner $10^{11}\ M_{\odot}$ of a typical galaxy (most of the region we see). If all the material expelled by these supernovae is mixed into intergalactic gas at each generation, then the participating galaxies would not be able to build up a gradually increasing internal metal abundance with the radial gradient seen in many objects (and normally explained by supernova ejecta flowing *inward* toward the galactic nucleus). This rather spoils the nice agreement between observations and models found in the usual picture of galaxy evolution (Tinsley, 1980). The two obvious ways out are that either (1) all the galaxies we have studied carefully are, by chance (?), last-generation objects that retained their SN-ejected gas, or (2) most of the gas in all cases really falls back into the galaxy (along its rotation axis?), while a small amount carries virtually all the energy outward. Ikeuchi (in NATO81) has addressed this latter possibility with a "fountain" model.

Many of the consequences of supernova-triggered galaxy formation remain to be explored. Currently, at least, the possibility seems to deserve further study, in competition with the other, older models that invoke gravitational instability, "pancake" formation, or cosmic turbulence (reviewed, e.g., by Jones, 1980, and by several speakers at IAU Symposium No. 104, Abell and Chincarini, 1983).

I. Neutron stars and pulsars

The literature of this subject is enormous. The following section addresses only the questions of whether, when, and where neutron stars and pulsars are the products of supernova events. For an initial probe of other aspects of the objects, the monographs by Smith (1976), Taylor and Manchester (1977), and Irvine (1978), and the conference proceedings edited by Gursky and Ruffini (1975), Giacconi and Ruffini (1978), Smarr (1979), and Sieber and Wielebinski (1981) are recommended. A discussion of models that aspire to make neutron stars via Type II supernova explosions appears in Sec. IV.B of Part I.

1. The Crab nebula

Baade and Zwicky (1934) proposed the basic identity "supernova = formation of neutron star." And Baade (1942) and Minkowski (1942) pointed to a particular ("south preceding") star near the center of the Crab Nebula as the probable culprit for SN 1054. All concerned were gloriously entitled to say "I told you so" when Cocke, Disney, and Taylor (1969) showed that the pulsar NP 0532 was indeed that bright particular star. No one, so far as I know, has subsequently doubted that the pulsar and nebula were born together, as they are much the same age (e.g., Ostriker and Gunn, 1969) and more or less in the same place (e.g., Minkowski, 1970).

The identification of the remnants with the 1054 event continues to be debated from time to time. Ho, Paar, and Parsons (1972) believe that they are not in the same place, the event having been seen "several inches southeast of T'ien-kuan," and the Crab now being about a degree northwest of Zeta Tauri. I am clearly not competent to judge whether Chinese scribes always got their directions right or whether T'ien-kuan is precisely the same as Zeta Tauri. Needham (1957, 1970) thought it was all all right, though he heartily disapproved my pronounciation of T'ien-kuan and the rest.

Williams (1981), a historian of science, remains puzzled by the positional discrepancy, and also questions whether the 1054 event was as bright as generally advertised, on the grounds that "visible by day like Venus" may have been a late interpolation into one of the accounts of the sighting. Williams in addition believes that the birth of the nebula and the historical sighting occurred at different times; but he has neglected to allow for the magnetic field and relativistic electrons within the nebula. These both produce the observed synchrotron radiation and result in an outward pressure of the right size to accelerate the nebula expansion to its present value, starting in 1054. Woltjer (1958) first did the calculation. It still works nicely with more recent numbers for the expansion velocity, mass, field strength, and so forth.

If the 1054-Crab-0532 association is not correct, then we have no firm evidence for any supernova ever having made a neutron star anywhere. Modern astrophysics could probably survive this blow. But my view is that the chances are very small of two supernovae having occurred within about 100 yr and 1000 pc of each other, one of which was not seen, and one of which left no remnant.

2. Other pulsars

The 0.089-s pulsar 0833-45 is well within the Vela supernova remnant (Large, Vaughn, and Mills, 1968), at about the same distance (Kristian, 1970), and of approximately the same age (Shklovskii, 1970). And the 0.15-s pulsar 1509-58 (Manchester, Tuohy, and D'Amico, 1982) is well within the SNR MSH 15-5(2), but is not obviously of the same age. The measured $\dot{P}$ implies a lifetime of only about 1600 yr for the pulsar (Seward and Harnden, 1982), while the age of the remnant is greater than 10^4 yr. These are the only other generally accepted pulsar-SNR identifications.

No radio pulsar has been found at the locations of the events of 185, 1006, 1181, 1408, 1572, 1604, or 1680, independent of whether all were "real" supernova or whether all their remnants have been correctly identified. The upper limits are well below any reasonable expectation based on the observed fluxes of the Crab and Vela pulsars.

Among older remnants and longer-period pulsars, there are a number of two-dimensional positional coincidences (Morris *et al.*, 1979; Jones, 1974, 1975) and some three-dimensional ones (Morris, Radhakrishnan, and Shukre, 1978). None of these involves a Crab-like (filled-center; plerionic) SNR (Caswell, 1979; Weiler and Panagia, 1980); and all have the $P/\dot{P}$ ages of the pulsars considerably greater than the expansion ages of the remnants, except for PSR 0748-28 ($P=0.167$ s, $P/\dot{P}\sim 10^5$ yr), which is probably rather younger than the superposed H I shell, GS 241-01 + 15, whose size is that of a 10^{6-7}-yr old SNR (Stacy and Jackson, 1982). At least two other SNR's, 4C21.53 and G78.1 + 1.3, contain compact, steep-spectrum radio sources, which could be pulsars of large dispersion measure (Erickson, 1980; Cordes and Dickey, 1979). The latter shows interstellar scintillation, and so has angular diameter $\lesssim 10^{-6\prime\prime}$ and linear diameter $\lesssim R_\odot$. One other pulsar, 0656-14, is at the center of a 50-pc x-ray ring, which could be a $(6\text{--}9)\times 10^4$-yr old supernova remnant (Nousek *et al.*, 1981). The pulsar does not have a measured rate of period change, but its 0.385-s period is at least plausible.

A particularly significant nonidentification is that of PSR 1930 + 22, which is not surrounded by a supernova remnant, to a flux level $\frac{1}{6}-\frac{1}{8}$ of that expected from its $P/\dot{P}$ age of 3.6×10^4 yr (Goss and Morris, 1980). We return to the meaning of these (non)associations in Sec. VI.I.4. The short-period binary pulsar has apparently been spun up by mass transfer and so is too old for an SNR to be expected (Taylor and Weisberg, 1982).

3. Other neutron stars

Neutron stars that do not emit pulsed radio waves (for whatever reason) may nevertheless emit detectable radiation due to accretion, cooling, or both (see Sec. VI.E.3.*b*), though their small size means that the effective temperature must be high enough that most of the radiation comes out as x rays for luminosities $\gtrsim 10^{-2}\,L_\odot$. In addition, a pulsar beamed away from us can be expected to power a small but extended x-ray source (Blandford, Ostriker, and Rees, 1973; Gopal-Krishna, 1978). Finally, one might deduce the existence of a central pulsar indirectly, as in the case of the SNR G21.5-0.9, whose x-ray-emitting electrons seem to have a lifetime of only a few years (Becker and Szymkowiak, 1981).

The best candidate for an accretion-powered neutron star in an SNR is perhaps the 3.5-s pulsed x-ray source in G109.1-1.0 found by Fahlman and Gregory (1981). The optical counterpart, with $m=+22$ and $M\sim +6$ (Fahlman *et al.*, 1982) has yielded an orbit with $P=6870$ s and $a_x \sin i=1.5\times 10^{10}$ cm, eccentricity $=0.3$–0.9, some evidence of perihelion advance at the expected ratio of 2°/orbit, and a mass function of 0.21 $M_\odot$, meaning 0.5 $M_\odot$ for the companion, if the neutron star has 1.4 $M_\odot$ (Gregory, 1982). The infrared emission pulsates at the x-ray period, and the optical emission is expected to, but has not yet been investigated. The system presents two puzzles—the rather peaceful appearance of the binary system, given that the surrounding remnant is only about 10^4 yr old, and the small total mass of the presupernova star (<3.5 $M_\odot$) implicit in the requirement to eject less than half the initial binary mass to prevent unbinding the system. And then there is always SS 433 (Beer, 1981), though the compact object may be a black hole rather than a neutron star, the putative supernova remnant W50 may be more the product of continuous ejection from SS 433 than of a discrete supernova event; and we don't really know that it is powered by accretion.

Several other supernova remnants show compact or at least concentrated x-ray emission near their centers. The ones of which I am aware are, in order of decreasing x-ray luminosity, the Crab, G21.5-0.9, MSH 15-52, 3C58, G74.9 + 1.2, Vela, CTB 80, and G326.3-1.8 (Tuohy and Garmire, 1980; Lamb and Markert, 1981; Becker *et al.*, 1982; Helfand, 1980, 1981, 1982). This sequence joins smoothly onto that of small, but extended, x-ray sources identified with known pulsars (1055 − 52, 0355 + 54, and 1642 − 03). The 0355 + 54 source is extended along the proper-motion vector of the pulsar, and its length is just equal to the distance the pulsar has traveled in the synchrotron lifetime (40 000 yr) of electrons radiating at the observed frequency ($\sim 2.5\times 10^{17}$ Hz) in an interstellar field of 1 μG. The strong implication (Helfand, 1982) is that all or most of these are indeed synchrotron sources due to particles accelerated by neutron stars of various ages, radiating in the field of a surrounding supernova remnant or the general interstellar medium, as suggested by Blandford, Ostriker, and Rees (1973). 3C58 and CTB 80 have been advertised as the remnants of supernovae 1180 and 1408, but are not so regarded by Becker *et al.* (1982), who found the x-ray emission (cf. also van den Bergh, 1981).

All other SNR's, including the securely identified historical ones (1006, 1572, 1604, Cas A), have so far yielded only upper limits, some of them low enough to rule out neutron stars cooling in the conventional way (Nomoto and Tsuruta, 1981).

4. Statistics and models

The individual examples of SN-NS associations are neither very numerous nor wholly unequivocal. Can we do better on statistical grounds? Possibly. Large, Vaughn, and Mills (1968) were among the first to note that if one supernova each 100 yr makes a pulsar, then pulsars must remain detectable for about 10^7 yr. Subsequent age determinations (from period derivatives and proper motions) show that they do, more or less. The approximate statistical agreement has persisted (Large, 1971; Guseinov and Kasumov, 1978; Gailly, Lequeux, and Masnou, 1978; Chevalier, 1981; Lyne, 1982), with a brief interruption (Taylor, 1977) when the pulsar birthrate got out of hand at $\frac{1}{6}$ yr or so, owing to incorrect treatment of old, faint, nearby objects.

The temporary discrepancy between high pulsar birthrate and lower supernova rate prompted several models for hiding supernovae. The "silent" ones (core collapse with little envelope ejection) appear in Sec. IV.C.2 of Part I (Miyaji *et al.*, 1980; Ivanova, Imshennik, and Chechetkin, 1978); and Wheeler, Mazurek, and Sivaramakrishnan (1980) and Shull (1980) model events exploding inside giant molecular clouds, which would show up only as infrared sources. Support for their occurrence is provided by the correlation between ages of young, open clusters and the presence or absence of gas therein (Wheeler and Bash, 1977). A supernova might also hide inside the dust of a circumstellar shell shed by the parent red supergiant. Morris and Jura (1982) have suggested this could eventually happen to NML Cygni.

This year's pulsar birthrate of about $\frac{1}{30}-\frac{1}{40}$ yr (Lyne, 1982) is once again in reasonable accord with the supernova rate, or, at worst, a bit larger than the Type II supernova rate (Tammann, in NATO81). The birthrate of neutron stars in binary systems that remain bound and keep up the supply of accretion x-ray sources is, at most, a 10% increment to the pulsar birthrate (van den Heuvel, 1978).

