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THE INTERACTION OF SUPERNOVAE WITH THE INTERSTELLAR MEDIUM

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1 INTRODUCTION

More than 40 years ago, Baade and Zwicky realized the large energy release in extragalactic supernovae and envisioned a very interesting process for the production of the energy (Baade & Zwicky 1934). They speculated that a stellar core could collapse to form a neutron star and that the resulting release of gravitational energy could power an explosion. The hypothesis of collapse resulting in explosion is now commonly accepted as a model for the supernova phenomenon. Energy can be stored in the rotation of the compact object, but at present there is no reason to believe that this energy is larger than that in the ejected material. This review concentrates on our theoretical understanding of the interaction of the energy release in the supernova explosion with the ISM (interstellar medium). Observations of individual SNRs (supernova remnants) are not comprehensively reviewed. Woltjer (1972) discussed the data available at that time. More recently, a review of observational aspects of SNRs with an emphasis on radio remnants has been given by Mills (1974), and X-ray observations of remnants have been described by Gorenstein & Tucker (1976).

The discussion here carries further the standard picture of SNR evolution as taking place in a number of phases (Spitzer 1968, Woltjer 1972). Initially there is the supernova itself, at which time about 10^{49} ergs of optical radiation are emitted; most of the energy is deposited in the kinetic energy of the ejecta. The first phase of SNR evolution is one of free expansion. After the ejecta have interacted with approximately their own mass in the ambient medium, the energy is transferred to the ISM, resulting in an adiabatic blast wave. This is the second phase, which ends when the cooling time behind the shock wave becomes shorter than the hydrodynamic time. The resulting formation of a dense shell is the third phase of evolution. Recently, investigators have examined in detail the transition between the phases, have checked on the effects of heat conduction, and have estimated the

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effects of an inhomogeneous ISM. These developments and the various aspects of the ISM for which energy deposition by supernovae is important are discussed in this review.

2 THE SUPERNOVA EXPLOSION

In order to understand the interaction of supernovae with the surrounding medium, it is necessary to consider the form of energy release by the initial explosion. Ionizing radiation emitted at the time of the explosion can have a fairly direct effect on the surroundings, while the kinetic energy of the ejecta has a delayed effect.

Hydrodynamic models of supernova explosions show that although there is some release of ionizing energy in the supernova, it is a small fraction of the total kinetic energy (estimated to be 10^{51} ergs). Models of Type II supernovae (Colgate 1974a,b, Chevalier 1976a) indicate that there are ultraviolet and hard X-ray or γ-ray bursts when the shock wave reaches the stellar surface. The energy in these bursts may be in the range 10^{47}–10^{49} ergs. The prompt effects of Type I supernovae may be smaller than those of Type II supernovae because their initial radii may be smaller. Colgate (1974b) estimates that 10^{44} ergs of hard γ-ray radiation emerges at the time of shock break-out. However, models of Type I supernovae with extended envelopes have been constructed (Lasher 1975), and these would have burst properties similar to the Type II supernovae.

The most stringent observational limit on the emission of hard radiation from supernovae can be deduced from the X-ray and γ-ray background radiation. The radiated energy per supernova above 0.2 keV is found to be less than 6×10^{49} (τ/100 yr) ergs, where τ^{-1}, the supernova frequency per galaxy, is assumed to be the same for all galaxies (Silk 1973). Considering the theoretical estimates of radiated energy, it is possible that supernovae do contribute to the background radiation.

No definite limits for emission below 0.2 keV are available. Morrison and his colleagues (Morrison & Sartori 1969, Chiu, Morrison & Sartori 1975) have proposed models for the light from Type I supernovae which require the release of a large amount of ionizing radiation at the time of the explosion. The mechanism for producing 10^{52} ergs of radiated energy is not given. Colgate (1972) has investigated ways of converting the kinetic energy into ionizing radiation at early times and found that the efficiency is low (see also Kahn 1974b). Another problem with the Morrison theory is that the medium in which the light pulse is moving must be very uniform with radius to give a constant decay time in the light curve. As the medium is a result of stellar mass loss (Morrison & Sartori 1969), its density is likely to decrease with distance from the star. Kafatos & Morrison (1971) claim that the existence of the Gum Nebula around the Vela XYZ supernova remnant lends observational support to the ionizing flux conjecture. On the other hand, Beuermann (1973) found that the flux from the hot stars in the Vela OB association could provide the required ionization energy for the nebula; but this result is still controversial (Kafatos et al. 1975). The remnant of Tycho's supernova, which was a Type I event, has been searched for a fossil H II region without success (van den Bergh et al. 1973).

Table 1 Properties of supernovae

	Type I	Type II
Ejected mass ($M_\odot$)	0.5	5
Mean velocity (km sec^{-1})	10 000	5000
Kinetic energy (erg)	5×10^{50}	1×10^{51}
Visual radiated energy (erg)	4×10^{49}	1×10^{49}
Ionizing radiated energy (erg)	10^{44} or 10^{48}–10^{49}	10^{48}–10^{49}
Frequency (yr^{-1})	1/60	1/40
Stellar population	old disc	young disc

Estimates of the basic properties of supernovae are summarized in Table 1. The ejected mass of Type I supernovae is highly uncertain, but is probably in the range 0.1 to 1.0 $M_\odot$. A lower limit to the mass of Type II supernovae can be deduced from the fact that they occur only in the spiral arms of spiral galaxies (Tinsley 1975, Maza & van den Bergh 1976). The actual ejected mass may be greater than that listed in the table. The mean velocity is derived on the hypothesis that supernovae eject shells (see the arguments for Type II supernovae in Chevalier 1976a). The velocities can be estimated from the photospheric radii at the time when the photosphere reaches its maximum extent, or from the velocities indicated by absorption lines at late times. Of course, there is material moving with far greater velocities but it is unclear whether this material contributes substantially to the kinetic energy, which is computed here from the given mass and mean velocity. The estimate of visual radiated energy is based on visual light curves and spectrophotometric temperatures, assuming a Hubble constant of 50 km sec^{-1} Mpc^{-1}, and it is probably accurate to a factor of 2 or 3. There may be a considerable intrinsic spread for Type II supernovae. The ionizing energy is based on uncertain theoretical predictions, as discussed above. The supernovae frequency in our galaxy and the stellar population of the progenitors are taken from Tammann (1974) and Tinsley (1975).

