# 16. DISCUSSION FOLLOWING THE REPORTS BY SALPETER AND WOLTJER

*(Saturday, September 13, 1969)*

Chairman: L. Davis

**Editor's remarks:** During the second half of this Discussion van de Hulst commented on the overall flow of energy in the interstellar medium. That part of the Discussion has been transferred to the Final Discussion (p. 362). The rest has been rearranged into the form presented here.

## 1. Discussion of Salpeter's Report

**Mestel:** I would like to repeat a point I made this morning when presenting Salpeter's paper. Pagel has emphasized that there is no evidence in support of a steady increase of the heavy-element content of stars continuing from the galactic birth. This picture is a theorist's idealization. If you consider M67, the prototype of the oldest galactic clusters, you will find that it does not contain significantly fewer heavy elements than the Sun. But the oldest globular clusters are certainly deficient in heavy elements. Salpeter concludes that there was an early phase of rapid heavy-element formation, perhaps during the collapse of the Galaxy, and subsequently only a very modest increase. This corresponds to very different star formation laws in the two phases, which is reasonable enough, as the gas dynamical conditions were certainly different.

**Pikel'ner:** For some problems it is important to know what fraction of the interstellar gas is still primordial, and what fraction has gone through a stellar state. One such problem, for example, is the question of how many quarks there are in our vicinity. Together with Okun' and Zel'dovich, I estimated that between 10 and 30 per cent of the gas is still primordial. But I think that a more reliable result can be obtained from Salpeter's fractions.

**Mestel:** I do not know if any of the primordial gas is left over.

## 2. Discussion of Woltjer's Report

**Bisnovatyi-Kogan:** I should like to give a short description of a mechanism for supernova explosions that is not based on neutrino emission and detonation of a nuclear explosion. The model I have in mind is the explosion of a rotating star (Bisnovatyi-Kogan *et al.*, 1967). Let us consider a star at the edge of rotational stability. The stability is lost and the star starts to collapse at the moment disintegration of iron ($Fe \rightarrow n, p, \alpha$) begins. In the core the collapse will stop after the formation of a neutron star; in the outer part centrifugal forces will stop the matter and form a flattened disk with a mass of the order of or greater than the mass of the neutron star. The disk will

*Habing (ed.), Interstellar Gas Dynamics, 236–248.* 

be in differential rotation with the rotational velocity decreasing outwards. If there is some momentum transfer from the core to the disk-like envelope, then compression of matter can occur, a shock wave can be produced, and an explosion may follow. The momentum transfer can be accomplished by a magnetic stress following from a field of at least $3 \times 10^9$ G. In this way we can understand why supernova remnants have rotational velocities much less than pulsars.

Finally I want to draw attention to calculations by Imshennik and Nadezhin from the Institute of Applied Mathematics in Moscow who studied supernova models of $10 M_{\odot}$ and $30 M_{\odot}$ and found a mass loss of 5 per cent and $3 \times 10^{50}$ erg of kinetic energy in outflowing matter. [Bisnovatyi-Kogan, G. S., Zel'dovich, Ya. B., and Novikov, I. D.: 1967, *Astron. Zh.* **44**, 525 (Translation: 1967, *Soviet Astron.* **11**, 428).]

**Krat:** The transfer of angular momentum from the center of a star to the atmosphere can be one of the causes of stellar explosion. As far as I remember the effect was first noted by Hoyle. The efficiency of the mechanism is very strongly dependent on form and strength of the magnetic field. It may remove much angular momentum from stars to the interstellar medium, so it is a very important effect to study.

**Colgate:** I have a couple of comments. First, I want to discuss the iron production in a supernova. There are arguments that per supernova explosion $\frac{1}{4} M_{\odot}$ of iron is produced. (a) This amount is suggested by the present theories of nucleo-synthesis by Truran *et al.* (1967) and by Bodansky *et al.* (1968), which predict that all iron is produced through $Ni^{56} \rightarrow Co^{57} \rightarrow Fe^{56}$. (b) A recent paper by Clayton and Silk (1969) indicates that the gamma rays produced in this process may explain the observed overabundance of gamma rays in the Universe. They require $\frac{1}{4} M_{\odot}$ of iron per supernova. (c) Recent work by McKee and myself (Colgate and McKee, 1969) ascribes the optical emission of supernovae to the sequence of beta-decays mentioned above. $\frac{1}{4} M_{\odot}$ of iron synthesized to $Ni^{56}$ gives a beta-decay energy of $10^{49}$ erg – which is the total amount of light put out by a supernova.

To explain all the iron in the Galaxy by supernova explosion, you need one supernova per ten years. That seems pretty high. But according to Salpeter's Report there was a rapid formation of metals in the early history of the Galaxy, and that would agree with a high supernova rate in the young Galaxy, but a lower rate now. Fortunately there is a large probability that within the next two years measurements will select the correct theory. The measurements follow from a suggestion by Clayton *et al.* (1969), that we look in a supernova for gamma rays from decaying Ni, Co, and Fe. If a supernova occurs in one of the 50 to 100 nearest galaxies, one should be able to see the gamma-ray lines and the intensity as a function of time. This function of time gives you the thickness of the matter expanding around the star; and from this you can get both the total mass and a mean velocity distribution.