What, then, do we do about the lack of individual correlations? The first remark is also statistical in nature—most cataloged pulsars are nearby, old objects, and their remnants should long ago have faded away (but note the exception in Sec. VI.I.2); and most cataloged supernova remnants are bright, distant objects whose pulsars or neutron stars would be too faint to see (but note the exceptions among the historical and other young remnants).

Beyond this, we can go in several directions. Most of the early discussions focused on the beaming of pulsar emission, which, if cone shaped, results in about one object in five pointing at us. Among the historical SNR's, 1:7 is clearly 1:5 within astrophysical accuracy. The absence of thermal x rays from neutron stars in the young remnants has gradually pulled attention away from beaming.

Weiler and Panagia (1978, 1980) deduce a one-to-one correlation between having a neutron star (which is usually a pulsar, even if beamed away from us), being a filled-center remnant, and coming from a Type II supernova. This accords with both radio and x-ray data. Filled-center remnants are, however, rather rare. Thus most of the conspicuous, long-lived remnants we see must have come from Type I events.

Amnuel' and Guseinov (1974), Radhakrishnan and Srinivasan (1981), and Lominadze *et al.* (1980) take the opposite tack and put a neutron star in every remnant, which in some sense is powered thereby, but allow only a subset of the neutron stars to put energy into relativistic particles, so as to show up as pulsars and plerions. The others put out only electromagnetic radiation at the rotation frequency, which then makes a shell-type remnant. Kochhar (1981) is still more generous with neutron stars, and attributes filled remnants to the second one formed in a close binary system (hence the pulsar/SNR age discrepancies in most of the suggested identifications). Litvinova and Nadyozhin (1982) permit only linear-light-curve SN II's to make neutron stars.

All these hypotheses have in common the implication that the approximate agreement among rates of supernova events, pulsar births, and remnant formation (Sec. III.A.1 of Part I) is more or less a coincidence. We should, therefore, be able to point to specific cases of each of the three happening without the others. We can to a certain extent. Cas A (Chevalier, 1981) was, at least, not the product of a normally bright SN. Chevalier attributes it to a very massive star that lost its hydrogen-rich envelope before being disrupted, perhaps by an electron-positron pair production supernova (Sec. II.A.1 of Part I). PSR 0802 + 02 is, according to Shklovskii (1980), the product of a core collapse that made no classical supernova or remnant. And PSR 0656 − 14 (Goss and Morris, 1980) lacks a supernova remnant of its own age.

There are no clear cases of SN + PSR (pulsar) without SNR or of supernovae that left neither pulsars nor remnants. MSH 15-5(2) + PSR 1509-58 is, however, a case of SNR + PSR without SN, if (a) the age is really the 1600 yr implied by $\dot{P}$ and (b) the remnants are not those of SN 185 (about 5° away, according to Clark and Stephenson, 1977). The chief problem in sorting out which combinations are possible and what stellar populations might produce each is the woefully inadequate data base of historical supernovae of known type (zero to seven, depending on your prejudices).

5. Sorting out the mess

The next galactic supernova, whenever it may come, cannot disentangle the supernovae, SNR's, and PSR's for us, as it can belong to (at most) one of the possible types. We must go outside the Milky Way. Some bits of data already exist. We know there are x-ray binaries and filled-center remnants in the Magellanic Clouds (Long, Helfand,

and Grabelsky, 1981). But SN 1885 in M31 has yet to show any signs of developing a remnant that could grow into Cas A. And the radio emission from extragalactic supernovae, though blamed on a young pulsar by Pacini and Salvati (1981) and Shklovskii (1981), clearly does not look like it could evolve smoothly to match either Cas A or 0532 (Fig. 3).

What would help? Clearly we need better statistics of rates and types versus galaxy type (see Sec. VIII.B below) and data outside the optical range on many more events. IRAS should be able to see extragalactic supernovae that go off inside dense molecular clouds (Shull, 1980), thus either confirming or ruling out rates large enough to make pulsars and remnants separately. It would be nice to know whether or not there are x-ray binaries in elliptical galaxies (thus constraining the NS$=$SN II hypothesis). This probably requires going outside the Local Group, as the dwarf spheroidals are so low in mass that one expects none, even if the normalized birthrate were as high as in the Milky Way. The required detector sensitivity is rather less than 10^{-6} Crab Nebulas and will not be achieved by anything ahead of AXAF (Holt, 1981). Extragalactic pulsars are even more intriguing and at least as difficult. An 0532 in Andromeda will be 10^5 fainter than ours, again out of range of x-ray missions in this decade and radio collecting areas smaller than Project Cyclops. The x-ray emission from the remnants of extragalactic supernovae that went off early in the century might be as high as 10^{39} ergs/s and within the range of recently past and projected detectors, but so far none has been seen (Canizares, Kriss, and Feigelson, 1982)

Clearly the associations among supernovae, pulsars, and remnants that we would like to know and understand cannot be pinned down unambiguously in the near future. Meanwhile I am inclined to meditate on a remark of van den Bergh (1977): You'd be amazed how often the conventional view turns out to be right.

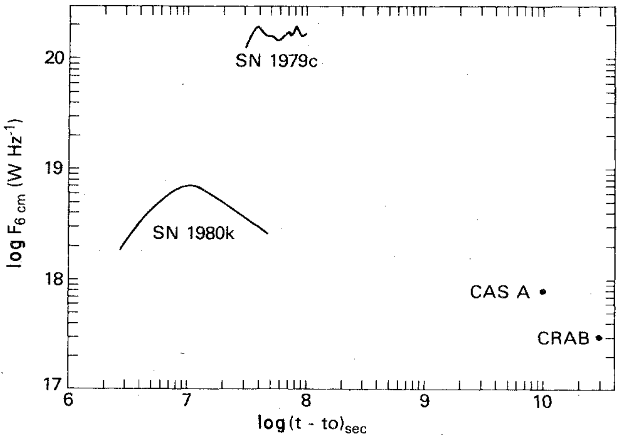

FIG. 3. Evolution of the 6-cm radio power from the extragalactic supernovae 1979*c* and 1980*k* (data courtesy of K. W. Weiler). The isolated data points at 300 and 1000 yr are for Cas A and the Crab pulsar at the same frequency. Neither seems to be a natural extrapolation of the extragalactic objects' radio power evolution, which, therefore, probably represents a completely separate physical phenomenon.

VII. NUCLEOSYNTHESIS AND GALACTIC EVOLUTION

Nucleosynthesis means the transformation, in an astronomical context, of various sorts of nuclides into other sorts of nuclides, mostly but not exclusively light ones into heavy ones, so as to yield the abundance patterns we see around us. This leaves nucleogenesis to mean the formation of nucleons out of other things or nothings. This is, to say the least, an important problem, but it is not ours here. (Sato, 1982, and Schramm, 1982, are good places to start to probe it.)

Burbidge, Burbidge, Fowler, and Hoyle (1957;B^2FH) and Cameron (1957) erected the basic framework of nuclear reactions and their siting in stars that allows us to say with some confidence that, in a general sort of way, we understand nucleosynthesis. It occurs in stars, mostly massive ones, and its products are ejected, mostly in supernovae.

The next scientific generation saw this framework largely covered with a superstructure of galactic evolution models that enables us to say that we understand, again in a general sort of way, how populations of stars change with time, each generation feeding the next, so as to produce galaxies with the chemical (and some of the dynamical) properties that we see. This advance was due in unusual measure to the work of one person, the late Beatrice M. Tinsley (1968, 1971, 1972a, 1972b, 1973, 1975a, 1975b, 1977, 1978, 1979, 1980b, 1981).

Reviews of nucleosynthesis and galactic evolution have appeared in these pages (NATO74) and elsewhere (Tinsley and Larson, 1977; Ahrens and Protas, 1979; Tinsley, 1980; Strom and Strom, 1982) in recent years. The sections that follow focus on aspects of the subject that seem to be coupled particularly closely to the problems of understanding supernovae.

A. The grand scheme

According to the framework established by B^2FH and later work, the elements and isotopes we see can be subdivided into about 11 groups, categorized by the dominant process producing each and the places where that process occurs. Table III shows that subdivision. "Massive" stars are those whose cores burn through to iron and collapse, giving rise to Type II supernovae, according to the scenario presented in Sec. II.A of Part I. "Intermediate-mass" stars range from 1 to 6 or 8 $M_{\odot}$. They have lifespans less than the age of the galaxy, but are not expected to make Type II supernovae via core collapse.

The basic scheme is still in reasonably good condition, in the sense that it is possible to put together populations of stars that, over the age of the galaxy, will combine their products, direct and indirect, with those coming out of the Big Bang to add up approximately to what we see around us (Arnett, 1978; Tinsley, 1980; Wheeler, 1981; Tutukov and Krügel, 1981; Twarog and Wheeler, 1982)

TABLE III. Outline of nucleosynthesis: elements and isotopes classified by dominant production mechanism and site.

Products	Process	Site
H,He	Cooling from thermodynamic equilibrium at $\gtrsim 10^9$ K	Early universe (big bang)
Li,Be,B	Spallation of C,N,O	Cosmic rays hitting interstellar gas
C^{12},O^{16}	Helium burning	Intermediate and massive stars
C^{13},N^{14},N^{15}	Hydrogen burning by CNO tricycle	Cores of massive stars; shells of intermediate-mass stars
O-Ne[a]	Carbon burning	Massive stars
Mg group[a]	Neon burning	Massive stars
Si group[a]	Oxygen burning	Massive stars
Iron group[a]	Silicon burning Carbon-oxygen deflagration	Massive stars Type I supernovae
Most tightly bound isotopes of elements beyond iron	Slow addition of neutrons to iron-group seeds (*s* process)	Intermediate and massive stars
Neutron-rich isotopes of heavy elements	Rapid addition of neutrons to iron-group seeds (*r* process)	Type II supernovae (?)
Neutron-poor isotopes of heavy elements	*p* process (addition of protons to, or removal of neutrons from, products of *s* and *r* processes)	Type II supernovae (?)

[a] Abundances are fine tuned by explosive nucleosynthesis processes as supernova shock moves out through star.

without grossly contradicting other things we think we know. The observations agree with the models, for instance, in distinguishing primary nuclides (which can be made from H and He in a single generation of stars) from secondary ones (which can only be made in a second or later generation from products of the first one). The secondary, *s*-process products are more deficient in the oldest stars than are the primary, *r*-process ones (Spite and Spite, 1978). The same applies to other nuclides like Na and Al, whose production depends on the initial metal abundance of the synthesizing star, vs Mg, whose production does not (Tomkin and Lambert, 1980). And the relative abundances of C, O, and Fe in stars as a function of age strongly suggests that, within the first generation or two, the most massive stars contributed their products first (Wheeler, 1981), as is proper, since they have the shortest lifetimes. These early generations probably also had different relative proportions of high- and low-mass stars than those being born today (Wheeler, 1981), which is also not unexpected.

B. Massive population I stars (SN II progenitors)

Arnett (1975, and references therein) pioneered calculations of the products of hydrostatic helium, carbon, neon, oxygen, and silicon burning in stars as a function of mass. His initial models were helium cores, with the calibration of helium core mass to initial main sequence mass necessarily somewhat uncertain. The chief result was that the main groups of elements from carbon to iron could be produced in essentially their observed cosmic proportions by a mix of 12—70 $M_\odot$ stars (2—32 $M_\odot$ cores), half the synthesis being contributed by stars below about 22 $M_\odot$ and half by those above. Systematically, the lower masses expelled larger proportions of light elements (C,O,Ne) and the higher masses larger proportions of heavy elements (Si—Fe). And the gross match between synthesis products and observed abundances could be fine tuned by explosive burning as a supernova shock wave passed out through the star, to give detailed matches to both elemental and isotopic abundances (Woosley, Arnett, and Clayton, 1973).