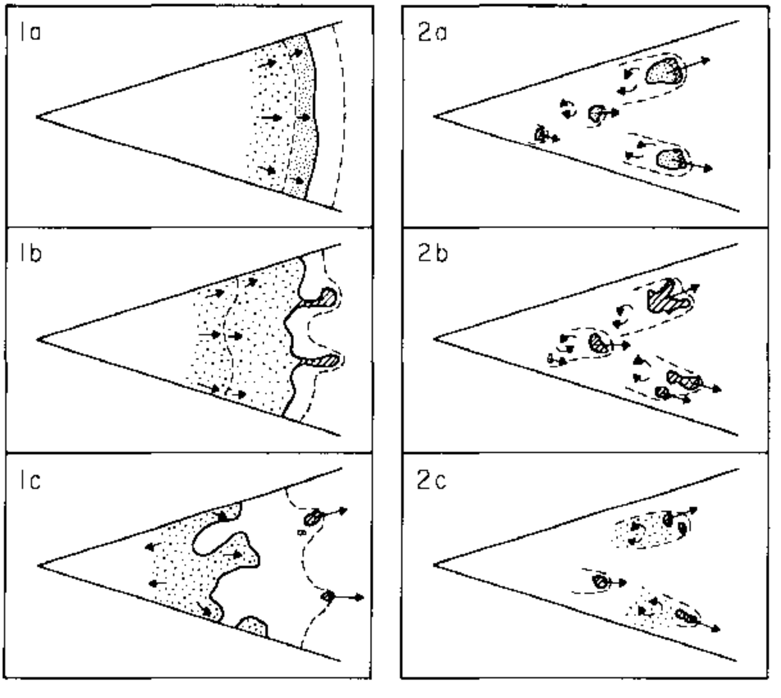
In conclusion, most of the observable supernova energy (i.e. excluding neutrinos and gravitational radiation) emerges in the form of the kinetic energy of the ejecta. The ejected material may be subject to a Rayleigh-Taylor instability at some phase of the explosion (Falk & Arnett 1973, Chevalier 1976a), so the ejecta may be clumpy. No detailed models of the outcome of the instability have been calculated. It is likely that part of the ejected material is in a relatively smooth shell and part is in clumps, but it is not known how the mass is divided between these two states.

3 THE EVOLUTION OF A SUPERNOVA REMNANT

3.1 *Transfer of Energy to the ISM*

In the last section we noted that the supernova energy is primarily deposited in the kinetic energy of the ejecta. In the hundreds to thousands of years following the explosion, this energy is transferred to the surrounding medium.

If the ejected shell is smooth, it sweeps up the surrounding medium as it expands. While the amount of swept-up gas is small, the expanding shell acts like an expanding piston with constant velocity. The interaction of such a piston with a uniform medium has been considered by Taylor (1946). For a $\gamma = 5/3$ gas, a shock wave forms at 1.1 times the piston radius and the ISM is compressed to 4 times the ambient density in the shock. As the amount of swept-up mass becomes comparable to the ejected mass, two effects become important. The first is a result of the low pressure in the ejected material which has been adiabatically expanding. The pressure difference between the shocked ISM and the ejecta drives a shock wave into the ejecta (Ardavan 1973, Kahn 1974a, McKee 1974, Mansfield & Salpeter 1974; see also Figure 1a). The converging shock wave may be unstable (Somon 1971), giving the shock front a corrugated appearance. The reverse shock wave is the beginning of the deceleration of the supernova ejecta, which leads to the second effect: the



Figures 1 and 2 Schematic views of two models for the early evolution of SNRs. Dashed lines are shock fronts, solid lines are contact discontinuities, and the arrows indicate velocities. The supernova ejecta are stipled, the cool, compressed parts of the ejecta are hatched, and the ISM is plain. Figure 1 depicts the interaction of a smooth shell with the ISM, including the formation of a reverse shock wave and the development of the Rayleigh-Taylor instability (cf Gull 1975). Figure 2 shows the interaction of clumpy ejecta with the surrounding medium. The actual situation may be a combination of these two cases. See Section 3.1 for a detailed description.

Rayleigh-Taylor instability at the interface between the dense shell and the ambient medium. The deceleration of a dense gas by a low-density gas leads to the breakup of the dense gas as it is penetrated by the low-density gas (Figure 1b). Gurzadyan (1953, 1969) long ago pointed out that this instability would cause the breakup of expanding shells in the ISM. Gull (1973a, 1975) suggested that the instability in young SNRs generates turbulent motions that are important for the acceleration of relativistic particles (see Section 5.1). The fragments that form as a result of the instability are themselves subject to breakup by further instabilities (Figure 1c). Cowie (1975) pointed out that the breakup may be halted at a size determined by the action of viscosity.

The expansion of a uniform shell can lead to an interesting magnetic effect if the ambient field lines in the supernova environment are approximately straight. The tension in the swept-up magnetic field lines gives the dominant pressure close to the contact discontinuity between the expanding shell and the ISM (Kulsrud et al. 1965). The effect can be analyzed by estimating the swept-up magnetic flux in a plane perpendicular to the field lines. The magnetic pressure leads to a bulging out of the shock wave perpendicular to the field lines, although the deviation from sphericity is small. Kulsrud et al. further pointed out that the Rayleigh-Taylor instability at the contact discontinuity may cause the formation of magnetic filaments.

As mentioned in the previous section, it is possible that much of the ejecta is initially in clumps. Evidence for this phenomenon is found in the young SNR Cassiopeia A. Velocity studies of the fast-moving knots can be interpreted as undecelerated motion since the time of the explosion (van den Bergh & Dodd 1970). The overabundance of Ar, S, and O in these knots relative to H (Peimbert & van den Bergh 1971, Peimbert 1971) shows that the knots are supernova ejecta. While Cas A may have been a peculiar supernova (cf Chevalier 1976b), it does provide evidence for the early breakup of the supernova shell. The evolution of a knot depends on the internal velocity dispersion it receives at the time of formation. If the dispersion is significant, a shock wave similar to the reverse shock will move into the knot (Figure 2a). The deceleration would again be accompanied by instabilities (cf Blake 1972 and Figures 2b and 2c), and because the knot is surrounded by hot gas, heat conduction is expected to act on the knot (Chevalier 1975b). As the heated gas expands, it is more rapidly decelerated by the surrounding medium. Because the deceleration is larger for a knot of smaller radius on the assumption that the knot density is constant, the deceleration of a knot may proceed rapidly once it begins to break up.

3.2 *The Supernova Ejecta*

After the supernova ejecta have interacted with their own mass in the surrounding medium, significant deceleration is expected. In both types of evolution discussed above, the ejecta are likely to be at a fairly high temperature (greater than 10^6 K) at this time. In the reverse shock, the initial shock velocity is low and the gas density is high, so that cooling may occur behind the shock wave. However, the shock moves more rapidly as the density of expanding gas decreases, so that the shock wave soon heats the gas to a temperature at which its cooling time is long. Only a few percent of the ejected mass may be cool after the reverse shock has passed. It is unlikely that the Cas A knots formed in this way because of the large observed range in knot velocities (van den Bergh & Dodd 1970); only the outer, high-velocity part of the shell would be expected to cool in this model. In the case of initial knot ejection, the densities may be high enough so that a shock wave that brings a knot into pressure equilibrium is a cooling shock wave. Heating by conduction may bring the ejecta to X-ray emitting temperatures.