In the second place, I should like to raise an objection against the Morrison-Sartori (1969) theory of the optical emission of supernovae, which is based upon fluorescence of an envelope around the supernova by UV radiation from the supernova star. Since the fluorescing medium is He, we consider only UV photons with $h\nu > 54$ eV. No more than $10^{-1}$ of the energy of all photons will be in this part of the spectrum;

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kinetic energy cannot be converted into photons with an efficiency higher than $10^{-1}$; the efficiency of the fluorescence mechanism is at best $10^{-2}$. This means that with a light output of $10^{49}$ erg we need a supernova energy of $10^{53}$ erg. This large an energy seems unlikely.

In the third place, the present theories of supernovae with neutron star formation, including my own work (Colgate and White, 1966) and that of Arnett and Schwartz, are, according to a recent paper by Arnett and Truran (1969), all necessarily wrong. They are wrong because they result in the ejection of too much heavy-element matter. Instead Arnett and Truran would claim that the vast majority of supernovae were thermonuclear ($C^{12}+C^{12}$) in origin and that neutron stars are formed without significant mass ejection. (Truran, J. W., Arnett, W. D., and Cameron, A. G. W.: 1967, *Can. J. Phys.* **45**, 2315; Bodansky, D., Clayton, D. C., and Fowler, W. A.: 1968, *Phys. Rev. Lett.* **20**, 161; *Astrophys. J. Suppl.* **16**, 299; Clayton, D. C. and Silk, J.: 1969, *Astrophys. J. Lett.* **158**, L43; Colgate, S. A. and McKee, C.: 1969, *Astrophys. J.* **157**, 623; Clayton, D. C., Colgate, S. A., and Fishman, G. J.: 1969, *Astrophys. J.* **155**, 75; Morrison, P. and Sartori, L.: 1969, *Astrophys. J.* **158**, 541; Colgate, S. A. and White, R. H.: 1966, *Astrophys. J.* **143**, 626; Arnett, W. D. and Truran, J. W.: 1969, *Astrophys. J.* **157**, 339.)

**Sunyaev:** I agree with Colgate that $10^{52}$ erg in UV radiation per supernova is too much. Such a flux would give a background radiation from the Metagalaxy which is 10 to 100 times more than is observed. Also, if the UV flux is in 100 eV photons the effects on the interstellar medium become important. For the heating of all interstellar matter in the Galaxy we need $10^{40}$ to $10^{41}$ erg $\sec^{-1}$; this allows per supernova only $10^{49}$ to $10^{50}$ erg in UV photons.

**Colgate:** To bring up another point, there is also the question of the energy spectrum of ejected matter. The existing theories predict about $10^{52}$ erg in the form of particles with a kinetic energy between 2 to 5 MeV per nucleon. About $10^{50}$ erg is in relativistic matter. Apparently the large mass of low-energy matter is not observed, I think for the following reason: the slowing-down time by collision is $10^{6}$ yr. But in $3\times10^{4}$ yr the matter is so far expanded (radius $3\times10^{21}$ cm), that the magnetic energy inside this volume is $10^{52}$ erg, and the matter can easily escape along the field lines without forming a shock. Instead, a small fraction of the mass, whose velocity is only $3\times10^{8}$ cm $\sec^{-1}$ will slow down in 100 yr by collisions (the collisional cross-section $\sigma\propto V^{-4}$) and form an easily visible (and sharp) shock front at a radius of $10^{19}$ cm.

**Syrovat-skii:** From the total mass of the interstellar gas in the Galaxy and the total amount of matter traversed by cosmic rays we can estimate that all the sources in the Galaxy produce (1 to 3) $\times 10^{40}$ erg $\sec^{-1}$ in cosmic rays. If there is one supernova per 30 yr, you have (1 to 3) $\times 10^{49}$ erg of cosmic rays per supernova. This is less than Colgate mentioned, although not by a large amount.

**Tsytovich:** I am not convinced that the 2 to 5 MeV particles escape without forming a shock front. If fast particles penetrate into a plasma they excite waves, for example Langmuir waves. The group velocity of these waves is much smaller than the particle velocities, and the waves accumulate near the surface where the particles enter the plasma. The layer of accumulated waves can act as a very sharp shock wave and reflect cosmic rays. Theoretical work on this subject has been done by Feinberg and Shapiro.

**Colgate:** I have argued many times for such an electrostatic shock. The problem is that the energy distribution of the ejected matter is monotonically decreasing with time; it has no peak. Therefore, I am not convinced that it will excite electrostatic waves. Are the cosmic rays electrostatically unstable? I am not sure.

**Tsytovich:** I think they are. If you have a monotonic distribution inside the supernova, the faster particles enter the surroundings more quickly and some kind of instability must exist. In addition the outgoing cosmic rays have an anisotropic velocity distribution locally, where they penetrate into the undisturbed plasma.