The work since NATO74 has provided, in the main, confirmation of these results. Lamb, Iben, and Howard (1976) followed a 25 $M_\odot$ Population I star from main sequence hydrogen burning, not quite to core collapse, but far enough to confirm the general structure of heavy-element synthesis and Arnett's calibration of the core-mass—to—total-mass relation. The 15 $M_\odot$ star modeled by Sparks and Endal (1980) made less of everything than the corresponding Arnett star only because it had a smaller convective core at all stages. This was a direct result of their choosing a different set of hydrogen reaction rates and a larger initial metal abundance.

Weaver, Zimmerman, and Woosley, (1978) have followed 15 and 25 $M_\odot$ Population I stars, with hydrogen envelopes intact, from the main sequence to core collapse, and the larger mass on through a simulated supernova explosion (Weaver and Woosley, 1980; Woosley and Weaver, 1982a, 1982b, and in NATO81), incorporating an improved treatment of convection and semiconvection, as well as a more elaborate nuclear reaction network. They find, on the whole, good agreement with earlier results and with observed values both for relative proportions of light and heavy metals and for individual isotopes.

The 25 $M_\odot$ stars of Lamb, Iben, and Howard (1976) and Woosley and Weaver (in NATO81) both make some *s*-process isotopes, especially those just above iron. Nuclides in the range $A=69$—77 are also made by explosive carbon burning as the SN shock moves out through the star's carbon-rich zone (Wefel *et al.*, 1981). Most *s*-

process material, especially the heavier elements, must still come from intermediate-mass stars, as the larger ones make neither enough nor the right isotope ratios. The rearrangements during explosive burning can produce several other interesting species. These include Li^7 and B^{11}, provided that the shock is strong enough (Epstein, Arnett, and Schramm, 1976), and Al^{26} in either the explosive hydrogen-burning zone (Arnould *et al.*, 1980) or the carbon and neon zones (Morgan, 1980). The former are interesting because neither the big bang nor cosmic-ray spallation makes quite as much of them as we see. The latter is important because of its 10^6-yr half-life, which makes it a useful clock for the early history of the solar system (Sec. VI.G).

None of the models extended as far as core collapse has yet included explicit mass loss, although OB main sequence stars and their supergiant descendants are seen to be shedding winds substantial enough to reduce their masses by 10—50% over their lifetimes. The omission is not a fatal one, however, as the core of a star is largely blind to mass loss after the completion of hydrogen burning, while that occurring earlier tends to make the star mimic one of smaller initial mass. And the mix of star masses used in models of galactic evolution is determined observationally, by looking around at stars that are, on average, about halfway through hydrogen burning. Thus the "initial-mass function" found already reflects part of the effect of mass loss.

Nucleosynthesis in single, massive, Population I stars appears to be reasonably well under control, though calculations, especially for the less common isotopes, will inevitably improve as better laboratory cross sections for the relevant reactions are measured and as greater computing power makes possible more exact treatments of semiconvection, meridional circulation, and other effects now included only approximately. A detailed calculation of synthesis by a nonspherical, rotating magnetic star is probably still far in the future. The hydrostatic stages should not be grossly changed by the amounts of rotational and magnetic pressure support implied by observations of real stars. But explosive nucleosynthesis could be very different if the basic ejection mechanism is highly aspherical, as Ardelyan *et al.* (1979) and others believe it may be.

C. Other massive stars

Back in 1972, Tinsley (private communication) remarked that the largest gap in galactic evolution calculations came from lack of information on evolutionary tracks and nucleosynthesis for massive stars with low initial metal abundances (Population II). The gap is filling only rather gradually. There are evolutionary tracks extending as far as carbon ignition for about a dozen masses (Wagner, 1978; Alcock and Paczyński, 1978; Harris and Deupree, 1976; Dearborn *et al.*, 1978, 1980; Brunish and Truran, 1982, and references therein), which show that massive Population II stars are bluer, brighter, have larger convective cores, and ignite helium nearer the main sequence than Population I stars of the same mass. And they produce a higher ratio of helium to heavy elements.

Detailed nucleosynthesis has been explored only for one 25 $M_\odot$ star (Woosley and Weaver, 1982b). It made more helium and carbon but less oxygen, neon, magnesium, silicon, and sulfur than the corresponding Population I star followed with the same evolutionary code. In addition, the Population II star made less of the neutron-rich isotopes of light elements (O^{18}, $Mg^{25,26}$, etc.) because the low initial CNO abundance meant less C^{13} and Ne^{22} available later in the outer zones to supply neutrons by the $C^{13}(\alpha,n)O^{16}$ and $Ne^{22}(\alpha,n)Mg^{25}$ reactions. Finally, nuclei synthesized in Population II stars ought to show an enhanced odd-even effect (that is, smaller than normal ratios of odd-A nuclides like Na^{23} and Al^{27} to the adjacent even-A nuclides Mg^{24} and Si^{28}; Pardo, Couch, and Arnett, 1974; Woosley and Weaver, 1982b). Predictably, one set of data shows the advertised effect (Peterson, 1980) and another does not (Spite and Spite, 1980).

Most models of galactic evolution do not yet incorporate these differences in evolution and nucleosynthesis between Population I and Population II stars. The omission remains a potentially major source of error and uncertainty (Tinsley, 1980), since, of necessity, at one time in galactic evolution, all the stars were metal poor.

The other relatively neglected class is massive stars in close binary systems. Their omission from galactic evolution models is, *a priori*, less serious than that of the Population II stars, as they are rather less than 50% of the massive stars at all times. Evolutionary tracks for them abound (see Sec. II.B of Part I). Luminosities and colors differ from those of single stars because energy is gained and lost with the gas that flows between the stars and out of the system. The qualitative effect on nucleosynthesis is obvious—when the stars begin life close enough together that mass transfer occurs during hydrogen burning, the larger star in effect turns into a smaller one, and conversely. Mass lost completely to the system at this stage will reduce total synthesis. A detailed quantitative study (Vanbeveren and Olson, 1980) indicates that mass loss at the rate implied by observed binary colors and luminosities reduces metal production so much that these stars contribute hardly at all to nucleosynthesis (except of helium) over the life of the galaxy. We do not really lose a full factor of 2 in metal production, though, as the reduced masses are already partly accounted for in the way the stellar birthrate function is determined, as for the case of mass loss from single stars (cf. Miller and Scalo, 1979, for instance).

D. Type I supernovae

Carbon (or oxygen) detonation (or deflagration) supernovae, whether in single stars or binaries, of necessity make large quantities of explosive carbon-burning products, mostly Ni^{56}, which decays in due course to Fe^{56} (Sec. IV.C of Part I). Most models disrupt the exploding star completely, and the products therefore all contribute to nucleosynthesis. At least 0.3 $M_\odot$ of Ni^{56}, and possibly more like 1 $M_\odot$, must, in any case, be ejected to make the

Type I light curve come out right in most models (Sec. III.C.1 of Part I; Shklovskii, 1981a), even if the stellar core remains bound (Sec. IV.D of Part I). Given a Type I rate in the Milky Way of at least one per century, we find that SN I's could easily make all the iron in the galaxy—and then some, if we are not careful (Tinsley, 1980a). This is all right, in the sense that spectra of Type I's in external galaxies do show evidence for lots of iron (Sec. III.B.3 of Part I). And the amount of iron contributed by massive stars could be small, as it depends very much on the exact mass of the core that remains bound after an SN II (Woosley and Weaver, 1982b). But we remain puzzled at the scant evidence for excess iron in any supernova remnant where it has been looked for (Sec. V.D above).

No one has yet explored in detail the other products of Type I's. The carbon detonation should, however, act very much like explosive carbon burning as studied in other contexts (Arnett, Truran, and Woosley, 1971; Mazurek and Wheeler, 1980) and so yield close to a solar mix of the abundant isotopes of Cr, Mn, Fe, Co, and Ni (Woosley and Weaver, in NATO81). Explosive burning of an outer, helium-rich zone in a detonating star makes enough Ca^{44} (as Ti^{44}, which decays, providing a late-time energy source for the remnant) to account for this otherwise underproduced nucleus (Woosley and Weaver, in NATO81; cf. NATO74). Other models (Nomoto, 1982) leave part of the envelope unburned or partially burned and so can eject a few tenths of a solar mass of C, O, Ne, etc. This contribution is much smaller than that coming from massive stars. Those detonations triggered by helium shell flashes on accreting white dwarfs will also contribute some *s*-process material (Fujimoto and Sugimoto, 1982), but again probably not the dominant component.

E. Other sites of nucleosynthesis

Massive stars and supernova explosions are, obviously, not the only places where nuclear reactions and so nucleosynthesis occur. The early universe makes all the elements up to helium (Alpher, Bethe, and Gamow, 1948; Wagoner *et al.*, 1967; Schramm, 1982) plus, perhaps, as much Li^7 as is seen in the oldest, metal-poor stars (Spite and Spite, 1982; Yang *et al.*, 1979); and cosmic-ray spallation of CNO in the interstellar medium is probably the dominant source of lithium, beryllium, and boron (Reeves, 1974). The following sections address nucleosynthesis sites that are, in some sense, in direct competition with supernovae.

1. Pregalactic and supermassive stars

A modest amount of nucleosynthesis before the galaxies acquired their identities would be from several points of view a good thing. It would obviously account for our never having found any stars in our galaxy with zero metals (Bond, 1981) and for the relative scarcity of stars with low metal abundances (Truran and Cameron, 1971). In addition, pregalactic stars can contribute helium to the store coming from the big bang, some portion of the radiation we now see as the $3K$ background, and enough dust to affect the spectrum of that background (Rees, 1978; Rowan-Robinson, Negroponte, and Silk, 1979). Carr, Arnett, and Bond (1982) discuss some of their other virtues.

There are several reasons to suppose that such pregalactic stars might be wholly or partly of very large masses. First, we do not see any low-mass stars left from that era (Population III). Second, the minimum mass unstable to gravitational collapse (Jeans mass) increases as metal abundance (the primary source of cooling) goes down. And third, stars of more than $\sim 100\ M_\odot$ are now rare or nonexistent, and it would be a shame to waste all the work done on them.

Ober, El Eid, and Fricke (1982) and Woosley and Weaver (in NATO81) have evolved stars in the mass range 100—500 $M_\odot$ (cf. Sec. II.A.1 of Part I). They find that hydrostatic burning is terminated by a pair-creation instability while the core still consists largely of oxygen. Thus the primary nucleosynthesis products are oxygen and its burning products. This accords nicely with the observation that very old stars, while deficient in both oxygen and iron, often have the ratio O/Fe larger than that in the sun (Sneden, Lambert, and Whitaker, 1979). The most massive stars evolved may also produce primary nitrogen, for which there is some evidence among the oldest stars (Barbuy, 1981) and from observed abundance gradients in several galaxies (Blair, in NATO81).

Interesting amounts of nucleosynthesis occur if about 1% of the mass that ended up in our galaxy went through very massive stars first (Ober, El Eid, and Fricke, 1982). Useful production of helium and radiation requires a larger throughput—50% to 100%. The fraction of heavy elements produced before the era of galaxy formation can, in principle, be deduced by the effects on the spectrum of the $3K$ background radiation, given rather more accurate data than are at present available (Varshalovich, Khersonskii, and Sunyaev, 1982).

2. Intermediate-mass stars

Intermediate-mass stars are, by our definition, those that burn hydrogen and helium hydrostatically, but nothing else (Sec. II of Part I). They must, then, synthesize helium, carbon and oxygen, nitrogen (in CNO-cycle hydrogen burning), and those heavy elements that can be built up from iron (etc.) seeds by neutron capture on time scales longer than beta-decay lifetimes (*s*-process nuclides). But most of the products will be left behind in degenerate cores after the stars shed their outer layers as planetary nebulae. Nevertheless we have observational evidence that there is some contribution to galactic nucleosynthesis. Both evolved stars and planetary nebulae show abundance anomalies that can be associated with reactions that should occur in these stars. The observations thus tell us that nuclear reaction products are somehow mixed to the surfaces of these stars.