Once the supernova energy has been transferred to the ISM, the standard picture of SNRs describes the subsequent evolution by the self-similar adiabatic blast wave solution for a point explosion in a uniform medium (Sedov 1959). Of course, the supernova is not a point explosion and the supernova ejecta contribute to an enhanced density at the center of the explosion (Mansfield & Salpeter 1974). Chevalier (1975b) suggested that the enhanced X-ray emission observed at the center of the Cygnus Loop (Rappaport et al. 1973) can be explained as emission from the supernova ejecta. Rappaport et al. argued for a central point source but the more sensitive observations of Weisskopf et al. (1974) cast doubt on this interpretation.

As it is likely that the supernova ejecta are heated to X-ray emitting temperatures, observations of X-ray lines are of particular importance. Spatial resolution as well as spectral resolution will probably be important because regions with large overabundances of heavy elements may only occupy a small fraction of the volume of the SNR. X-ray lines have now been definitely observed in Cas A and in Tycho (Davison et al. 1976, Pravdo et al. 1976), which confirms the thermal nature of these sources. The strengths of the lines, which are probably due to Fe XXV and Fe XXVI, do not indicate a large Fe overabundance. While the study of X-ray lines holds much promise, their interpretation must be undertaken with care because the hot gas is not likely to be in ionization equilibrium. If the departure from equilibrium occurs during heating (ionization), line strengths may be anomalously high (cf Kafatos & Tucker 1972 on Si lines), while if it occurs during cooling (recombination), the lines may be anomalously weak (cf Chevalier 1975b on O lines). Solar astronomers have already gained experience in this field from X-ray studies of the active regions (Culhane & Acton 1974). Another probable nonequilibrium situation involves the electron and ion temperatures behind the high-velocity shock waves that occur in young SNRs. This subject has not progressed beyond the discussion of Shklovsky (1968), who noted that Coulomb interactions are not sufficient to bring the electrons and ions into equilibrium, but that plasma instabilities in a collisionless shock may bring about equilibrium more rapidly (see also McKee 1974). Gorenstein et al. (1974) conjecture that the approach to equilibrium may be slow and that this may explain why the temperature derived from X-ray spectra (the electron temperature) is lower than the expected post-shock temperature in young remnants.

3.3 *The Effect of Heat Conduction*

Another assumption of the standard blast-wave solution is adiabaticity. If heat conduction is effective, deviations from the adiabatic solution are to be expected. Assuming the absence of a magnetic field and the applicability of the collisional heat conduction coefficient, Chevalier (1975a) showed that an electron conduction front can move out from the hot gas generated by a supernova more rapidly than a shock wave. The reason for this behavior is the high electron thermal velocity compared to the proton thermal velocity. A point is eventually reached where a transition to a shock wave is made. Cowie & McKee (1977) showed that the classical conduction coefficient can give a large overestimate of the conductive flux when the electron mean free path is larger than the electron temperature scale height (saturated conduction). They point out that the velocity of a thermal wave cannot greatly exceed twice the sound speed of the hot gas. They further conjecture that plasma instabilities do not allow a conduction front to propagate ahead of the shock wave.

Another effect of conduction is to smooth the interior temperature profile. Assuming infinite conductivity, Solinger et al. (1975) have investigated isothermal blast-wave solutions for supernova remnants. This solution would apply to a phase after thermal waves were important and before radiative cooling sets in. Solinger et al. show that the basic properties of SNRs (age, ambient density, and initial energy) derived from X-ray and optical observations (radius, X-ray temperature, and X-ray luminosity) are approximately the same for both the adiabatic and isothermal models. X-ray spectra to high energies will probably be most useful for discriminating among models. Chevalier (1975b) found that the high interior temperatures in the adiabatic models can give a significant deviation from a one-temperature bremsstrahlung spectrum on the assumption that the electrons and ions are in temperature equilibrium. Lerche & Vasyliunas (1976) have shown that the isothermal blast-wave solutions are unstable to radial perturbations. However, the one-dimensional computations of SNR evolution with heat conduction (Chevalier 1975a) should include these effects. The computations do not show any irregular behavior, but the temperature profile is never completely isothermal.

After shell formation, conduction results in a fairly smooth interior temperature distribution. This has two effects on X-ray observations of an old remnant: the X-rays are emitted closer to the dense shell and the characteristic X-ray temperature is higher than in the absence of conduction. Both of these effects go in the direction of bringing the dense shell model for the Cygnus Loop (Cox 1972c) into better agreement with the X-ray observations.

Conduction may also be important for the evaporation of clouds that are immersed in hot gas, as mentioned above. McKee & Cowie (1975) have analyzed the types of conduction fronts (or thermal waves) possible from considerations of the jump conditions at the front. They classify the fronts in a way analogous to the classification of ionization fronts. Cowie & McKee (1977) have further analyzed the evaporation of clouds by heat conduction and have derived rates of cloud mass loss for both classical and saturated conduction. The results show that cloud evaporation may be important in the evolution of SNRs if magnetic fields do not impede conduction.

3.4 *The Radiative Shock Phase*

As the SNR shock wave weakens (possibly because it enters a high-density region), radiative cooling causes the gas temperature to drop behind the shock wave.

Pikel'ner (1954) realized that the cooling radiation might have a characteristic spectrum, and he calculated approximate line intensities for comparison with observations of the Cygnus Loop. A more thorough calculation of the emitted radiation was undertaken by Cox (1972a), who included radiative transfer through the shocked gas and the effects of a magnetic field. Spectrophotometry of old remnants (cf Miller 1974, Osterbrock & Dufour 1973) has given strong support to the hypothesis that a radiating shock wave is being observed, although there are differences in detail. A new set of shock calculations has been completed by Raymond (1976), who improved the calculation by starting with the ionization balance of the pre-shock gas, rather than assuming ionization equilibrium at the post-shock temperature, and by separately following the flow of neutral and ionized species in cases where they do not behave as a single fluid. He also increased the parameter space covered by the calculations. It may now be possible to understand some of the details of observed shock spectra; for example, Raymond suggests that differences in spectra taken in different parts of the Cygnus Loop (Miller 1974) have to do with the pre-shock ionization state.

Shock spectra are a potentially powerful means of investigating old SNRs and the ISM. Characteristic line ratios can yield a good estimate of the shock velocity. The pre-shock density can be estimated either from the absolute flux in the Balmer lines or from density-sensitive line ratios if pressure equilibrium in the post-shock gas is assumed. The difficulty in applying the last method is shown by Miller's (1974) observations of the Cygnus Loop, where the density derived from the [S II] doublet ratio is 5 to 7 times higher than that derived from the [O II] doublet ratio, although the temperatures of the emitting regions are presumably similar. Inaccuracies in the atomic physics data may provide an explanation. Shock spectra may yield information on the pre-shock magnetic field; Raymond (1976) notes that the lines of neutral and singly ionized species are weak if the magnetic field is strong. Finally, it is possible to estimate element abundances. The results on the Cygnus Loop indicate that abundances of certain elements are higher than in a standard grain depletion model, perhaps implying that some grains are destroyed by the shock wave (Raymond 1976).