**Colgate:** But the density ratio between the high energy particles and the ambient plasma is probably very small. When you put in the Landau damping, the density ratio, the velocity gradient, and in addition, the magnetic field diffusion for the outside field, the problem is very difficult to solve.

**Tsytovich:** I agree, but still I think that possibilities for instabilities exist. May I now ask Dr. Woltjer what evidence he has that the high-energy particles in the Crab Nebula have been accelerated recently?

**Woltjer:** In the case of the electrons there is evidence from the spectrum of the synchrotron radiation. The radio emission can be explained as coming from electrons injected shortly after the supernova explosion. But the optical synchrotron radiation, emitted by electrons with energies of several hundreds of GeV, cannot be explained in this way. The combined effect of expansion and synchrotron radiation gives these electrons a lifetime shorter than the age of the Nebula. The argument holds even more strongly for the X-rays, but here we are not certain that the X-rays are really synchrotron radiation.

**Tsytovich:** I think that there is a possibility for compensation of the energy losses of fast particles. Usually the energy losses are proportional to the square of the particle energy and to the square of the magnetic field strength. But in a turbulent region the acceleration rate $d\bar{\varepsilon}/dt$ is also proportional to the square of the particle energy. It therefore exactly compensates the losses. However, the acceleration depends also very strongly on the density and the temperature of the turbulent plasma. In the Report by Kadomtsev and me, we give a table (Table I, p. 129) that predicts the acceleration time. It shows that in a plasma with a temperature of 10 eV the acceleration time is very short for a density of $10^{20}$ cm$^{-3}$ and very long for $10^{2}$ cm$^{-3}$. So the question is, in what density does the acceleration take place? Another point is that one usually assumes that the emission is synchrotron radiation. But plasma turbulence may emit light with the same spectrum. And induced effects can give polarization without a magnetic field.

**Woltjer:** First, the energetic electrons do not radiate only near the star, but they radiate all through the nebulosity. The surrounding density must be quite low, certainly less than 100 cm$^{-3}$, and probably much less. I think, therefore, that you can not compensate for the radiated losses of the particles by plasma turbulence. The clue

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to the energy input in the Nebula may well be given by the wave-like phenomena that are observed near the center of the Nebula, near the location of the pulsar. As Baade first observed, near the location of the pulsar you see from time to time small waves moving out with velocities on the order of one tenth the velocity of light. (Of course, the fact that these waves propagate so fast tells you that the density there must be very low.) Second, I agree, of course, that you can obtain some polarization with a suitable anisotropy. But the linear polarization observed in the Crab Nebula goes, at some places, up to 60 and 70 per cent. On whether you can get that much polarization just from anisotropy in the turbulence, I would still be a bit doubtful.

**Tsytovich:** I think that it is possible to have a very high degree of polarization. But the plasma turbulence should give a rapid change in polarization angle.

**Woltjer:** The effect of polarization is extremely regular in the Nebula, and this would suggest that magnetic field is the cause.

**Syrovat-skii:** I have some remarks to Tsytovich concerning the acceleration of particles by high-frequency plasma waves. There are reasons to believe that for most of the cosmic rays high-frequency plasma turbulence is not the acceleration mechanism. The first reason is that the acceleration by high-frequency plasma turbulence is not effective at high energies. We have seen in the Kadomtsev-Tsytovich Report (p. 108) that at high energies the acceleration is inversely proportional to the energy. It means simply that the acceleration by plasma turbulence heats the particle to some effective temperature of the order of the temperature of the plasma disturbances. But in cosmic rays we have particles up to $10^{20}$ eV and this seems too high a temperature for a turbulent plasma in interstellar space. The second reason lies in the chemical composition of the accelerated particles. All the statistical mechanisms of acceleration are based essentially on thermal injection. It means that the particles are accelerated from the tail of the Maxwell distribution. In this case the acceleration is very sensitive to the mass and the charge of the particles. It was shown about ten years ago, by Korchak and myself (Korchak and Syrovat-skii, 1958), that, if you have thermal injection, then the heavy ions are accelerated faster than the protons or electrons. The same argument may be used for plasma turbulence. But we observe that the cosmic-ray particles have almost the cosmic abundance, and in addition, there is a large number of electrons. So it seems to me that a more realistic mechanism is cumulative acceleration. The first example of such a mechanism has been given by Colgate (Colgate and White, 1966). In this mechanism all particles are accelerated together in the thin outer envelope of the exploding supernova star, because an ultrarelativistic shock wave blows up the outer layer of the star. However, this theory has difficulties with the structure of the shock wave and may not work. Another possibility of cumulative acceleration comes from studies of solar flares and the magnetosphere. An example of such a mechanism is the current sheet which develops near magnetic zero (neutral) lines. When the current sheet is disrupted, then all the plasma particles are accelerated to very high energy. Perhaps a mechanism of this sort can account for the interstellar cosmic rays. [Korchak, A. A. and Syrovat-skii, S. I.: 1958, *Dokl. Akad. Nauk SSSR* **122**, 792 (1958, *Soviet Phys. Dokl.* **3**, 983); Colgate, S. A. and White, R. H.: 1966, *Astrophys. J.* **143**, 626.]