Models are numerous (or perhaps, better, attempts at models, as none really provides a calculated star to match every observed one in mass, temperature, and surface composition). Renzini and Voli (1981) provide a particularly nice set, including the effects of mass loss, convective dredge-up, and burning at the bottom of the convective envelope, in a parametrized format that allows the reader to put in his favorite amounts of these processes. Some parameter sets yield a modest amount of primary nitrogen and C^{13} (cf. preceding section). These models have not yet been folded into a calculation of galactic evolution. The earlier ones of Iben and Truran (1978) have been, and lead to the conclusion that intermediate-mass stars are responsible for about half the C, N, Ne^{22}, and neutron capture products on light nuclides (the rest of these come from massive stars), and most of the *s*-process material in the range $A = 70$—204.

Observationally, some planetary nebulae, like NGC 7027, show precisely the enhancements expected from the mixing out of CNO-cycle and triple-alpha reaction products (Perinotto, Panagia, and Benvenuti, 1980). Others are more complicated (Pottasch, Gilra, and Wesselius, 1982) but not inexplicable.

Evolved stars display a wider variety of enhancements and anomalies. Those of CNO can again be associated with hydrogen and helium burning, though the models do not predict observable effects for stars as faint as some that show them; and not all stars of the same mass and age (e.g., giant members of a single globular cluster) can be doing the same thing (Carbon *et al.*, 1982). This may mean that cluster members did not all have the same initial composition (Peterson, 1980, on sodium, for instance), reflecting supernova-type nucleosynthesis while the cluster was forming. One is thereby tempted to formulate a supernova trigger model of globular cluster formation (cf. Secs. VI.G and VI.H above). The field is wide open.

Apart from CNO, we see several other self-produced compositional anomalies in intermediate-mass stars. These include excess lithium (Lambert, Dominey, and Sivertsen, 1980), presumably Li^7 on theoretical grounds (Canal, Isern, and Sanahuja, 1980), which is, however, probably destroyed before a planetary nebula can be expelled and so does not contribute to the galactic supply. The *s*-process nuclides also appear in various and sundry interesting patterns (cf. NATO74), at least some of which must be intrinsic to the stars. In the case of technetium in giant stars (Merrill, 1952), the half-life of 2×10^5 yr is much less than the ages of the stars. And in the case of FG Sge (Herbig and Boyarchuk, 1968) and perhaps CI Cyg (Audouze *et al.*, 1981; Kenyon *et al.*, 1982) the abundances of some *s*-process nuclides have increased before our very telescopes, in a way that can be at least understood, if not predicted (Sackmann, 1980).

Finally, Nørgaard (1980) has suggested that the double shell burning phase in intermediate-mass stars may produce excess Al^{26}. This could be incorporated into dust grains that survive the planetary nebula stage (many planetary nebulae (PNe) show dust-attributable infrared excesses) and decay to Mg^{26} in those grains. Such dust grains, if incorporated into the condensing solar nebula, would produce Mg isotope anomalies that tell us nothing about the early history of the solar system and are not evidence for supernova-triggered star formation (Sec. VI.G above).

3. Novae

The standard model of classical novae (which are to be carefully confused with recurrent novae, dwarf novae, and several sorts of novalike variables) invokes explosive burning of accreted hydrogen on the surface of a carbon-oxygen white dwarf in a close binary system (Sec. II.B.2 of Part I; Gallagher and Starrfield, 1978, etc.). Insofar as this merely adds to the world's supply of CNO-cycle processing, it is not very interesting nucleosynthetically. Even if typical nova ejecta contain something like 10% CNO (mixed into the accreting material from the surface of the white dwarf, and partially processed), ten events a year over the history of the galaxy contribute less than 1% of the total CNO we see.

The interest arises from the high temperature of the hydrogen burning in novae, which facilitates production of otherwise rare isotopes, including O^{17}, F^{19}, and Ne^{21} (Hoyle and Clayton, 1974), Al^{26} (Wallace and Woosley, 1981), and, just possibly, Ne^{22} (Hillebrandt and Thielemann, 1982). Since some novae, like some planetary nebulae, but unlike Type II supernovae (Dwek, 1982), show evidence for *in situ* grain formation (which can be modeled, sort of; Clayton and Wickramasinghe, 1976; Fujimoto, 1982), this production mechanism, like the production of Al^{26} in red giants (preceding section), reduces the evidence for supernova-induced formation of the solar system.

F. Sites of the *r* and *p* processes

Because iron is the most tightly bound of the nuclides, the building up of heavier elements from it is necessarily endothermic. And, since the Coulomb barrier grows as Z_1Z_2, to assemble them from charged-particle reactions would require temperatures at which photodisintegration would tear things apart faster than they are put together. Thus heavy elements must be formed by neutron capture on iron-peak seed nuclei, unless they result from a process that works down from previously existing heavier nuclides or more neutron-rich material, like prestellar matter (Ambartsumyan, 1954; Ambartsumyan and Mirzoyan, 1982) or neutron star ejecta (Bisnovatyi-Kogan and Chechetkin, 1974; Symbalisty and Schramm, 1982).

The double shell burning phases of both intermediate and massive stars provide a suitable site for the capture of neutrons on time scales long enough that every beta-unstable nucleus can decay before another capture occurs. This slow or *s* process yields a unique nuclide (usually) for each value of A (NATO74, Sec. III.E). We also observe nuclides with larger and smaller numbers of neutrons at given A than found on this unique path. The former are relatively abundant, the latter very rare, and each set requires at least one additional process to make it. B^2FH called them the *r* (for rapid) and *p* (for proton, or possibly photodisintegration) processes. They have generally been supposed to occur in supernovae, as each requires high temperatures and rapidly changing conditions. But identification of the precise sites and reactions involved has proven difficult.

1. The *r* process

Building the observed distribution of neutron-rich isotopes requires exposure of seed nuclei (iron and, perhaps, *s*-process products) to a dense sea of neutrons for about 1 s (the sum of the beta-decay half-lives for the most neutron-rich stable nuclides along the path from Fe^{56} to Pu^{244}). The (n,γ) and (γ,n) reactions need not be in equilibrium (Blake and Schramm, 1976). But the wrong neutron density leads to wrong isotope ratios, and the wrong time scale results in most of the matter getting stuck near the iron peak or most of it piling up around Pb and Bi. The right sorts of conditions occur near the edge of the collapsing iron core of a Type II supernova. Seeds will be abundant and so will neutrons, once electron captures set in.

The trouble is that this zone lies very deep in the star's gravitational potential well, and it is not at all clear that *r*-process material formed there can be got out. And anything energetic enough to toss it out is likely also to be capable of inducing enough nuclear processing to spoil the carefully balanced *r*-process isotope ratios. Finally, if *r*-process material is ejected from just above the neutronized core, then a great deal of iron will also be ejected, and we don't really need it (Sec. VII.D). This last problem disappears if *r*-process material is torn out from neutron stars by interactions in binary systems long after NS formation (Symbalisty and Schramm, 1982).

Hillebrandt and Thielemann (1977) and Truran, Cowan, and Cameron (1978) have suggested a promising alternative site—the region of a massive star that undergoes explosive helium burning as the supernova shock exits. The seeds then include both iron and *s*-process material from the star's hydrostatic evolution. The primary neutron source is $Ne^{22}(\alpha,n)Mg^{25}$.

The difficulties with this site are in getting it to make both enough *r*-process material and the right isotope mix (Blake *et al.*, 1981). Recent changes in both neutron capture cross sections and beta-decay rates (Klapdor *et al.*, 1981) have made the situation look much more promising. Explosive helium burning, either in supernovae (Klapdor *et al.*, 1981) or in low-mass stars that ignite degenerate helium off center (Cowan, Cameron, and Truran, 1982), could be the context in which rapid neutron capture occurs.

2. The *p* process

The neutron-poor (or proton-rich) isotopes of the heavy elements are the least abundant of the stable nuclei (cf. NATO74) and do not dominate any single element. Their abundances are, therefore, known only within the solar system. They could be made from *s*- and *r*-process seeds either by adding protons (Audouze and Truran, 1978) or by knocking off neutrons (Woosley and Howard, 1978). The latter process is perhaps slightly favored by the observed abundance ratio of In^{113}, Sn^{114}, and Sn^{115} (Ward and Beer, 1981).

The site of this process has never properly been established. An important new clue is that some meteorite composition anomalies show clear separation of the *r*- and *p*-process components (Lee, 1979), so that the sites of the two processes must be disjoint and their products not thoroughly mixed at any stage before final solidification. This would be slightly more informative if we knew the site of the *r* process! Weaver and Woosley (1980) and Woosley and Weaver (in NATO81) have found that the neon-rich zone of an exploding massive star reaches the right temperature $[(2-3)\times 10^9 \text{ K}]$ for photodisintegration to yield *p* processing with both the right isotope ratios and the right total abundance relative to Si^{28}. This is not very well separated from the *r*-process site if the latter occurs in explosive helium-burning zones in the same stars, although the existence of the oxygen-rich filaments in Cas A (Sec. V.D above) shows that supernova explosions need not mix products of the various regions of the parent star, at least during the first few hundred years, and grains have apparently begun to form in Cas A (Dinerstein *et al.*, 1982). There is no difficulty about separation if the explosive helium that results in *r* processing occurs in intermediate-mass stars (Cowan, Cameron, and Truran, 1982).

Domogatsky and Nadyozhin (1978) have explored a completely different mechanism, in which the proton-rich nuclei are the result of inverse beta decay of *s* and *r* products, induced by the large flux of neutrinos passing through the outer zones of a massive star during supernova explosion. It seems difficult with this mechanism to keep the *r* and *p* nuclides from being produced in more or less the same zones, and Woosley (1977) points out that zones of a massive star close enough to the central neutrino source to experience this sort of nucleosynthesis get so hot that the necessary iron seeds are probably all photodisintegrated. Similar induced beta decay could, however, be responsible for the production of Li, Be, and B, and possibly some deuterium (Domogatsky, Eramzhyan, and Nadyozhin, 1978; Domogatsky and Nadyozhin, 1980a), as well as Al^{26} (Domogatsky and Nadyozhin, 1980b). These calculations deserve to be redone with more recent values for the beta-decay constants and neutrino fluxes as part of one of the extensive codes that treats a full reaction network in the exploding envelope.

G. Miscellanea galactica

Supernovae may interact with the large-scale evolution of galaxies in several ways besides their contribution to chemical enrichment. The points of contact include (1) turbulence and the stellar birthrate function, (2) galactic winds, and (3) infall of gas into the galactic disc of halo or intergalactic material.

1. Turbulence and the stellar birthrate function

Sections VI.F and VI.G noted that, while supernova events might trigger star formation, a high supernova rate, by making the surrounding interstellar medium hotter and more turbulent, might also inhibit star formation, providing a sort of self-regulator of the star formation, supernova, and nucleosynthesis processes. The very erratic star formation rates in Magellanic irregular galaxies may be an example of this effect (Hunter, Gallagher, and Rautenkranz, 1982).

Gas turbulence, in addition to affecting the total star formation rate at a given place and time, also influences the initial mass function (number of stars formed as a function of initial mass), in the direction of discouraging low-mass ones. There is some observational evidence that this actually occurs (Hunter and Fleck, 1982). Too much of the effect would, however, be a bad thing. It has the opposite effect to metal enhanced star formation (Talbot and Arnett, 1975). That is, low-mass stars with long lifetimes would be formed preferentially where the metal abundance was low, because of the low supernova rate and low turbulence. The deficiency of low-metal G dwarfs in the solar neighborhood (compared to the predictions of a homogeneous star formation model; NATO74) would then become even more inexplicable.