If the shock front around most of the SNR becomes radiative, the remnant is encompassed by a dense shell. Subsequent to the analytic work of Cox (1972b) on the formation of a dense shell, numerical calculations were performed that followed the shell formation stage in detail (Rosenberg & Scheuer 1973, Chevalier 1974, Mansfield & Salpeter 1974, Straka 1974, Falle 1975). These spherically symmetric calculations show that the gas recombines behind the shock wave to form a cool neutral shell. There have been neutral hydrogen radio observations of some SNRs that in fact show a supersonic, expanding shell; they are HB 21 (Assousa & Erkes 1973) and S 147 (Assousa, Balick & Erkes 1973). A subsonic expanding shell has been observed around W 44 with a radius many times that of the nonthermal emission (Knapp & Kerr 1974). Cornett & Hardee (1975) have interpreted this expansion as being due to preheating of the region around the SNR by either ionizing radiation or cosmic rays. Heiles (1976) has found large expanding shells in his survey of 21-cm emission. The momentum carried by the shells is consistent with a supernova origin.

The dense shell evolves primarily by momentum conservation. While there is hot gas in the interior of the shell, it loses most of its energy to radiation at the inner boundary of the shell. In fact, a shock wave can form at the inner edge of the shell as hot gas cools and accretes onto the shell (Chevalier 1974, Falle 1975). The momentum of this gas is added to the shell.

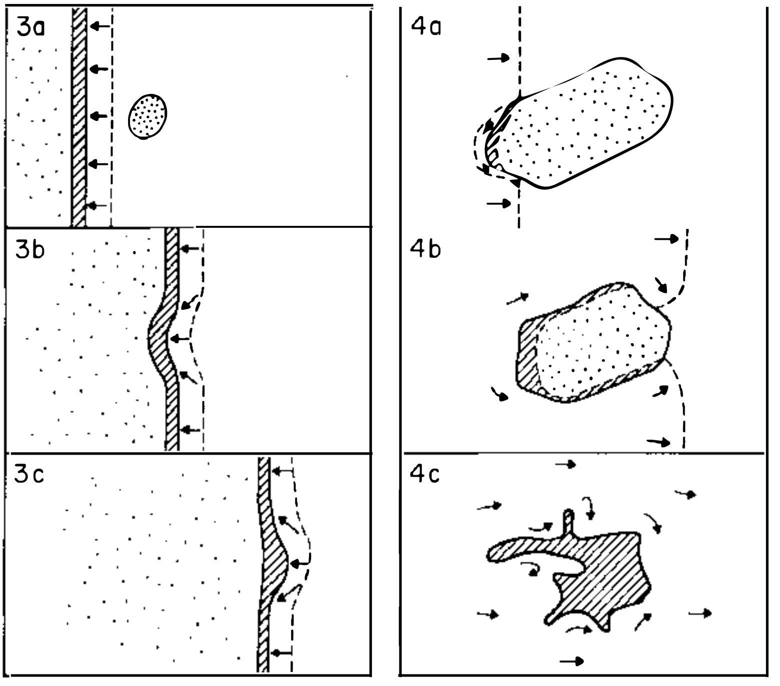
A substantial amount of the energy radiated behind the shock wave may be emitted in the infrared (Cox 1972a, Chevalier 1974). Radiation in fine-structure transition lines and in radiatively heated grains is expected. It has also been suggested that young remnants may have a large infrared flux from collisionally heated grains (Silk & Burke 1974). This process is of particular importance for supernovae that occur in dense clouds (densities greater than 10^2 cm^{-3}). Despite these predictions, the infrared stands out as a wavelength band in which SNRs have not been extensively observed. Even upper limits on the infrared fluxes of remnants may be of interest.

McCray, Stein & Kafatos (1975) have pointed out that narrow density fluctuations in the ambient medium are magnified in the cooling region behind the shock wave. This effect is only marginally observable; the cooling region in the Cygnus Loop subtends an angle of less than 1″ arc (Cox 1972a). However, this instability may be important in the interpretation of shock spectra. Also important is the frequently observed chaotic structure of the shock front, to be discussed in the next section.

3.5 *The Irregular Structure of Old Remnants*

Because supernova remnants are observed to have a highly irregular structure (cf van den Bergh et al. 1973), one-dimensional calculations cannot adequately describe them. The expanding neutral hydrogen shells mentioned above are by no means smooth or complete. A possible cause for the irregular structure was found by Chevalier & Theys (1975), who investigated the passage of a cooling shock wave over a density fluctuation using a two-dimensional hydrodynamic code. The part of the shock front passing over the region of increased density was retarded. If the flow was adiabatic, the shock front tended to straighten out after passing fluctuation; but with cooling included, the shock front became more irregular with time. In this sense, a cooling shock wave is unstable. While the instability is probably related to the Rayleigh-Taylor instability, the initial conditions are considerably more complicated. The numerical calculations can be understood as follows (see Figure 3). After passing the density fluctuation, the shocked gas is channeled toward the lagging part of the shock front (Figure 3b). In the case of adiabatic flow, this material is of high pressure and it re-expands. However, with radiative cooling, a long-lived clump can form because it is no longer a high-pressure region. The clump has a larger radial momentum per unit area than the rest of the shell, so that it eventually moves ahead of the rest of the shell (Figure 3c). Now, further clumps form around the initial one and the growth of irregular structure continues. This theory does not clearly predict the arclike structure observed in old remnants such as S 147. However, magnetic stresses, which were not included in the numerical calculations, may be the dominant pressure in the dense shell. As one part of the shell moves ahead, magnetic stresses may create the arclike structure that is observed.