**Tsytovich:** I want to say that the efficiency of the acceleration by plasma turbulence increases with particle energy up to very high values. For example, if a supernova of approximately one solar mass explodes, the density is very high in the first stage, and particles with an energy of $10^{16}$ eV can be produced in the time in which the supernova doubles its radius. Near the neutron star one can produce particles up to $10^{18}$ to $10^{19}$ eV, and therefore it seems possible to produce all cosmic rays by plasma turbulence in supernova explosions. As regards the problem of injection: Melrose has shown that Alfvén-turbulence leads to preferential acceleration of heavy ions. But Langmuir-turbulence is very effective for acceleration of protons and electrons. As an example, Shklovskii has stated that supernovae seem to produce more relativistic electrons than relativistic protons.

**Zel'dovich:** Dr. Woltjer, you described the shock wave as a front between undisturbed gas and gas set in motion. But is it not possible that the radiation should ionize the gas even in advance of the shock wave? One must therefore distinguish a region where gas is ionized but not moving, and then the shock wave going into ionized gas. And only in the later stages, perhaps, will the shock wave overtake the ionization front.

**Woltjer:** In the very early stages, the energy per particle behind the shock is so large compared to the ionization energy, that it makes little difference for the velocity of the shock whether the gas in front of the shock is ionized or not.

**Zel'dovich:** No, perhaps that is true for the velocity, but the physical state of the gas is not the same, and there may be a large difference in the UV and X-ray emission.

**Woltjer:** In the case of the Cygnus Loop, one can show that depending upon the amount of UV radiation emitted in the original supernova explosion, the gas which is swept up at this moment could easily be either ionozed or not ionized. In principle, this gives small differences in the observable spectra. At this moment it is not possible to distinguish observationally between the two possibilities.

**Zel'dovich:** The shock wave is a very stable phenomenon. This can be demonstrated for shock waves moving in water. The shock waves reflect light. If one perturbs the shock front the image wiggles and after a short time it is normal again. But there is another front, namely that which divides the compressed interstellar gas and the expanding shell. There is pressure equilibrium, but the front is unstable. My question now is: does one observe this instability?

**Woltjer:** The possible instability of such a front is very interesting. We have been considering the possibility that the filamentary structure of the envelope in the Crab Nebula may be due to the instabilities that you mentioned.

**Lüst:** I would like to discuss an experiment which is of interest for the question of instabilities occurring in a spherical expansion. This year we have carried out an artificial plasma cloud experiment at 12.5 Earth radii in the distant magnetosphere. The density in this region is so low that collisions among particles are of no importance; furthermore in the initial phase the kinetic energy density in the radially expanding cloud was large as compared to the magnetic energy density of the Earth's magnetic field. The initial spherical cloud broke up very soon into filaments elongated along the magnetic lines of forces, and we believe that this disruption was caused by flute instabilities. The theoretical estimates of the characteristic times are in good agreement. In this case the observed structures are not related to the injection mechanism but are due to the acceleration in the expanding cloud.

**Silk:** Dr. Woltjer, your explanation of the energy in the Cygnus Loop was based on $H\alpha$ emission. Is it not possible that there is a substantial region of high-temperature gas which would be emitting lines observable primarily in the soft X-ray region?

**Woltjer:** The cooling time of the high-temperature gas is shorter than the lifetime of the Cygnus Loop. That means that at the present time there is a steady state behind the shock wave. For every incoming proton, there is one in the gas behind the shock that has to recombine.

**Silk:** My comment relates supernova explosions to observations of H I regions. The discussion by Spitzer and Tomasko of the heating of H I regions by low-energy cosmic rays indicated that $\approx 10^{51}$ erg per Type I supernova must be injected in low-energy cosmic rays, with a frequency of one supernova per hundred years. The alternative explanation of the observed temperatures and electron densities in H I regions makes use of soft X-rays. This mechanism has been proposed by Sunyaev in the Soviet Union and by Werner and myself in the United Kingdom. Supernova remnants may be strong sources of soft X-rays. We require something like $3 \times 10^{30}$ erg of soft X-rays per supernova. Heiles (1964) and Shklovskii (1968) have suggested that a substantial amount of the initial kinetic energy of the supernova shell is radiated in bound-bound emission during the deceleration phase. These authors considered only O VII and O VIII emission at $\approx 20$ Å, where the interstellar medium is essentially transparent. I would like to point out that appreciable emission will also occur in the lines of C V at 34 Å and C VI at 40 Å and in two photon decays from the $2s$ states of these oxygen and carbon ions. Most of the photons will not escape from the Galaxy, and so a substantial fraction of the supernova energy may provide a soft X-ray input to the interstellar medium. For example, if we take $\approx 3 \times 10^{51}$ erg for the initial kinetic energy of the supernova envelope, and assume that 10 per cent of this energy is converted into soft X-rays of energy below 0.3 keV, then a supernova rate of one per century is sufficient to give a heat input to the interstellar medium of $3 \times 10^{-26}$ erg $cm^{-3}$ $sec^{-1}$ and a hydrogen ionization rate $\zeta$ of $5 \times 10^{-16}$ $sec^{-1}$. (Heiles, C.: 1964, *Astrophys. J.* **140**, 470; Shklovskii, I. S.: 1968, *Supernovae*, Wiley, London.)