2. Galactic winds

An interstellar medium whose structure is dominated by a hot, ionized phase consisting of old supernova remnants (Sec. VI.F above) is likely to turn into a wind and escape completely from the parent galaxy. The clearest evidence that this has happened comes from elliptical galaxies, whose metal abundance is a strong function of mass, as if winds had been able to escape precisely where the escape velocity was low, carrying the newly synthesized metals with them. A model based on the assumption that loss occurs wherever the specific energy contributed to the gas by supernovae exceeds the binding energy (Vigroux, Chièze, and Lazaroff, 1981) provides a good fit to observations of metal abundance versus mass over the range from dwarf spheroidal galaxies in the Local Group to giant ellipticals in the Virgo Cluster. If anything, the observed functional dependence is slightly steeper than the model one. An implication of the model is that a typical dwarf spheroidal began life with 100 times the mass and 100 times the binding of its modern counterpart. Globular clusters, which are compact though low in metal abundance, do not fit onto an extension of the galaxy relationship. They must have lost a much smaller fraction of their initial masses (perhaps half; Hanes and Madore, 1980).

3. Infall

Infall of virgin intergalactic (or relatively unprocessed halo) gas into the galactic disc is one way to keep the disc metal abundance roughly constant with time, and so account for the observed numbers of stars versus metallicity in the solar neighborhood (Larson, 1972a, 1972b; Tinsley, 1975a). Recent models suggest that this may roughly have doubled the mass of the disc over its lifetime (Vereshchagin and Piskunan, 1982). If, as has generally been concluded, the light elements Li, Be, and B are made largely by cosmic-ray spallation of interstellar CNO, then infall will affect their production rate in a rather complex fashion. The near constancy of their abundances (at least from the formation of the solar system to the present time) also favors continuing dilution by a relatively large infall rate. This could, in principle, be tested from its effect on the dynamics of the galactic disc, which should be contracting locally at a rate of about 2 km/s (Reeves and Meyer, 1978).

Infall presumably occurs in other galaxies if it does in the Milky Way. Hunter, Gallagher, and Rautenkranz (1982) find that their data on star formation rate versus metal abundance in irregular galaxies are best fit with a galactic evolution model including infall. The Magellanic Clouds, on the other hand, show a significant increase in metal abundance with time for stars formed over the last 10^9 yr (Hodge, 1982, and Butler, Demarque, and Smith, 1982; but disputed by Barbano, 1982, and Cowley and Hartwick, 1982), suggesting that infall has done little recent diluting of nucleosynthesis products. Perhaps tidal effects of the Milky Way prevent infall there.

4. Back to the lab

Our understanding of supernova events and their products is heavily dependent upon accurate values of cross sections and energy releases for a wide variety of nuclear reactions. This is particularly so for nucleosynthesis. Since the time of NATO74, significant advances have occurred in measurements and calculations of reaction rates for several interesting processes.

Routon *et al.* (1974a, 1974b, 1976) have measured cross sections for a number of (p,γ), (p,n), and (p,α) reactions on isotopes of elements between Si and Mo, using thick targets. This permits extraction of stellar reaction rates from the measured yield quite directly. Our understanding of heavy-element reactions, especially silicon burning, has also benefited from measurements of other (p,γ), (p,n), (α,γ), and (α,n) reactions, which show decreases by factors around 3 in the cross sections for the γ-producing reactions above the threshold for the corresponding n-producing reactions (Zyskind *et al.*, 1980 and references therein). The silicon-burning rates now in general use (Woosley *et al.*, 1978) are semiempirical, parametrized ones and include terms representing these important effects. The reaction rates for neutron capture reactions needed in calculations of the s and r processes are also available in parametrized form (Holmes *et al.*, 1976).

The increasing range of isotopic anomalies found in meteorites (Wasserburg and Papanastassiou, 1982) has focused new attention on some long-known processes. Ward and Fowler (1980) have, for instance, considered the effect of equilibrium between short-lived isomeric states and long-lived ground states on the production of Al^{26}. And it seems increasingly probable that not all of the observed anomalies can be matched by combining assorted proportions of the products of the standard processes outlined by B^2FH, Cameron (1957), or even NATO74. Sandler, Koonin, and Fowler (1982), for instance, attribute a particular mix of Ca and Ti isotopes found in Allende to neutron capture at rates neither very large nor very small compared to the beta-decay rates (cf. Blake and Schramm, 1976).

VIII. THE FUTURE OF SUPERNOVA RESEARCH

A. Supernovae as a cosmological tool

Cosmology can comprise anything from "a search for two numbers" (Sandage, 1970) on up to the investigation of all conceivable problems connected with the early history of the universe and its large-scale structure and evolution. The "two numbers" are Hubble's constant H_0 (the present expansion rate, generally given in $\mathrm{km/s\,Mpc^{-1}}$) and the deceleration parameter q_0 [dimensionless and equal to $-\ddot{R}R/\dot{R}^2$, where $R(t)$ scales the separation of any two objects moving with the general expansion]. The associated problems can include big bang nucleosynthesis and baryon synthesis, the origin of structure on various scales, the development of that structure into recognizable galaxies and clusters, the search for still larger-scale structure and nonluminous matter, and whatever else appeals to you.

Supernovae, because they are bright and conspicuous, have surely been going on for a long time, and are themselves direct contributors to galactic chemical evolution, ought to be able to help with most of these. On the whole, promise still exceeds fulfillment; hence the inclusion of this topic in this section.

Wilson (1939) and Zwicky (1939) both suggested that supernova light curves were all so nearly alike (only one type was then known) that the objects should be good extragalactic distance indicators of the "standard candle" variety. The chief problem from that day to this has been calibration—figuring out the absolute brightness of individual supernovae or classes to compare with the observed brightnesses. The latter must often be corrected for reddening and absorption by dust in the parent galaxies. This also presents difficulties, particularly for Type II's, which occur only in dusty, late-type spirals. Infrared observations of radiation from interstellar grains heated by a supernova may eventually enable us to tell how deep in the parent galaxy an event went off, and so help pin down the reddening (Pearce, 1982).

If we knew absolute brightnesses and could correct properly for absorption, then ground-based observations could determine H_0 (Wagoner, 1977) and Space Telescope (ST) ones q_0 (Colgate, 1979) with only $\sim 20\%$ uncertainty beyond that inherent in the calibration. In addition to the obvious advantages of ST in measuring apparent brightnesses of distant objects, its high angular resolution will reduce the contamination of measured SN fluxes and colors by light from the parent galaxies, facilitating the calibration of absolute brightnesses from model light curves.

1. Calibration of absolute luminosities

Three ways of getting hold of absolute brightnesses of supernovae, individually or collectively, appear in the literature. The oldest (as per Wilson and Zwicky) assumes that all SN I's (or, less often, SN II's) have the same peak brightness and determines that brightness from events in nearby galaxies, whose distances are known from Cepheids, brightest stars, etc. Each step presents difficulties (some of them discussed in Secs. III.C.2 and III.C.3 of Part I). Kowal (1968), Tammann (1979 and in NATO81), and Sandage and Tammann (1982) presented evidence that SN I's are standard candles. Branch (in NATO81) indicated that they are not. Observational scatter, reddening and absorption corrections, and imperfect distance indicators are all problems.

It is probably safe to say that the real scatter in M_B at maximum light is $\lesssim 1^m$. This may permit statistical determination of H_0 from supernovae in galaxies whose recession velocities are dominated by Hubble expansion, but it is not good enough for measuring q_0 or looking for large-scale structure. The assumption of constant M_B must surely break down as we look to large redshifts and supernovae occurring in stars of different masses and chemical compositions from those blowing up locally. A real dispersion in $M_B^{\max}$ in the sense advocated by Branch (in NATO81) turns the Sandage and Tammann (1981) value of $H_0 = 46\ \mathrm{km/s\,Mpc^{-1}}$ into an upper limit on H_0 (Branch, 1982)!

Not surprisingly, the distance scales derived by this method are closely correlated with the distance scales derived by the same authors using other methods (cf. Hodge, 1981). When the distance scale is used to get a value of H_0, it is usual to measure the redshift of the parent galaxy directly. But this may not be necessary. Colgate (1979) pointed out that SN I's, at least, may all have such similar light curves that a recession velocity could be determined from the color changes and time dilation of the SN light curve itself, for redshifts in the range 0.3—1.0 needed to measure q_0. Clearly, however, systematic changes in supernova light curves as a function of cosmological epoch could fool one badly!

The intrinsic scatter in brightness is not necessarily any larger for Type II's than for Type I's (Tammann, in NATO81), but they are a bit fainter and much more prone to absorption in their parent spiral galaxies, thus less suitable as standard candles. The standard candle method probably belongs more to the past than to the future of supernova research.

The second approach to calibration (Schurmann, Arnett, and Falk, 1979) starts with computed light curves derived from hydrodynamical models of the explosions of Type II's (Sec. III.C.2 of Part I). Distance-independent properties of an observed event—colors most often, or decay time, expansion velocity, etc.—are then used to pick out the best model from a computed family (whose members differ in envelope mass, explosion energy, etc.). And the model tells you the absolute luminosity for whatever time and wavelength range you want. The chief difficulty is, of course, in picking the correct model on the basis of imperfect (and sometimes much reddened) optical data and rather uncertain transformations between observed and computed colors. Nor is uniqueness guaranteed.

Arnett (1982) has approached Type I supernovae in the same way. He finds that both the absolute luminosity and distance-independent characteristics like decay time depend largely on the amount of Ni^{56} synthesized, so that it is possible to pick out the correct model from a set unambiguously. He finds values of H_0 near 70 km/s$\,\mathrm{Mpc}^{-1}$ both toward the Virgo Cluster and in other directions. This approach clearly deserves further attention, using a wide range of model light curves for both SN types.

The third way of calibrating supernova luminosities descends from the Baade (1926)-Wesselink (1946) method of getting brightnesses for Cepheid variables. In crudest form, it requires measurements of apparent brightness at two times when the object of interest is the same color and a detailed radial velocity curve between the two times. On the assumption that same color means same effective temperature and specific emissivity, the ratio of apparent brightnesses yields the ratio of radii at the two times. An integration of the radial velocity curve gives the difference in radii in absolute units. The two equations are then solved for the two unknown radii and these combined with a temperature deduced from the colors to get the luminosity.

Modifications of this method, of gradually increasing sophistication, have been discussed and applied to supernovae by Searle (1974), Branch and Patchett (1973), Kirshner and Kwan (1974), Branch (1977,1979), and Wagoner (1977, 1980, 1981, and in NATO81). Because supernovae generally do not pass through the same color twice (at least during well-observed parts of their light curves), the ratio of radii or angular diameters must be extracted from observations of the objects at different temperatures.

More important, supernovae are clearly not blackbodies, and their photospheres are extended and differentially expanding. Thus model atmospheres are needed both to transform colors into effective temperatures and to turn line profiles into photospheric velocities.

Wagoner (1980, 1981, and in NATO81) has drawn attention to some of the difficulties in doing all this with sufficient accuracy. The most important neglected factor has been the contribution of scattering to opacity. Scattering dilutes flux without lowering the associated color temperature. Thus, if its effects are left out, you derive too high an effective temperature, and so too large a luminosity for the supernova. The implied distance is then an overestimate and the value of H_0 an underestimate. The error can easily be a factor of 2 in luminosity or 50% in distance scale and Hubble constant according to Wagoner (1981, and in NATO81). Fortunately, the depth of the Balmer jump (which is nearly absent in Type II supernovae, though prominent in stars of similar color) can probably be used to pin down the ratio of scattering to absorptive opacity and so to get the right model atmospheres for Type II's. Type I's may present a more intractable problem. But the error due to neglect of scattering in them is partially compensated by their uv flux deficiencies, which make one underestimate T and so L (Arnett, 1982).