The inhomogeneous nature of the interstellar medium undoubtedly has a profound effect on SNR evolution. The effect described in the previous paragraph depends on small density enhancements; much larger enhancements, interstellar clouds, also exist in the medium into which the supernova shock expands. The interaction of supernova blast waves with clouds has been investigated by Sgro (1972, 1975), McKee & Cowie (1975), and Bychkov & Pikel'ner (1975). The numerical calculations of Sgro show that the transmitted shock wave may be a cooling shock if the cloud density is greater than a critical value that depends on the shock velocity, ambient density, and thickness of the cloud. A lower density cloud will remain hot for some time, emitting X-rays. Sgro has applied these results to the X-ray emission from Cas A. For this model to be tenable, the mass in quasi-stationary floculli that do not cool must be considerably greater than the mass in those that do. McKee & Cowie (1975) describe the interaction of a blast wave with a cloud as follows (see Figure 4). After the shock front has reached the cloud boundary, there is a reflected shock and a transmitted shock into the cloud (Figure 4a). The pressure between the two shocks can be several times the initial post-shock pressure. If the flow past



Figures 3 and 4 Schematic views of the interaction of shock waves with density inhomogeneities. Dashed lines are shock fronts, solid lines are the boundaries between high and low density regions, and hatched areas are cool, compressed regions. Arrows indicate velocities; in Figure 3, the velocities are relative to the dense shell. Figure 3 shows the interaction of a radiative shock wave with a density fluctuation, while Figure 4 depicts the interaction of a blast wave with an interstellar cloud. See Section 3.5 for details.

the cloud is supersonic, the reflected shock is maintained; if not, it disappears. The shock velocity in the cloud is slow, so the blast wave rapidly envelops the cloud. The high-pressure gas can drive secondary shocks into the sides and back of the cloud (Figure 4b). These general features are also found in the numerical computations of Sgro (1972, 1975) and Woodward (1976). Woodward computed the continued flow past the cloud, which results in the growth of instabilities (Figure 4c).

Bychkov (1973), Sgro, and McKee and Cowie interpret the optical emission from the Cas A quasi-stationary floculli as being due to shocked clouds. McKee and Cowie and Bychkov & Pikel'ner (1975) give quantitative support for the hypothesis that the X-ray and optical observations of the Cygnus Loop can be reconciled in terms of a cloud interaction model (cf Woltjer 1972). The X-rays are from the blast wave in the low-density medium while the optical filaments are places where clouds are being shocked. Further observational results relevant to this subject have been presented by Kirshner & Taylor (1976), who find Hα emitting gas in the Cygnus Loop with velocities up to 270 km sec^{-1}. These observations present a further puzzle in that gas with such a high velocity would be expected to have a much smaller emission measure than that observed; further observations to confirm these results would be useful. This study brought out the fact that the distance to the Cygnus Loop, which is based on proper motion and radial velocity studies of the optical filaments, is not as well known as is commonly assumed.

McKee and Cowie conjecture that the irregular structure of old remnants can be understood solely on the basis of interactions with clouds. However, as they point out, the curvature of observed SNR filaments is opposite to that expected in such a model. It seems more likely that the structure is due to the action of a Rayleigh-Taylor type instability, as discussed above. This hypothesis is supported by photographs of explosions in the earth's atmosphere. The interface between the debris products and the surrounding atmosphere is Rayleigh-Taylor unstable and usually shows a structure similar to that of old SNRs.

In addition to the instability discussed above involving radiative shock waves, there is an adiabatic instability involving shocked clouds. Richtmyer (1960) showed that the boundary between high and low density regions is unstable after being shocked. He numerically modeled the adiabatic flow resulting from the incidence of a shock wave on the corrugated boundary of a high density region. Because of the adiabatic assumption, both the transmitted and reflected shock waves straightened out with time; yet the contact discontinuity was Rayleigh-Taylor unstable and the corrugation became more prominent (see also Woodward 1976). In an astrophysical context, in addition to this instability, the cooling shock wave instability would occur.

The large compressive forces that can occur in SNRs suggest the possibility of star formation in the dense shell. Spherically symmetric models indicate that the magnetic pressure may prevent star formation (Chevalier 1974). However, the above-mentioned factors can result in flow along magnetic field lines and the channeling of gas into clumps. Intersecting shock waves can result in a pressure which is several times that resulting from a single shock. Thus, if star formation can occur on a timescale less than 10^6 years, it is reasonable to expect young stars to be associated with an old SNR. Berkhuijsen (1974) has noted that the Origem Loop may be an old SNR with radius 60 pc. There appear to be H II and early-type stars associated with the Loop, which she suggests have formed in the shell. Once star formation has occurred, the stars decouple from the shell and are no longer decelerated. The velocity of the stars associated with the Origem Loop are consistent with this expectation. Sancisi (1974) has found expanding neutral H shells connected with two OB associations. The idea that the expansion of OB associations might be related to star formation in expanding supernova shells goes back to Öpik (1953). Sancisi's results can be interpreted as support for this hypothesis. Ögelman & Maran (1976) have speculated that as the massive stars formed in a SNR shell themselves become supernovae, a cascade process is initiated.

4 COLLECTIVE EFFECTS OF SUPERNOVAE ON THE ISM

4.1 *Ionization Energy*

As discussed in Section 2, supernova explosions themselves are unlikely to be significant sources of ionizing radiation. However, the medium that is shocked by the supernova motions is sufficiently hot to emit ionizing radiation. The ionizing luminosity has been calculated in the one-dimensional numerical models (Chevalier 1974, Mansfield & Salpeter 1974). The results show that a significant amount (about 30%) of the supernova energy may be emitted as ionizing radiation. However, as the total energy of a supernova is about 10^{51} ergs, this energy in ionizing radiation is considerably less than that produced by a hot star during its lifetime. As the birthrate of early-type stars is similar to the birthrate of supernovae, SNRs are probably only minor contributors to the total ionization energy of the interstellar medium. However, the ionizing radiation from SNRs does have the property of extending further into the soft X-ray range than does the stellar radiation. This radiation is capable of partially ionizing an extended volume, giving a warm, partially ionized component of the ISM (Salpeter 1976).

4.2 *Thermal Energy*

Supernovae may contribute to the heating of the ISM in a rather special way: the high velocities that occur in supernovae can generate exceptionally high temperatures in the gas. Cox & Smith (1974) suggested that this gas might occupy a substantial fraction of the volume of the interstellar medium. They pointed out that the fraction of the supernova energy lost to radiative cooling is small if the ambient density is small. Thus, if the fractional volume of hot gas is above a critical limit, supernova remnants overlap and a young remnant may expand into a low density medium, losing little energy to radiation. If the fractional volume never reaches the critical value, only 10% or less of the ISM may be in the hot phase and SNRs remain distinct. Detailed simulations of the growth of overlapping SNRs by Smith (1977) indicates that at least 30% of the volume of a spiral arm near the galactic plane can be maintained in the hot phase. He considered the fact that when a young SNR encounters an old one, it must break through a dense shell in order to join up with the old one. Rayleigh-Taylor instabilities facilitate this process.

Observational data bearing on the hot phase of the ISM are the soft X-ray background (Williamson et al. 1974) and interstellar O VI absorption lines (Jenkins & Meloy 1974). The strong O VI lines in the spectra of stars behind the Vela SNR (Jenkins et al. 1976) provide evidence that at least in this case, the O VI absorbing gas is associated with a SNR. The observations further show that the correlation of O VI column density with stellar distance is poor, implying that the O VI absorbing gas is not uniformly distributed through the ISM. The gas temperature required to give the soft X-rays is somewhat higher than that of the O VI absorbing gas (cf Shapiro & Field 1976). In an analysis of the soft X-ray observations of the Wisconsin group, Cox (1976) found that a one-temperature model did not give an adequate fit. In a two-temperature model, the lower temperature may be consistent with that of the O VI absorbing gas, a temperature in the range $3\text{-}8 \times 10^5$K. A region with this temperature might occur at the interface between the higher temperature X-ray emitting gas and cool gas. Conductive energy transfer would occur at the interface.