**Sunyaev:** I should like to continue this and discuss a specific mechanism for the production of UV and soft X-ray quanta. The mechanism is based on the supernova model (unpublished) by Morozov and Imshennik from the Institute of Applied Mathematics in Moscow, which shows a shock in a low-density stellar atmosphere with an electron temperature of about $10^6$ K behind the shock. In the dense regions of the atmosphere, which are optically thick for bremsstrahlung, optical radiation is produced with a temperature of about $10^4$ K. When this low-temperature radiation diffuses outward through the $10^6$ K electron gas, its temperature rises due to inverse Compton scattering, a process discussed first by Kompaneyets in the U.S.S.R. and later by Weymann in the U.S.A. In this process the number of quanta does not change. The resulting spectrum is sketched, qualitatively, in Figure 1. The spectral form depends only on one parameter ($y = \int [kT_e/(m_e c^2)] d\tau$, where $\tau$ is the optical depth for Thompson scattering). If $y > 1$, the maximum of the spectrum is around $h\nu \approx kT_e$, which means, for $T_e = 10^6$ K, in the soft X-ray region.

**Pikel'ner:** In the first place, I want to discuss the origin of filamentary structure in supernova shells. I studied this problem many years ago (Pikel'ner, 1954) and found that there are two types of mechanism which can form filaments. When the supernova shell is very young, it is accelerated by cosmic rays and magnetic pressure. Gravity acts on the shell and a Rayleigh-Taylor instability can develop in a short time,

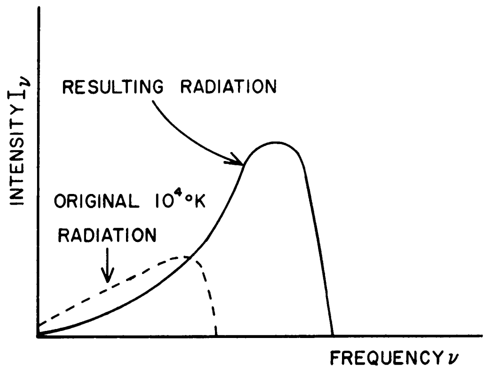


Fig. 1. (See the remark by Sunyaev.) Radiation resulting from interaction between photons emitted at $10^4$K and an electron shell of $10^6$K. The interaction process is the inverse Compton effect.

forming filaments. In an old shell like the Cygnus Loop, this mechanism does not work, because the shell is not accelerated. (Actually it is retarded.) In this case, some other formation mechanism may work, perhaps crossing of shock waves. The velocity of a shock wave is dependent on the density of gas in front of the wave. If there is some density fluctuation in the gas, the shock wave behaves as if it were focused by a lens, where the part of the lens is played by the density fluctuation. The focusing is not into a point but into a filament. Every density fluctuation should lead to a filament.

A second comment. Woltjer calculated the H$\alpha$ emission in supernova shells assuming that one H$\alpha$ quantum is produced per incoming proton. In my calculations of the emission of supernova shells like the Cygnus Loop (Pikel'ner, 1954), I found that collisional excitation of hydrogen can occur in a very thin, hot layer behind the shock front. This leads to an increase in total emission by a factor of about 2 to 3, so the layer is not very important. It would be interesting to know the new data on old supernova shells by Losinskaya from the Sternberg Institute in Moscow. She studied two old supernovae, IC 443 (velocity of expansion 65 km sec$^{-1}$), and Simeis 22 (velocity of expansion 35 km sec$^{-1}$). (Pikel'ner, S. B.: 1954, *Izv. Krymsk. Astrofiz. Observ.* **12**, 94. A discussion in English of this work may be found in Sections 9 and 10 of *Interstellar Gas Dynamics* by S. A. Kaplan, Pergamon Press, Oxford 1966).

**Woltjer:** I have a comment on the H$\alpha$ emission. First, the assumption was that each atom that comes in makes one recombination photon, not necessarily H$\alpha$. It may also be a photon of one of the other Balmer lines. But the point here is that the gas flowing into the shock front may already be in the ionized state due to the original UV radiation from the supernova. If the gas enters in that state, it remains ionized. Behind the shock there is no neutral hydrogen to be collisionally excited. And by the time that recombination becomes effective, the temperature is too low for direct excitation.

**Pikel'ner:** The emission in the filaments can be observed only if the density ahead of the shock front is not less than 10 particles $cm^{-3}$, and so the recombination time is less than the age of old nebulae, which is 20 000 years.