In the meantime, the very good agreement in distance to SN 1979*c* as found by three groups (Panagia *et al.*, 1980, 24 Mpc; Branch *et al.*, 1981, 23 Mpc; Kirshner, in NATO81, 22 Mpc) is somewhat artificial, as none of them included scattering effects in their models. This distance scale corresponds to $H_0=40$–50 km/s$\,\mathrm{Mpc}^{-1}$ for the Virgo Cluster. If we decide to correct both for scattering and for infall of the Local Group toward Virgo, the implied global value can easily climb to 100—120 km/s$\,\mathrm{Mpc}$.$^{-1}$ Some number in this 40—120-km/s$\,\mathrm{Mpc}^{-1}$ range should please virtually every practicing astronomer. As for which one is right, I heartily concur with Hodge (1981) in refusing to vote in public at the present time.

As the model atmospheres used in this approach to calibrating supernova luminosities become more complex, they will gradually merge into the hydrodynamic models of the explosions used in the second approach; and the two methods will merge into one that makes full use of our understanding of the physics of supernova events to model their light output.

In summary, calibration of a supernova-based distance scale has not yet been fully accomplished. The Type I's seem to be rather good standard candles and can sometimes be observed virtually free of reddening and absorption in elliptical galaxies; but their outer layers are not yet well enough understood to extract reliable absolute luminosities from the observations. The theory of Type II's, on the other hand, is in somewhat better shape; but they are a more variable class, and we don't quite know how to get hold of apparent colors and brightnesses properly corrected for reddening and absorption.

2. Wishful thinking

Once the distance scale problem has been solved for supernovae, then the universe is at our doorstep (at least to the same extent that, if the sky falls, we'll all catch larks). H_0 and q_0 can, in principle, each be determined by standard methods (Robertson, 1955) from the measured distance and Hubble velocity of a single object at suitable redshifts (0.03—0.1 and 0.3—1.0 for H_0 and q_0, respectively). Current observational techniques and the projected capabilities of the Space Telescope limit the accuracy of the requisite measurements at those redshifts rather severely, so that q_0 will probably be constrained only to ±40–50% by this method in the foreseeable future (Colgate, 1979; Wagoner, 1980).

At least some of the participants in NATO81 may live long enough to see light curves and spectra of supernovae at $z \gtrsim 1$. Heaven forbid that these should by then be needed to resolve the traditional cosmological problems or to measure distances to the parent galaxies, thus giving $L(z)$, etc. But they will enable us to probe early galactic evolution and nucleosynthesis directly. Interesting data would include (a) supernova rates and types, (b) distributions of supernova positions in parent galaxies, and (c) masses and compositions of parent stars (found by model fitting to light curves), all as a function of cosmological epoch and galaxy type. In addition, we could expect to see (or not see, at significant levels) supernovae contributing to nucleosynthesis in sites other than galaxies of recognizable types (intergalactic and intercluster space, protogalactic star clusters or gas clouds, quasistellar objects, and whatever else).

To make full use of such information, we clearly need the same kinds of statistical data for supernovae in galaxies (etc.?) here and now. These can be acquired with existing technology, but require more systematic identification and study of extragalactic supernovae than has so far been carried out. Several schemes to achieve this are underway or the subject of active discussion and proposal writing. Section VIII.B addresses these.

B. Supernova searches

1. Historical

In order to identify supernovae (or any other variable astronomical phenomenon) one needs (a) a device that records what the sky looks like at one time, (b) a device that records what the sky looks like at some later time, and (c) a way of comparing the two and spotting differences. The earliest searches used human beings for all three purposes, the record-keeping being done with drawings or accurate memories, and the comparison by looking, frequently with the additional requirement that two independent lookers agree they had seen something interesting before reporting it (P'eng, 1080).

All nine(?) supernovae known to have occurred in the Milky Way were found by this method (Clark and Stephenson, 1977). Eight of these were detected by Chinese astronomers, looking more or less deliberately for "guest stars" (Ho, 1962). European or Arab astronomers also spotted the events of 1006, 1054, 1572, and 1604, apparently by accident. SN 1680 was recorded by accident (by Flamsteed, who thus has the distinction of being the first astronomer to see a supernova through a telescope) but identified after deliberate searching of old star charts by Ashworth (1979). The first era of deliberate supernova searches ended with the gradual decline of the Chinese empire.

No events in the Milky Way have been spotted since, though van den Bergh, (1975) has suggested some may hide among very faint, red, slowly declining novae. It used to be claimed that when another astronomer as great as Kepler appeared, there would be a supernova for him to see. On this hypothesis, none of our colleagues could really feel discriminated against. If, however, the title up for grabs is only "greatest astronomer since Flamsteed," there may be some hurt feelings among 20th century practitioners.

2. Photographic

The advent of photographic plates enormously increased the efficiency and accuracy of recording "what the sky looks like." As a fairly direct result, about 20 extragalactic supernovae were discovered accidentally between 1885 (S Andromeda) and 1934, when Zwicky (1969) inaugurated the first modern search (further remarks in Sec. I.A of Part I). He pioneered the method of photographing at regular intervals areas of the sky (as large and to as faint a limiting magnitude as circumstances permit) selected to contain numerous and/or nearby galaxies, then comparing the most recent film or plate of an area with older ones by superposition under a binocular microscope.

Whenever a supernova was found on current plates, W. Baade began following the light curve, and R. Minkowski and M. Humason took spectra, W. S. Adams (then director of Mt. Wilson Observatory) having decided that other projects assigned time on the 100" telescope should give way to supernovae when necessary. Zwicky also tried (and rejected as search techniques) blink comparators and superpositions of new negatives on old positives. These have both subsequently been used by other groups.

The Palomar 48" Schmidt Supernova Search (Kowal, Huchra, and Sargent, 1976; Sargent, Searle, and Kowal, 1974, and references therein) was the direct descendent of Zwicky's work, using essentially his methods. It ended in 1975. Several other observatories have mounted (generally less extensive) supernova searches with photographic emulsions as recording devices and biomechanical comparison techniques. These include:

(a) Asiago Astrophysical Observatory (Rosino and Di Tullio, 1974; Rosino, 1977; Barbon, 1982). This survey, begun in 1959, has been particularly valuable because it has been followed up to yield light curves, on a standardized system, of some dozens of events. Acquisition and analysis of data is continuing.

(b) Konkoly Observatory (Detre, 1974; Lovas, 1979). This search, started in 1963, found the first supernova (1968a) to be seen in a Seyfert galaxy, NGC 1275.

(c) Zimmerwald (Wild, 1974). The search began in 1959 and averages a couple of supernovae per year, for which followup data have to be obtained at other observatories, owing to the lack of a suitable large telescope in Switzerland.

(d) Cerro El Roble (Maza, 1980). This first southern hemisphere survey project began in 1979 and has already found several events.

(e) European Southern Observatory (Muller, 1979). Modifications of the 1-m Schmidt telescope to facilitate searching for supernovae have been discussed.

Occasional "accidental" discoveries of supernovae have also continued to occur over the years.

The chief disadvantages of all these surveys are (a) the enormous amounts of telescope time involved (owing to the low quantum efficiency of photographic emulsions), (b) the even more enormous amount of observer (or slave labor) time required to blink plates, and as a result of these (c) the difficulty in identifying supernovae quickly enough to get good light curves, spectra, and other data.

3. Automated and/or electronic searches

Half a dozen past, present, and contemplated searches attempt to overcome these disadvantages by using electronic recording techniques, automated (computerized) comparisons, or both. These are discussed below in an ordering determined by whether they replace the photographic plate, the human comparator, or both.

(a) Corralitos Observatory. Hynek (1969, 1971, 1977) and his colleagues (Dunlap, Hynek, and Powers, 1972) instrumented a 24″ Cassegrain reflector with an image orthicon and storage tube, permitting direct, real-time comparison of a new image with a standard photograph of a field. A skilled human observer did the comparison visually. The first supernova turned up in February, 1968. When the search was in full operation, some 1300 galaxies were examined nearly 20 times a year, resulting in the discovery of 3—4 supernovae per year. The total was 12 by the time the project wound down, with the closing of Corralitos Observatory in 1976. The problem was inadequate funding.

Some of the search fields also showed flare-ups on time scales much shorter than supernova ones (Hynek, Dunlap, and Altizer, 1972). These (perhaps galactic dMe flare stars) will be a source of false alarms for any such search done in the future.

(b) Institute of Astronomy, Cambridge. Kibblewhite (1975; Cawson and Kibblewhite, in NATO81) and his colleagues have developed the hard- and software of an Automatic Plate Measurement facility, which can be used (among many other things) to compare plates taken at different epochs and search for changes. The current supernova search uses 48″ Schmidt plates from the Anglo-Australian Observatory, flown to England as expeditiously as possible. The first-epoch plate is scanned to locate all the galaxies on it. Their coordinates and digitized images are stored. A sample of stars is also scanned and recorded, to provide standards for photometry, seeing conditions, and unresolved image shapes. When the second-epoch plate arrives, the machine aligns it relative to the first one with a bilinear cross correlation technique. It then goes back to the position of each previously identified galaxy, records the new image, and subtracts it from the old one. Significant differences between epochs are flagged.

False alarms run 100—150 per plate pair. Many of these (associated with foreground stars, etc.) can be rejected by the software. Many more could be if pairs of first- and second-epoch photographs existed to eliminate plate flaws and the like. A human observer looks at the remaining 30—60 flagged positions, first at the digital difference images, then at the original plates, to cull out the rest of the false alarms. The four plates examined up to the time of NATO81 were ESO/SRC Sky Survey plates, rejected by the Survey as too dirty for astronomical use. They yielded three convincing supernovae.

The full-scale search project should find, on average, 1.5 SN per plate, most near $z=0.15$. At this distance, galaxies are spread rather uniformly over the sky, and fields need not be specially selected. A 48″ Schmidt devoted full-time to such a project could cover about eight fields per night, for an average discovery rate of 12 supernovae a day. Decisions about how many fields to examine how often will depend largely on whether the goal is to catch events very early to permit followup studies or to record the maximum number of events for statistical studies of rates versus parent galaxy types, etc. The former goal will probably require establishing an automatic plate measurement (APM) facility near the telescope to be used. That is, at least, probably easier than moving the telescope to the APM.

For surveys of this type, which look at large areas of sky, each containing many galaxies, in order to find distant supernovae not far from maximum light, photographic plates are actually better than other recording devices. Their large areas more than make up for their low quantum efficiency.

This is the last supernova search on our list that has, so far (February, 1983) found any supernovae.

(c) Institute for Astronomy, Hawaii. Thompson (1982) intends to compare deep ($m_r \lesssim 22$—22.5) plates taken at the prime focus of the Canada-France-Hawaii telescope, using pixel-by-pixel digital subtraction of the full 50′ fields. The plate material (pairs of first-and second-epoch plates of three fields) now exists; the requisite software does not, and is likely to require another year of work. The plate passband (IIIaF emulsion + OG 570 filter) includes "B" out to $z \sim 0.5$, the limit for detection of Type I supernovae. There should be 5—30 supernovae per field detectable on the existing plates. It will not, unfortunately, be possible to determine the types of the parent galaxies, as structure is largely lost in noise. This could, however, probably be done using CCD detectors after the supernovae have been identified.

(d) New Mexico Institute of Mining and Technology. Colgate (in NATO81) began development of an automated supernova search, based on remote computer control of both telescope and imaging system, in 1968. 1974 saw the completion of a 30″ automated telescope, cross-dispersed Echelle spectrograph, and the devices for recording what the sky looks like—image tube, Vidicon with digital readout, and microwave link to a suitable computer (Colgate, Moore, and Carlson, 1975; Colgate, Moore, and Colburn, 1975). Unsolved problems remained in the task of comparing old and new images of fields and flagging changes. The system shut down as funding dried up and the computer reached the end of its natural life.