A model of the ISM in which the evaporation of clouds by conduction plays an important role is that of McKee & Ostriker (1975). In their model, most of the volume of the ISM is made up of the hot gas from SNRs, although there are also cool clouds and a warm ($T \sim 10^4$K) component. The evaporation of clouds by a SNR significantly adds to its interior mass. There is a balance achieved between the formation of clouds in the late stages of SNR evolution and the evaporation of clouds by the hot gas. Rough agreement with the soft X-ray flux is obtained. In this picture, SNRs only enter the dense shell phase at a very large radius ($R \sim 170$ pc) as they are expanding in a low density medium. If it can be definitely shown that a relatively small remnant, like S 147, is in the dense shell phase, it would provide evidence against this model. Also, heat conduction is not the only mechanism for dissipating clouds. The radiation from an early-type star can ionize and heat nearby clouds, creating a region of near uniform density surrounding the star (Elmergreen 1976). The medium produced in this way is similar to that used in numerical simulations of SNR evolution. If most of the volume of the ISM is in the hot phase, as conjectured by McKee and Ostriker, there may be implications for the density wave theory of spiral structure. Galactic shocks would not form in the hot gas so narrow regions of star formation may not occur. A calculation of the propagation of a spiral density wave in a medium with various volume fractions of hot gas would be of some interest.

Jones (1975) has suggested that information on the fractional volume of the hot component can be deduced from statistics of SNR diameters derived from radio observations. He concludes that 80% of the ISM is in the hot phase. However, the observational data are subject to selection effects that are difficult to account for. For example, it is unclear how readily a large diameter SNR can be distinguished from the nonthermal radio background; the lack of such remnants forms a crucial part of Jones' argument. Also, as discussed in Section 5.2, the theoretical basis for deriving diameters from radio surface brightness measurements is poorly developed. It appears unlikely that useful information on the hot component can be deduced from radio observations at the present time.

The density gradient out of the plane of the Galaxy can have an important effect on SNRs. First, a strong explosion can break out of the plane of the Galaxy (Chevalier

& Gardner 1974) if it does not first reach pressure equilibrium with its surroundings. The SNR shock wave accelerates away from the plane because of the rapidly decreasing density. Another effect is that hot gas produced by a supernova is buoyant even after it has reached pressure equilibrium with its surroundings (Jones 1973, Chevalier & Gardner 1974). Thus hot gas produced by supernovae can contribute to a hot galactic corona. The idea of a hot corona was first discussed by Spitzer (1956), who suggested that the high temperature could be maintained by the motions of stellar ejecta.

A galactic fountain effect has been discussed by Shapiro & Field (1976). In this model, the hot gas radiatively cools as it rises out of the plane before reaching a height of 1 kpc. The cool, dense gas then falls back to the plane, perhaps giving rise to the high-velocity clouds. However, they have neglected the heat input of Type I supernovae, which probably have a scale height in the range 500–1000 pc. These may be able to maintain the gas at high temperature. In the absence of cooling, the scale height of 10^6K gas would be about 7500 pc; thus, the height of the hot gas above the plane may ultimately be determined by that of Type I supernovae.

If more hot gas is produced than can be held by the gravitational field of the galaxy, there is a flow of hot gas out of the galaxy. The properties of galactic winds in the spherically symmetric case have been discussed by Mathews & Baker (1971). The winds can occur even in the presence of radiative cooling; the cool material falls to the center of the galaxy. Winds driven by supernovae can be of particular importance in the early evolution of galaxies (Larson 1974). Certain characteristics of low-mass elliptical galaxies, such as their lack of central concentration, can be understood given the hypothesis that supernovae drove the ISM out of the young galaxies.

4.3 *Kinetic Energy*

Spitzer (1968) showed that supernovae can be important contributors to the kinetic energy of interstellar clouds; the energy is dissipated in cloud collisions. Recent calculations of SNR evolution have not substantially changed his estimates. Spitzer found that 3% of the initial supernova energy is in cloud motions when the motions have slowed to the mean velocity of interstellar clouds. Chevalier (1974) obtained an efficiency of 4% for an ambient density of 1 H atom cm^{-3} and an efficiency of 8% for a density of 0.01 H atom cm^{-3}. If the density is high, less energy is available for cloud motions because of radiative losses. Salpeter (1976) estimated a 10% efficiency and found that the kinetic energy supplied by supernovae may be larger than that required to maintain cloud motions. He conjectured that the excess energy may go into heating a neutral component of the ISM by cloud motions. Considering the large uncertainties in the input parameters, it can only be concluded that the amount of kinetic energy required for cloud motions is consistent with a supernova origin. Detailed characteristics of the clouds must be examined in order to make progress on this problem.

Observational data is available on the distribution of cloud velocities for the intermediate and high-velocity clouds. Siluk & Silk (1974) have compared this data with what would be expected on the hypothesis of the supernova origin of cloud motions. They assumed that interstellar clouds are to be identified with the dense shell that forms late in the evolution of a SNR and found that the supernova hypothesis is compatible with the data.

5 RELATIVISTIC PARTICLES

5.1 *Young Supernova Remnants*

Relativistic electrons can be studied by means of the nonthermal radio synchrotron radiation they emit. Young supernova remnants fall into two classes with regard to their radio properties. The first class is characterized by a centrally peaked, amorphous region of radiation and a flat spectral index ($\alpha = 0.0-0.25$ where α is defined by flux $\propto \nu^{-\alpha}$). The prototype of this class is the Crab Nebula; 3C58 is another example (Wilson & Weiler 1976). The second class is characterized by an apparent annular region of emission and a steeper spectrum (α in the range 0.4–0.8). Examples are Cas A, Tycho's SNR, Kepler's SNR, and the remnant of SN 1006. The energy content in relativistic electrons appears to be similar for the two types of remnants (Woltjer 1972).

Interaction with the ISM may have only a small effect on the properties of the first class of remnants; these remnants are probably dominated by a central pulsar that supples the energy for the nebula. However, the ISM may play a role in confining the relativistic gas produced by the pulsar (Max et al. 1976).

The large particle energies in the second type of remnant imply that recent particle acceleration has taken place. The apparent annular structure of the remnants suggests that acceleration is occurring in the outer parts. A plausible hypothesis is that there is a turbulent acceleration mechanism associated with the interaction of the supernova ejecta with the ISM.