**Woltjer:** If the density is that high, that would be true.

**Field:** Dr. Pikel'ner, if the supernova explosion emits X-rays, the ionized gas in front of the shock may have a very high temperature, $10^5$ or $10^6$ K, which would reduce the recombination coefficient.

**Pikel'ner:** The temperature of the gas behind the shock front is dependent on the density in front of the shock. If this density is that of the rarefied intercloud medium, we cannot observe emission behind the shock front. The emission is only observed when the shock penetrates into a rather dense cloud, and in dense clouds the temperature of the gas due to X-ray emission cannot be very high.

**Sunyaev:** But near the supernova it can be.

**Pikel'ner:** It is more than 30 pc away.

**Field:** I have been doing some calculations of the X-ray ionization around a supernova. If I remember correctly, I obtained an envelope of 100 pc completely ionized gas for a density of one atom per $cm^3$. I did not calculate the thermal equilibrium, but I guess that the temperature will exceed $10^5$ K. Of course, for a surrounding medium of higher density the envelope will be smaller.

**Pikel'ner:** I do not know these calculations and cannot discuss them directly, but I think there is some observational answer. If the gas in front of the shock wave were ionized and strongly heated, it should expand and not leave behind condensations of 10 to 20 particles $cm^{-3}$. If, therefore, emission is actually observed from condensed gas, the gas in front of the shock wave is not ionized and not strongly heated.

**Field:** You are probably correct, but I think that one ought to look into the expansion of a dense region with a temperature of $10^5$ K.

**Kardashev:** I want to suggest that per supernova explosion we may observe two flares: an optical flare and a radio flare. The optical flare corresponds to the moment of explosion. The radio flare corresponds to the moment when in the supernova remnant magnetic fields and cosmic rays have maximum energy. The time difference between two flares should be large, possibly many tens of years, because we would obtain too large energy losses for the cosmic-ray particles if we assumed that the radioflare occurs during the initial explosion. Also the radio emission at this moment would be too large. Obviously, it is very important to observe the radio emission of the initial stage after the supernova explosion and also the initial stage of the pulsar. I mentioned before (p. 193) that in the remnants of supernovae magnetic fields can be generated by regular twisting of the magnetic flux between the pulsar and the expanding and rotating envelope. Such a process gives an increase of the magnetic energy; subsequently the magnetic pressure accelerates the envelope. The total magnetic energy at maximum is of the order of $10^{49}$ erg. The structure of the twisted magnetic field is perhaps related to that of the ripples observed near the pulsar in the Crab Nebula. There are three possibilities: (1) If the coupling between pulsar and envelope continues to exist up to the moment of observation, we get the picture of a central concentration of brightness, like that in the Crab Nebula. (2) If the coupling disappears after a short time, we obtain an envelope with a radial magnetic field like that in Cassiopeia A (and probably in the Tycho and Keppler remnants). This type of coupling may occur if the conductivity is small during the collapse of the star to the gravitational radius. This is probably the case in supernovae of Type II which have large masses. (3) If the time needed for generation of magnetic fields is too small, there will be no remnants left with non-thermal radio emission, and we obtain an isolated pulsar. So in summary, the three types of objects observed after a supernova explosion (thin envelopes, nebulae with central condensation, and isolated pulsars) may be explained by different initial conditions before explosion relating to the mass, the angular momentum, and the magnetic field of the star.

**Verschuur:** A question to the theoreticians: If the supernovae inject kinetic energy into the interstellar medium, how could one observe this? I have made 21-cm observations in the vicinity of nine pulsars and in two cases (CP 1133 and CP 0950) the hydrogen structure looks pretty interesting. It looks as if I see two shells, either expanding or contracting. Velocities involved are of the order of 5 km $sec^{-1}$.

**Woltjer:** When the Cygnus Loop becomes a few times $10^6$ yr old, the expanding shell will have a velocity of the order of 10 km $sec^{-1}$. So you may be correct.

**Colgate:** To answer Verschuur, when a supernova injects $10^{52}$ erg in low-energy cosmic rays (2 to 5 MeV per nucleon), then certainly one would expect to see the bubbles that have been discussed by Parker.

**Syrovat-skii:** In discussing the content of cosmic rays in supernovae, Woltjer assumed that the cosmic rays are confined and accelerate the shell. But what about the observational data? Do the radio isophotes coincide with the optical boundary? Or is there some radio radiation outside the sharp boundary which indicates diffusion of cosmic rays out of the shell?

**Woltjer:** I think that the photometric evidence available at the moment suggests that the outermost isophotes coincide with the filamentary shell. I don't think, however, that this is very strong proof that the particles are contained by the shell. For the surrounding interstellar medium the magnetic field strength is likely to be down by a factor of the order of 100, and the emission from escaped particles would be down by an even larger factor and, therefore, would be very weak. I think, however, that, unless you say that the particles escape completely freely, the estimate of the upper limit of the cosmic-ray content cannot be changed very much.