The hardware is still in place on South Baldy peak in the Magdalena Mountains. The project revived recently when a new computer (Prime 300) and modest additional funding became available. The intention is to look about once a week at some thousands of nearby galaxies, thereby catching 5—10 supernovae a year well before maximum light, and many more near maximum. A survey with this sort of capability is necessary to make best use of the Gamma Ray Observatory's ability to detect line emission from nearby supernovae (Sec. VI.D.2).

(e) Steward Observatory. McGraw, Angel, and Sargent (1980; Angel, 1982) are developing a transit survey instrument that will continuously monitor an 8′ wide strip of sky at the zenith in two colors down to very faint ($\sim 21^m$) limiting magnitude. The instrument uses a very precisely figured 72″ Space Telescope test mirror with two CCD's at the focus. The intention is to run for a year, covering a range of colors from U to I. About 20 000 galaxies per night should pass through the field of view. A point source crosses the field in one minute, and the output is continuously integrated and recorded. Each night's data will be stored on disc memory (and later archived on tape), with the real-time reduction for positional information and variability. Data can be stacked to get very deep images.

In the year, 100—1000 supernovae should turn up, most near 21^m ($z \sim 0.25$), for which Space Telescope can be used to get the parent galaxy type. A much smaller number of nearby events may also be caught on the rising part of their light curves and can be followed up with other ground-based instruments. At present funding levels, the project should be on the air just in time to find SN 1984*a*.

(f) University of California, Berkeley. Muller (1982) and his colleagues (Kare *et al.*, 1982) are developing an automated supernova search using the 36″ telescope of the Monterey Institute for Research in Astronomy (MIRA) and a 512×320 pixel CCD detector. The detection threshold for supernova should be $m_v = 18.8$. About 6500 galaxies will be surveyed regularly—500 in the Virgo Cluster and nearer nightly to catch events at a fraction of a percent of maximum light, and 6000 others within 70 Mpc once every three nights—for an expected yield of 100 supernovae/yr.

The hardware is complete; the CCD has been tested and is on the telescope. It will couple to a dedicated minicomputer via a fiber optics cable. The programs enabling the computer to compare a new image with a stored one and to identify supernovae reliably in real time now amount to about 10^4 lines and are thought to be about half complete. The telescope control software is under separate development at MIRA.

The system includes provision to go back within a few minutes to a galaxy in which the computer spots a candidate event. False alarms due to cosmic rays hitting the CCD and due to asteroids (which move) are thus eliminated immediately. Variable foreground stars in the search fields will provide some initial confusion, but will be cataloged as they turn up and ignored thereafter. The project is currently (May, 1982) more or less on schedule, despite irregular funding. Automatic scanning tests with minimal software should begin in late summer 1982, with the first supernova found not long after that. It is intended to notify observers with access to the Gamma Ray Observatory, Space Telescope, and ground-based facilities immediately as each event is found, to permit the widest possible range of followup studies.

Projects (b), (d), (e), and (f) in this list ought to yield supernovae at a rate of about 100 per year each. Thus the investigators involved should rapidly match and exceed Zwicky's and Kowal's personal records of more than 100 discoveries (see Sec. I.A of Part I). The several projects are generally complementary to one another: (b), (c), and (e) will find (almost exclusively) faint, distant events—(e) in real time, (b) almost so, and (c) archivally—but in different regions of the sky. These are useful largely for statistical investigations of supernova rates, parent populations, etc. On the other hand, (d) and (f) will find relatively bright, nearby events, suitable for detailed studies of light curves and spectra in all regions of the electromagnetic spectrum.

Because of the greatly increased supernova discovery rate expected in the near future, the advent of an interactive, computerized data base that will include all available spectroscopic and photometric data (Branch *et al.*, 1982) is particularly timely.

C. Problems entrusted to the next generation

The past tillers in the field of supernovae whose works are cited in the preceding pages have generously reserved a few unsolved problems for future workers. One way to described them is as flaws, gaps, and uncertainties in the general scheme advocated in Secs. I—VII.

(1) Types and mechanisms. Are there, in fact, two separate physical mechanisms giving rise to two distinguishable sorts of supernovae, Type II = neutron star formation from massive stars and Type I = nuclear detonation in less massive stars and/or binaries? (Secs. III.A and IV of Part I.) There might alternatively be a class of events that derive roughly equal amounts of energy from the two processes (Shklovskii, 1981a; Ivanova and Chechetkin, 1981). Or detonations in single and binary stars might give rise to different classes of events. Or there might be a distinguishable class in which core collapse proceeds to black hole densities.

Some workers have separated both SN I's and SN II's into subtypes on the basis of the time scale and shape of the declining light curve (Sec. III.A.2 of Part I). These subtypes might be associated with different envelope masses (Branch *et al.*, 1981), different energy inputs (Arnett, 1982), or events with the presence or absence of a neutron star remnant (Litvinova and Nadyozhin, 1982). Good light curves and spectral coverage for a large number of events in many types of galaxies could help sort this out both by narrowing the possible range of progenitor populations (one SN II from a star of less than 18 $M_\odot$

is the tightest limit we have so far; Thompson, 1982a) and by defining the full range of properties that each class of models must match. Suitable search programs should be underway soon (Secs. VIII.B.2 and VIII.B.3).

(2) Where does the energy come from? When a neutron star or black hole is formed, its binding energy is so large ($\gtrsim 10^{53}$ ergs) that only about 1% need be deposited in an envelope to reproduce Type II light curves and spectra. How is this done? Neither neutrino transport nor core collapse has yet really been found capable of the task (Sec. IV.B of Part I). And effects of rotation and magnetic fields still largely remain to be explored using two-dimensional (and possibly three-dimensional) hydrodynamic codes. The problem seems to be largely a theoretical one.

In the case of nuclear detonation events, the observations seem to require just a bit more Ni^{56} to decay than can readily be made by typical parents or than can easily be accommodated within a galaxy's total supply of iron (Sec. I.C.3 of Part I). Can these numbers be pushed together, or is there additional energy added in some other way? A quick answer would come from measuring the mass of iron in a young Type I remnant, only so far the answer seems to be zero (Sec V.D), which is not very informative.

(3) Where does the energy go? Of the 10^{53} ergs liberated by neutron star formation, most does not appear in any conspicuous form. We suppose neutrinos and/or gravitational radiation must carry it off (Secs. VI.A and VI.B). Observational evidence for one or both of these would be most reassuring and would resolve the uncertainty about which predominates, but is unlikely to be forthcoming in the immediate future.

The 10^{51} ergs carried by a typical young supernova remnant is, in the long run, nearly all radiated away. But in the meantime it probably energizes the interstellar medium, accelerates cosmic rays, and may drive a galactic wind or trigger star formation, and so forth (Secs. VI.C, VI.F, and VI.G). Many of the intermediate steps, especially for cosmic rays, remain to be worked out. And we have not yet been able to do the complete sum to decide whether the input really covers all the outputs. The soft underbelly of this problem would seem to be the detailed structure of the interstellar medium, as probed by uv absorption lines (etc.) and whether or not it corresponds to the predictions of a supernova-remnant-dominated model (McKee, in NATO81).

(4) What is the relationship (or lack thereof) among supernova events, formation of pulsars, and birth of supernova remnants? (Secs. V.B and VI.I). Clearly the correlation is far from one-to-one-to-one for supernovae as a whole on both individual and statistical bases. Dividing up by types may or may not improve the correlations. Several different schemes have evolved in the dark of the data. One associates neutron stars and filled-center remnants with Type II events (Weiler and Panagia, 1980). Others associate neutron stars with only some Type II's (Litvinova and Nadyozhin, 1982) or with most events of both types (Radhakrishnan and Srinivasan, 1981; Lominadze *et al.*, 1980). In this latter case, only some of the neutron stars look like pulsars. Sorting this out would seem to require watching the evolution of a number of recent—which is to say extragalactic—events of known type. Detection of either pulsars or young remnants probably requires x-ray (Canizares, Kriss and Feigelson, 1982) and radio (Cowan and Branch, 1982) sensitivities rather in excess of what is currently available.

(5) Why is there so little evidence for nucleosynthesis? This question is actually left over from NATO74; and we can still say only that some young remnants have excesses of oxygen and its burning products (Sec. V.D) and some Type I spectra show excess iron after maximum light (Sec. III.B.3 of Part I). This is, perhaps, a somewhat slender thread on which to hang the chemical evolution of whole galaxies. Our *deus ex machina (machina ex* NASA?) is to be the Gamma Ray Observatory (Table II) which, with luck, will see at least a few lines revealing recent nucleosynthesis in extragalactic supernovae or galactic remnants.

Notes added in proof

Notes and corrections to Part I [Rev. Mod. Phys. 54, 1183 (1982)]

Each of the following addenda begins with the number of the section to which it pertains.

I.A. Paragraph 2, line 11. Curtis-Shapley, not Curtis-Shapely!

II.A.3. A recent determination of the white dwarf, supernova mass cut, from the three white dwarfs in NGC 2516, gives $8\pm2\ M_\odot$ (D. Reimers and D. Koester, Astron. Astrophys. **116**, 341, 1982).

II.A.6. An electron-capture supernova is the most likely model of the 1054 (Crab Nebula) event, as iron core collapse would have put more carbon than we see into the remnant (K. Nomoto, W. Sparks, R. Fesen, T. Gull, and D. Sugimoto, Nature **299**, 803, 1982).

II.B.1. Page 1193, line 6 should read: "That it does happen. . ." (not "That it does not happen. . .").

III.A.1. The case for a connection between 3C58 and SN 1181 has been greatly strengthened by the discovery there of high-velocity ($+850$ to -700 km/s) gas, identified from its optical emission lines (R. Fesen, Bull. Am. Astron. Soc. **14**, 936, 1982, and private communication).

II.A.2. The prototype SN III was 1961*i* and the prototype SN IV was 1961*f*.

III.A.3. A further constraint on masses of supernova progenitors comes from an analysis of the regions of M 83 that produced 1923*a* (Type II) and 1957*d* (type unknown) interpreted as containing stars of a single age. The limits are $18^{+22}_{-8}\ M_\odot$ for the former and $11^{+5}_{-2}\ M_\odot$ for the latter. (R. L. Pennington, R. J. Talbot, and R. J. Dufour, Astron. J. **87**, 1538 (1982). In addition, A. Maeder and J. Lequeux (1982, Astron. Astrophys. **114**, 409) suggest that Wolf-Rayet progenitors should produce low-luminosity Supernovae like Cas A.

III.B.1. Note all Type I supernova spectra imply high iron abundance. D. Branch *et al.* (preprint, submitted to Astrophys. J., "The Type I Supernova 1981*b* in NGC 4536: The First Hundred Days") find that, although 1981*b* showed strong Fe lines, they could be fit, three months past maximum light, by a synthetic spectrum using normal Fe abundance. In addition, the absence of Co II lines ruled out even the amount of iron seen from having been synthesized as Ni^{56} at the time of the explosion.

III.C.2. The absolute magnitudes of SN II's at peak brightness cover the range -15.8 to -19.45, a very serious objection to their use as standard candles (R. J. Buta Publ. Astron. Soc. Pac. **94**, 578, 1982).