Gull (1973a, 1975) has suggested that turbulence is generated by the Rayleigh-Taylor instability which occurs when the ejected supernovae shell interacts with the interstellar medium (see Section 3.1). Using a numerical model, he has calculated the amount of energy in the convective-like motions as a function of time. The basic parameters are the mass of the ejected shell, its velocity, and the density of the ambient medium. The total energy in turbulent motions does not exceed 1% of the supernova energy. Gull assumes that equipartition is reached between the turbulent motions, the magnetic field, and the relativistic electrons. The model has been used to derive parameters for Cas A and the remnant of Tycho's supernova (Gull 1973b).

Gull derives an age of 200 years for Cas A; his model requires considerable deceleration to have occurred. However, the observations of the fast-moving knots are consistent with no deceleration and indicate an age of about 310 years (van den Bergh & Dodd 1970). As mentioned earlier, it is likely that the knots formed during or soon after the supernova explosion. Therefore, another model of turbulent particle acceleration has been developed for this remnant (Scott & Chevalier 1975; Chevalier, Robertson & Scott 1976). In this model, the knots formed during the explosion and have been moving at near constant velocity since that time. As they move through the surrounding medium, they create turbulent wakes (Figure 2). The knots lose mass as they move because of instabilities and heat conduction. It is conjectured that many have already been evaporated at this time.

Fermi-type acceleration in a turbulent medium appears to be adequate to explain the observations of Cas A (Chevalier, Robertson & Scott 1976). The Fermi gains are offset by adiabatic expansion losses; because the time scales for these two processes are similar, the correct spectral index is obtained. However, there is no underlying physical reason for the similarity in time scales so the model does not explain the small range of spectral indices observed in SNRs. Chevalier et al. solved for the diffusion of particles in energy space with time and were able to fit the following observed properties of Cas A: the spectral index, the curvature of the spectrum, the rate of flux decrease, and the rate of spectral flattening. The model is oversimplified and is probably not unique, but it does show that turbulent acceleration mechanisms hold promise for explaining the properties of young SNRs.

The recent map of Cas A with the Cambridge 5-km telescope shows a wealth of detail in the remnant (Bell, Gull & Kenderdine 1975). The radio remnant does appear to have a well-defined edge, which Bell et al. suggest is the perimeter of the shock front. A sharp edge is also found in the remnant of Tycho's supernova (Duin & Strom 1975). These observations raise the question of the propagation of relativistic particles inside a young supernova remnant. If propagation is slow, e.g., limited to the Alfvén velocity, particle acceleration in the shock wave may be required. The Cas A map shows evidence for cellular structure, as does a high-resolution polarization map of Tycho's SNR (Duin & Strom 1975). These features may be giving information on turbulent processes. More direct information on turbulence can be obtained from observations of changes in the remnants. In comparing the 5-km Cambridge map of Cas A with a previous map by Rosenberg (1970), Bell found that the radio peaks move with random velocities of several thousand km sec^{-1}. The mean outward velocity of the radio peaks is considerably less than the velocities of the fast-moving optical knots at the same distance from the center of expansion. The generation of turbulence by the Rayleigh-Taylor mechanism may no longer be effective for the slow-moving material, so the turbulence may be generated by the fast-moving knots traveling through a shell (A. R. Bell, personal communication).

5.2 *Old Supernova Remnants*

The mechanisms described above involve the generation of turbulence by the interaction of the supernova ejecta with the ISM. After this phase, when most of the supernova energy has been transferred to the ISM, it is expected that a blast wave is driven into the ISM. If the gas acted like a fluid and the ambient medium were uniform, the shock front would be stable and the flow would be laminar. Further particle acceleration would not occur and adiabatic expansion losses of the particles would be the dominant effect. However, the gas is actually a collisionless plasma and turbulence probably plays a role in the shock transition. Also, as the shock front passes irregularities in the ambient medium, turbulence may be generated in the post-shock flow (S. F. Gull, personal communication). These possibilities have not been thoroughly investigated; it is possible that particle acceleration occurs in the blast wave phase. Such a theory may be required to explain the radio radiation from Tycho's remnant, which is probably in the blast wave stage of evolution (van den Bergh 1971).

The radio flux is likely to increase when the remnant, or parts of the remnant, enters the cooling phase and a dense shell forms. The compression of ambient magnetic fields and relativistic electrons can give rise to enhanced synchrotron radiation (van der Laan 1962). Old remnants that emit radio radiation primarily by this mechanism constitute the third class of radio supernova remnants. Examples are the Cygnus Loop, S 147, and IC 443. This class of remnants appears to be observationally distinguishable from the second class in that predominantly tangential magnetic field configurations are found as opposed to radial fields in the second class of remnants. Recent data that tend to confirm the basic radiation mechanism are the high-resolution Westerbork observations of IC 443 (Duin & van der Laan 1975). The radio emission is seen to follow closely the optical emission, indicating that the emission is from the compressed regions behind the shock wave.

The Σ-D plot is used to describe the relation between surface brightness and diameter of SNRs (cf Woltjer 1972). Considering that there are at least three classes of radio SNRs, it is surprising that any relation exists. Besides, the radio flux from the last two classes of remnants, and possibly the first as well, is probably dependent on the density of the ambient medium. In view of the lack of theoretical understanding of the Σ-D relation, it should be used with care in deriving distances of SNRs. For example, remnants in the late stage of blast-wave evolution and remnants in a low-density medium may be anomalously weak radio emitters. Clark & Caswell (1976) have compiled a catalog with all SNRs down to a uniform level of surface brightness. The numbers they find for the frequency and energy of events giving rise to typical radio remnants are in fair agreement with those found from supernova explosions themselves (Section 2).

5.3 *Cosmic Rays*

Turbulent acceleration mechanisms in young remnants are expected to yield relativistic protons and heavy nuclei as well as electrons. Young remnants are thus candidates for the acceleration sites of the cosmic rays observed at earth. The spectral index of cosmic rays is similar to that deduced for the relativistic electrons in SNRs, although the remnants generally have a somewhat flatter spectrum. The composition of cosmic rays can also give information on their origin. The analysis of Hainebach, Norman & Schramm (1976) shows that about equal amounts of supernova ejecta and interstellar material are required to produce the cosmic ray composition. This composition results naturally from the kind of acceleration discussed above. Most of the particle acceleration occurs when the ejecta have swept up their own mass in surrounding material because the turbulent energy is greatest at that time. Assuming that the ejecta are mixed in with the turbulent gas, the correct cosmic ray composition results. It should be noted that because the particle gyroradii cannot be larger than the size of the accelerating turbulent clouds, proton energies above a few times 10^{15} eV are not created by this mechanism.