**Menon:** One of the characteristics of the radio contours of most of the supernova remnants is the extremely steep intensity gradient at the edge of the shell. But in addition, it is also a common characteristic that the shell is not complete. That is, in

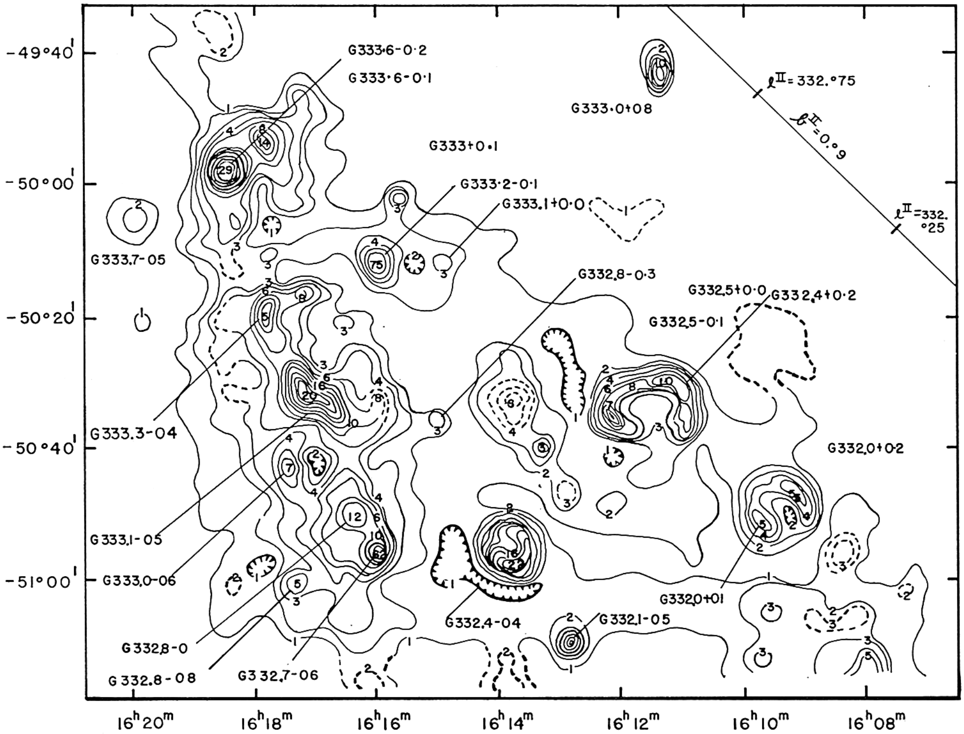


Fig. 2. (See the remark by Mills.) Radioisophotes in the constellation Norma at 408 MHz observed with the Molonglo radiotelescope. It shows several suspected supernova remnants. [This figure has been redrafted in the editorial office in order to improve the presentation. This was done, however, at the loss of some accuracy.]

almost all well-resolved cases, there appears to be a tail, perhaps a real blowout of particles. An example is the hole that you see in the Cygnus Loop. Often the structure shows symmetry, though not spherical symmetry. Usually the shell consists of two opposite arcs which are of fairly uniform brightness with some microstructuring inside them. In addition there is a very bright circular top part and a fairly well-defined bottom part. There are at least seven supernovae which show this structure. Symmetry of this type of structure is seen in objects, which are as different in age as the Cassiopeia remnant and the Cygnus Loop. I do not have an explanation, but I want to stress that this is a common characteristic and on probability arguments seven is a high number for formation on a random basis.

**Mills:** I have a slide (Figure 2) which shows that spherical supernova shells are an exception. The slide shows an area in the constellation Norma, observed with the Molonglo radio telescope; the resolution is 3′. The slide is from a paper by P. A. Shower and W. M. Goss, which is in press in the *Supplement Series* to the *Australian Journal of Physics*. The sources G332.0 +0.2, G332.4 −0.4, and G332.4 +0.2 are non-thermal and undoubtedly supernova remnants. However the sources G332.1 −0.5 and

G333.3 − 0.4 are both very dense H II regions in a ring-shaped structure. The remaining sources are also thermal. This is the sort of picture we find all along the Milky Way; and very, very rarely do the non-thermal sources have a nice symmetrical shape.

**Woltjer:** If you take a sample of supernova remnants, very likely it contains mainly old supernova remnants that have a long lifetime, and those are very thick. The first stages of a supernova remnant last for a much shorter time; therefore you have to select very special cases in order to discuss shells in the early stages.

**Mills:** Would you say then that the remnants in Figure 2 are all in Phase III?

**Woltjer:** Yes, if they are supernova remnants at all.

**Menon:** In your discussion of the various phases of the supernova phenomena, you put all observed remnants in the later stages except the Crab. On what parameters will the duration of Stage I depend?

**Woltjer:** The duration of Stage I will probably depend largely on the amount of matter injected, compared to the amount of interstellar matter in the same volume.