IV.B.2. The controversy over whether a core bounce shock can eject a massive stellar envelope continues. Bowers and Wilson (Astrophys. J. Suppl. **50**, 115, 1982) find no ejection; Mazurek (1982, Astrophys. J. **259**, L13) attributes the death of the shock to exhaustion of its energy by nuclear disintegrations; and Burrows and Mazurek (1982, Astrophys. J. **259**, 330) find that neutrino processes drain more energy from the shock than they can add. On the other hand, Ivanova and Chechetkin (1982, Sov. Astron. AJ **25**, 584) get low-energy (10^{49} ergs in the shell) ejection largely due to carbon detonation triggered by the shock wave. More energy must be added later from rotation of a central pulsar or something to make a standard SN II. Weaver, Woosley, and Fuller (1982, Bull. Am. Astron. Soc. **14**, 957) report that improved calculations of silicon burning produce lower-mass, lower-entropy cores than earlier versions, and thus increase the chances for ejection. And, finally, Arnett (1982, Astrophys. J. **263**, L55), Hillebrandt (talk at 11th Texas Symposium, December 1982), and Bludman *et al.* (1982, Astrophys. J. **261**, 661) conclude that the lowest-mass iron cores, near 1.4 $M_{\odot}$, yield at least marginal explosions for some, but not all, sets of input physics.

IV.C.1. Woosley, Taam, and Weaver (1982, private communication) agree with Nomoto (in Wheeler 1980, p. 164) that some detonating white dwarfs can produce enough Ni^{56} for a Type I light curve while still leaving a WD remnant.

IV.C.2. Several recent models of mass transfer onto white dwarfs in close binaries concur that it is a bit tricky to build the WD mass up to the point where detonation can occur. The best is rapid transfer, $\gtrsim 10^{-9}$ $M_{\odot}$/yr, perhaps occurring in two discrete stages (M. Y. Fujimoto and R. E. Taam, Astrophys. J. **260**, 249, 1982; J. P. De Grève, Astrophys. Space. Sci. **84**, 447, 1982; and W-L Law and H. Ritter, "The Formation of Massive White Dwarfs in Cataclysmic Binaries", submitted to Astron. Astrophys.).

Notes added to Part II

V.B. Types of even rather old SNR's may be determined, according to P. Thaddeus (1983, private communication; cf. Bull. Am. Astron. Soc. **14**, 932), from the consideration that those closely associated with molecular clouds and young star associations (a majority of those mapped in CO) should be largely of Type II. The rate of SNR formation deduced from the observed $\Sigma - D$ relation will be affected by interarm SNR's being fainter for their sizes than SNR's in spiral arms, presumably because of the difference in ambient gas density (Landecker *et al.*, 1982, Astron. J. **87**, 1379). Nakar and Sofue (1982, Publ. Astron. Soc. Jpn. **34**, 199) report, however, that there are no interarm SNR's in M 31.

V.C. Additional evidence for asymmetric ejection in supernovae comes from the precession seen in x-ray binaries, which must mean that the SN event tilted the neutron star's rotation axis relative to the orbit plane (Cherepaschuk, 1982, Sov. Astron. AJ Lett. **8**, 82). One can probe the amount of the asymmetry from its tendency to polarize light scattered by electrons near maximum light (P. R. Shapiro, and P. G. Sutherland, 1982, Astrophys. J. **263**, 902).

VI.D.1. The notion of neutron star formation making a gamma-ray burst has recently been revived by Bann (1982, Astrophys. J. **261**, L71) in connection with the 1979 March 5 event.

VI.D.2. Mahoney, Ling, Jacobson, and Lingenfelter (1982, Astrophys. J. **262**, 742) have set new, tighter limits on the flux of Fe^{60}, Na^{22}, and Al^{26} nuclear decay gamma-ray lines at about 6×10^{-4} $\gamma/\mathrm{cm}^2\,\mathrm{s}^{-1}$. They may actually just have seen the Al^{26} line at about the same level.

VI.F.2. The dominant heat input to the warm ISM may come from acoustic waves produced by SN shocks (L. Spitzer, 1982, Astrophys. J. **262**, 315).

VI.F.3. Superbubbles, rather than being cavities blown out by large numbers of OB stars and/or supernovae, may be either just stray bits of spiral structure (I.V. Gosachinskii, 1982, Sov. Astron. AJ Lett. **8**, 113) or the products of a rare class of exceedingly powerful supernova explosion (C. Heiles, 1979, in IAU Symposium No. 84, p. 301; H. Weaver, 1980, talks at University of Maryland and elsewhere; and S. I. Blinnikov, V. S. Imshennik, and V. P. Utrobin, 1982, ITEP preprint No. 127).

VI.G. The infrared excess observed in Cas A is probably largely or wholly line emission rather than continuum, and so provides no evidence for *in situ* dust formation in young supernova remnants (H. Dinerstein, 1982, private communication).

VI.I.1. The case for the identification of the Crab Nebula with the 1054 event recorded by Chinese astronomers is strengthened by the probability that a star shown on the 1247 CE Soochow star map northwest of Tien Kuan (where the Crab really is) does represent the 1054 guest star (work by Bo Shu-ren *et al.*, reported by K. Brecher *et al.*, 1983, Observatory issue No. 1054, in press).

VI.I.2. The pulsar PSR 0809 and a nearby H I shell should be added to the class of possible pulsar-SNR associations as both are probably about 10^6 yr old (L. Velden, and W. Hirth, Astron. Astrophys., 1982, **113**, 340). 4C21.53, on the other hand, should be removed from that list, because the continuum emission is apparently thermal and not that of an SNR (Erickson, 1983, Astrophys. J. **264**, L13). It is, however, the site of a pulsar with period equal 1.5578 ms (D. C. Backer, S. R. Kulkarni, C.

Heiles, M. M. Davis, and W. M. Goss, 1982, Nature **300**, 615). The rate of change of the period, dP/dt, is rather less than 2×10^{-19}, implying an age in excess of 10^8 yr, a dipole magnetic field less than 5×10^8 G, and an enormously smooth surface (M. Ashworth, A. G. Lyne, and F. G. Smith, 1983, Nature **301**, 313). Theorists from Berkeley to Bangalore (in numerous preprints and talks at the 11th Texas Symposium, December 1982) have advanced models, the most popular being an old neutron star, spun up by mass transfer in a close binary system (presumably once visible as an x-ray source), and then liberated by the demise of its companion.

VI.I.5. Despite the extreme faintness expected for any pulsar outside the Milky Way, the 0.99757-s object in the direction of the LMC is probably in it (P. M. McCulloch *et al.* 1982, IAU Circular No. 3703).

VII.E.3. Nova explosions may be an important source of nitrogen in the galaxy, because nitrogen is the least abundant of the CNO elements and the one produced most copiously by incomplete CNO-cycle hydrogen burning (R. E. Williams 1982, Astrophys. J. **261**, L77).

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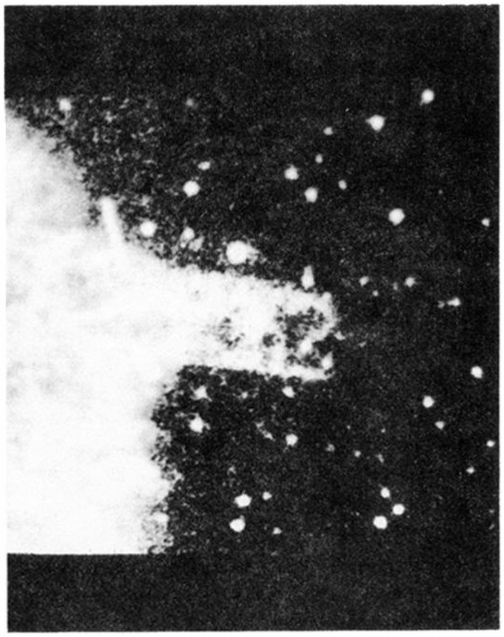

FIG. 1. The Crab Nebula jet, an emission-line feature extending out of the main body of the nebula into the faint Hα halo. It does not point back toward the pulsar or nebular expansion center, and neither its existence nor its sharp edges is understood. Photograph courtesy of Gull and Fesen (1982).

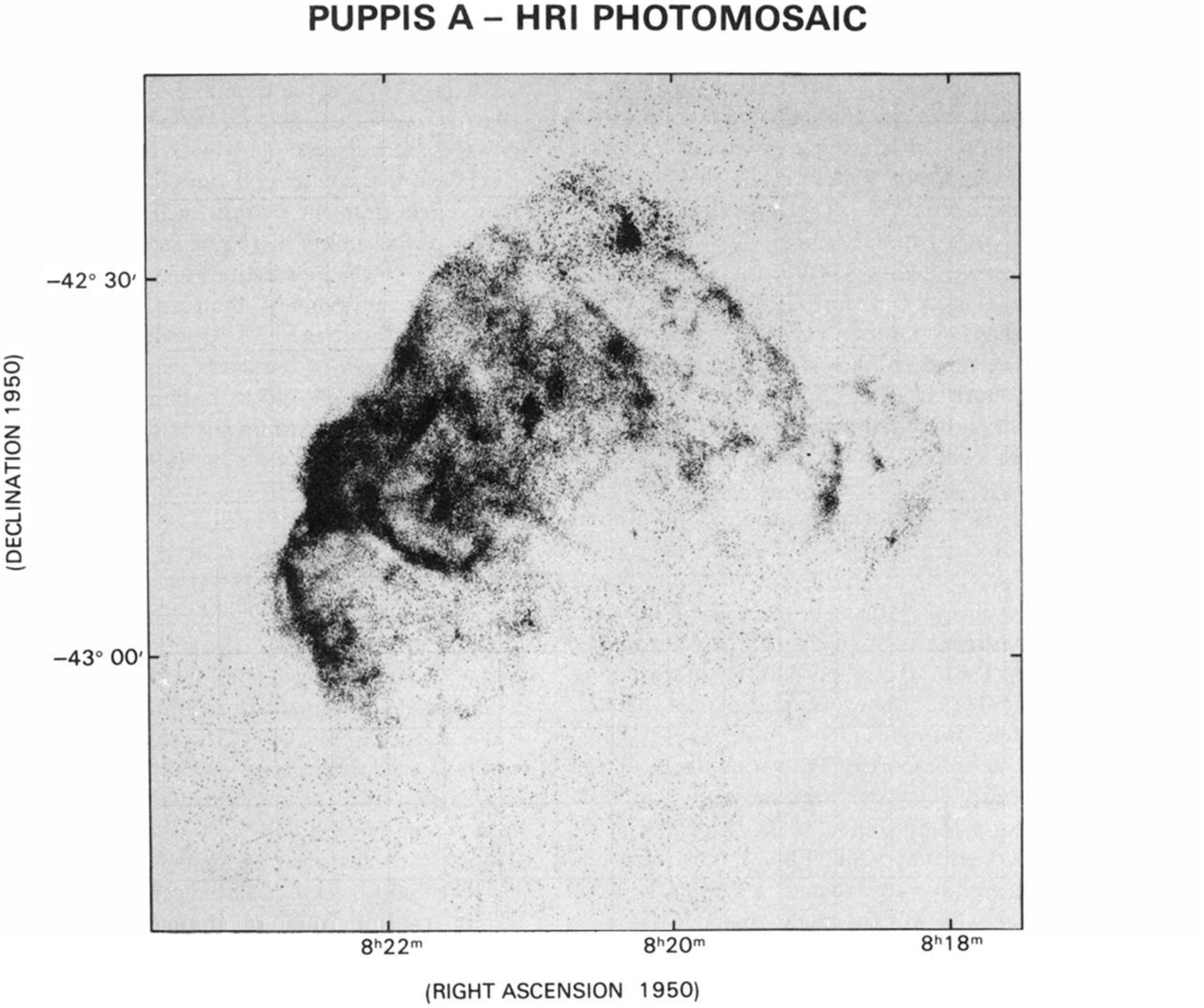

FIG. 2. An x-ray picture of the intermediate-age supernova remnant Pup A (from Petre *et al.*, 1982). Clearly, a spherical shock wave expanding into a homogeneous medium is, at best, an approximation to what is really going on!