Another factor to be considered is whether supernovae can provide the energy of observed cosmic rays. The turbulent acceleration mechanism can probably yield at most a few percent of the total supernova energy, that is, a few $\times 10^{49}$ ergs. If Cas A has 100 times as much energy in relativistic protons as relativistic electrons and the particles are in energy equipartition with the magnetic field, this is approximately the particle energy that would be deduced from the synchrotron emission. This is also the energy per supernova required for cosmic rays based on the mass traversed by cosmic rays, the supernova rate, and the mass of gas in the galaxy (cf Lingenfelter 1973). However, the cosmic rays experience adiabatic losses while their energy density is larger than the mean galactic energy density (Wentzel 1973, Kulsrud & Zweibel 1975). This results from a hydromagnetic instability that is excited when relativistic particles stream along magnetic field lines. The cosmic ray energy is transferred to Alfvén waves that dissipate the energy in the thermal gas. This mechanism can reduce the cosmic ray energy produced in a remnant like Cas A by more than an order of magnitude. Yet if a significant fraction of supernovae occur in a low density medium, the adiabatic loss problem may be alleviated. It is also possible that a more complex model of cosmic rays in the Galaxy is required, taking into account inhomogeneities within the Galaxy. The long lifetime of cosmic rays found by Garcia-Munoz et al. (1975) may indicate that the required energy per supernova has been overestimated.

In addition to initially producing cosmic rays, SNRs can increase the energy of ambient cosmic rays by the betatron effect during the dense shell phase (Chevalier 1977). Cosmic rays may initially be reflected by the SNR shock, but it is assumed that they are eventually swept up by the shell because of the tangled nature of the ambient magnetic field. The energy increase can be more than 0.1% of the supernova energy if some particles escape from the dense shell or if there is moderate pitch angle scattering. Regardless of any energy increase, the cosmic ray energy content of the dense shell may be 10^{48}–10^{49} ergs. These particles can result in an observable flux of γ-rays through pion decays. Thus, γ-ray observations of old remnants may only yield information on swept-up interstellar cosmic rays rather than on recently accelerated particles. As the resolution of γ-ray experiments improves, observations of young remnants such as Cas A and Tycho's remnant should indicate their relativistic proton content. Because these would be particles produced in the remnant, we will then be in a better position to decide whether young remnants can supply the bulk of galactic cosmic rays.

6 CONCLUSIONS AND FUTURE PROSPECTS

Supernovae are likely to be important sources of energy in the ISM. In particular, they may give the kinetic energy of cloud motions, create the hottest ($T \approx 10^6$K) component of the ISM, give soft X-rays that partially ionize a component of the ISM, and accelerate the bulk of cosmic rays. Individual supernova remnants act as interstellar laboratories in which a wide range of physical phenomena may be observed. Examples are the action of heat conduction, turbulent amplification of magnetic fields, turbulent acceleration of relativistic particles, and the growth of Rayleigh-Taylor type instabilities. Future observations relevant to the interaction of supernovae with the ISM hold a great deal of promise. Possible observations in each band of the electromagnetic spectrum will be reviewed in order of increasing frequency.

Radio observations of young SNRs will be of particular interest. Temporal differences in the structure and spectrum of Cas A have already been found. Recently, Cas A has shown a flux increase at low frequencies, as opposed to a continued decrease at higher frequencies (Erickson & Perley 1975, Read 1977). This may be due to a sudden injection of relativistic particles or to an increase in the magnetic field if the electron spectrum steepens at low energy. As information on turbulent processes in the remnant may be obtained, monitoring of the spectrum should be continued. With the turbulent acceleration hypothesis, there are many acceleration sites throughout the remnant and there is no reason to expect each one to produce particles with the same spectral index. Detailed spectral index maps may give information on the diffusion of particles in the remnant. In this regard, a low-frequency interferometric map of Cas A would show whether the observed flux increase is localized. These types of observations may eventually be extended to fainter sources, like the remnant of Tycho's supernova.

Infrared studies of SNRs have not yet yielded significant results, although, as discussed in Section 3.4, radiation from cooling shock waves and collisionally heated grains in hot gas may be expected. Optical spectra of old remnants act as probes of the surrounding ISM (Section 3.4). Further spectrophotometry of old remnants will be valuable as improved theoretical calculations of shock wave spectra become available. The hot gas in remnants can be investigated in the coronal lines and, possibly, Hα (Kirshner & Taylor 1976). The Fe XIV line at λ5303 is the most suitable coronal line for detailed study (cf Woodgate et al. 1974), and it may become possible to map older remnants in this line. The Ca XV line at λ5694 is emitted by higher temperature gas, but is expected to be considerably fainter than the Fe XIV line. The future coronal line studies will supplement X-ray studies of the hot gas.

The energies to which particles can be accelerated by a turbulent mechanism in a remnant like Cas A is an important problem. Efforts should be made to detect nonthermal radiation from Cas A at infrared and optical wavelengths. This emission could be identified as such by comparison with the high-resolution radio maps of Cas A and by its polarization properties.

Lines from a wide range of ionized species are available in the ultraviolet. The Copernicus satellite has been used to observe stars behind the Vela remnant (Jenkins et al. 1976). Studies of high-velocity features in the ultraviolet may indicate whether they can be identified as SNR shells. If so, this would provide further evidence for the hypothesis that supernovae are important contributors of kinetic energy to the ISM. Imaging of SNRs in the ultraviolet is just beginning (Carruthers & Page 1976). It provides the opportunity to observe gas that is somewhat cooler than the X-ray emitting gas and thus may yield information on the transition regions between hot gas and cool clouds.

Future X-ray experiments promise improved spatial and spectral resolution. The source of the softer X-rays from the young remnant Cas A for which there are presently several theories will become clear. Information on the interaction of hot gas with clouds will be obtained, and it will be interesting to see whether soft X-rays become more pronounced near clouds. High spectral resolution observations of young remnants will be of particular interest if the hypothesis that the supernova ejecta are heated to X-ray emitting temperatures is correct. We will then have information on the initial process of mixing of supernova ejecta into the ISM. As discussed in Section 5.3, γ-ray observations will play a crucial role in determining whether SNRs produce the bulk of galactic cosmic rays.

There are two broad areas of theoretical research in this field that will probably command a great deal of attention in the future. The first is the plasma physics of supernova remnants. The structure of the collisionless shock waves in young remnants is poorly understood. This is a topic where experience from interplanetary shock waves, especially the earth's bow shock, may yield important insights. Turbulent processes leading to the amplification of magnetic fields and particle acceleration require further exploration. In these areas, the theory must be closely tied to observational results, as any general understanding of these processes is lacking. Finally, questions concerning the diffusion of relativistic particles through and out of a supernova remnant require further attention.

The second area is the role played by the hot gas phase in a complete picture of the ISM. It now seems likely that supernovae are capable of contributing hot gas to a galactic corona, as first envisioned by Spitzer (1956). There may be a continual recycling process through the corona; this process may be important for the structure of the galactic magnetic field, and it may play a role in a galactic dynamo. Further problems involve the importance of the hot gas for the propagation of cosmic rays and its interaction with the pressure perturbations generated by spiral density waves.

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