**Menon:** But then, is it not a coincidence that of all the remnants known to us and identified, all the others have velocities of 7000 km $sec^{-1}$ and more, whereas the Crab has a velocity of only about 1000 km $sec^{-1}$? If you classify supernovae on the basis of light curves, even Minkowski himself would agree that the classification of the Crab is most uncertain, because the light curve is not very reliable. Describing the Crab as a Type I supernova is, I think, rather dangerous, because the Crab has no parameters in common with all the other remnants.

**Woltjer:** It is true that one cannot classify the Crab Nebula as a supernova of Type I, Type II, or any other type. However, if you look at the current energy content, both in the pulsar and in the form of relativistic particles, it is clear that in the future the Crab Nebula will never reach an expansion velocity of the order of 7000 km $sec^{-1}$. There simply is not enough energy to accelerate the present shell to that kind of velocity. On the other hand, the total energy of the Crab at this moment is not very different from what you infer for the supernova that gave rise the Cygnus Loop.

**Shklovskii:** I want to point out a difficulty in comparing the Kepler supernova with the Tycho supernova. The properties of both supernovae, i.e., dimensions, brightness, etc., are practically equal. This would mean that the density of the matter surrounding the Kepler nova should be similar to that of the Tycho nova. But the Kepler nova is far from the plane (between 600 and 1000 pc) and the Tycho nova is not (100 pc). So here is a problem. Is the outside density the same?*

**Woltjer:** I would like to quote a counter example, namely the supernova of AD 1006. If this object has been properly identified, it is at about $b = +15°$, and it seems to have a radius that is far larger than that of the Tycho object. Perhaps one can interpret this in terms of a low interstellar density at that level, $z = 1000$ pc.

**Ozernoi:** In supernova explosions gravitational waves are also emitted. A few years ago I made some calculations (Ozernoi, 1965) which indicated that one can observe

* Dr. R. Minkowski (private information) suggests that the difference in distances to the Kepler and the Tycho supernovae, respectively, may have been overestimated in the past, the ratio between the distances being closer to 1.3 than to 2 as supposed by Shklovskii. (Ed.)

the gravitational radiation of an anisotropic supernova at a distance of about 10 Mpc. But the precise value of gravitational radiation depends on the degree of anisotropy in the explosion. I think that in the Crab Nebula there is an indication that the initial process of explosion was anisotropic. Does Dr. Woltjer agree with this? [Ozernoi, L. M.: 1965, *Zh. Eksp. Teor. Fiz. Pis. v. Red.* **2**, 83 (*Soviet Phys., JETP Lett.* **2**, 52).]

**Woltjer:** Yes, I do.

**Weymann:** May I ask Dr. Mestel why there used to be a discrepancy between the rate of star deaths and the supernova rate? Do the theorists think it is possible that stars greater than, say, $1.5\,M_{\odot}$ can die without leaving a trace? Can a collapse occur but not be observable as a supernova? And do the statistics still support the discrepancy which I mentioned? In the past we could not account for this discrepancy by appealing to slow continuous mass loss.

**Mestel:** I recall that when the figure of one supernova per 500 years was accepted, it then looked difficult to account for all the white dwarfs, assuming that a star evolving into a white dwarf must go through a nova or supernova phase. The new upper limit of one supernova per 30 years clearly releases the conditions, but more and more white dwarfs tend to be discovered. However, there are other ways in which stars can lose mass, e.g., by stellar wind-type mass loss in the red-giant phase, which may enable stars a little above the (modified) Chandrasekhar limit to evolve into white dwarfs. More to the point is the fairly violent phenomenon that enables an evolved star to transmute into a planetary nebula surrounding a hot central star which subsequently cools into a white dwarf. However, I am not well up on the statistics.

**Weymann:** I think that the planetary nebula phenomenon occurs only on those stars that are already near the white dwarf limit, stars of about 1.2 to $1.4\,M_{\odot}$. Could someone answer the question whether or not it is possible for a collapse to occur without producing supernova luminosity?

**Field:** I cannot answer that question. However, if Webber is correct in his estimate of the intensity of gravitational radiation by the Galaxy, the production of gravitational radiation is $10^6$ times that of electromagnetic radiation over all observed wavelengths (visible, infrared, and radio wavelengths).

**Colgate:** Lingenfelter (1970) has calculated the frequency of pulsar formation in our neighborhood, taking the distance from the electron dispersion and the time from the slowing down of the pulse rate. He found a frequency of pulsar creation of one per 100 years for the whole Galaxy. If one assumes that not all pulsars are observed, because they emit their radiation in beams, then the formation rate would be higher than this. In other words, 1 per 100 years is probably a lower limit. (Lingenfelter, R. E.: 1970, VIth International Conference on Cosmic Rays, Budapest, 1969.)

**Woltjer:** I want to comment on what Colgate said. Many of us have tried to make the connection between pulsars and supernovae and to discuss the frequency, and I think the general experience has been that you can get whatever you want. For example, an error in the distance scale of a factor of two gives you immediately a factor of ten in the frequency.