Lecture Notes

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GALACTIC RADIO SOURCES. II

by

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The first radio source to be identified optically was the galactic source Taurus A, found to be associated with the Crab Nebula. The nebula was known to have optical peculiarities which distinguished it from the usual H II region, and it was, in fact, identified as the remnant of a supernova which was observed visually by the Chinese in 1054. The new information that it was also a radio source prompted a series of important papers, which led to the following two conclusions:

(a) The electron temperature of the nebula, were it radiating like an H II region, would have to be ~ 5 x 10^6°K to produce the observed flux at meter wavelengths. Since this is ten times greater than the upper limit put on the kinetic temperature by the optical observations, a nonthermal mechanism is required. It was shown by Shklovsky that the mechanism of synchrotron radiation would satisfy the observations; this same mechanism has, of course, been applied to the other nonthermal radio sources, both galactic and extragalactic. Detection of polarization in the radiation from the Crab, at both optical and radio wavelengths, provided confirmation of the theory.

(b) The search for radio sources associated with the other two supernovae observed visually -- Tycho's of 1572 and Kepler's of 1604 -- was successfully undertaken, and a source was also found to be associated with the filamentary nebula in Cygnus, the Cygnus Loop. In addition, optical studies made of the region near Cas A resulted in the discovery of a number of faint, high-velocity filaments, now thought to be supernova remnants.

At the present time all of the galactic nonthermal sources, with the important exception of Sagittarius A, are considered as probable supernovae remnants. Before discussing the radio properties of these objects, however, it is worthwhile to review the data from optical studies.

Since there have been only three supernovae observed visually in our galaxy, our knowledge comes almost entirely, therefore, from the observations of about one hundred outbursts in extended galaxies. It is assumed that the external supernovae have properties similar to those in our galaxy. Among the hundred supernovae observed it is found that there are at least two distinct classes, called Type I and Type II, although the most recent work (cf. Zwicky, 1964) suggests that there may be as many as five classes. The following summary of properties has been adopted from Minkowski (1964).

Type I supernovae are distinguished by their light curves which, about one hundred days after maximum, begin a sharp decline with a half-life of between forty and seventy days. They have appeared in all classes of galaxies, from elliptical to irregular, and the frequency of occurrence is apparently independent of galaxy type. This suggests identification of Type I supernovae with the "old" population (population II). If the Crab Nebula is typical, then the expansion velocity of the shell is in the range 1000 to 2000 km/sec. From studies of external galaxies, the estimated frequency of occurrence is one per galaxy every four hundred years.

It has been proposed by Hoyle and Fowler (1960) that such supernovae would result during normal evolution of a star of mass approximately one solar mass, and is caused by the ignition of degenerate nuclear fuel in the inner regions of the star.

On the basis of what is known about the light curves, all of the three supernovae observed in our galaxy could be of Type I. The properties of the remnants of the supernovae of Tycho and Kepler differ markedly from those of the Crab, however, so that the classification is by no means certain.

Type II supernovae are at maximum probably fainter, by about 1-1/2 magnitudes, than those of Type I, and have light curves which decline irregularly. They have been observed only in spiral galaxies, and about two-thirds have appeared right in spiral arms. Thus, it is fairly certain that supernovae of this type belong to the very young population of stars (extreme population I). The envelope has large mass (several solar masses), expands rapidly (5000 km/sec), and is apparently rich in hydrogen. The frequency of occurrence is not known accurately — it certainly is as great as 1 per galaxy per four hundred years, but it could be as much as ten times greater.

Hoyle and Fowler suggest that massive stars (30 solar masses) might undergo a catastrophic implosion of the core. The resultant explosion would blow off the stellar envelope, which could contain as much as one-third of the total mass.

Three of the prominent galactic radio sources — Cas A, the Cygnus Loop, and IC 443 — appear to be remnants of this class of radio source.

There are now about fifteen discrete sources which have been suggested as supernovae remnants. The most extensive survey of the radio properties is that of Harris (1962), although for individual sources there are more detailed discussions. His results can be summarized as follows:

(a) There is a wide range in spectral index, from -0.8 for Cas A to about 0.0 for some of the large faint sources such as S 147. Harris actually assigns positive indices to a few, but the observations are very uncertain. Because this range includes the index for thermal radiation (-0.1), there is a possibility that free-free emission may contribute in some cases. However, Harris shows that for three of the brighter sources the free-free emission, predicted on the basis of the optical surface brightness, must be less than 10 percent of the total.

(b) There is a strong correlation between the radio spectral index and the linear dimension of the source. Since the distances are very uncertain, this conclusion was checked by comparing the surface brightness, which is independent of distance, with the spectral index; again a correlation is found. It is in the sense that a source with a steep spectrum, like Cas A, has a smaller dimension and higher surface brightness than the Cygnus Loop, whose spectrum is flat. Since the age of Cas A is ~ 250 years, and that of the Cygnus Loop ~ 5 x 10^4 years, the immediate inference from this correlation is that it represents an evolutionary effect.

We therefore must consider the question of how these objects change with time. One possible mode has been proposed by Shklovsky (1960), with quite spectacular success. Assume that the nebula expands, that the decrease in magnetic field strength during this expansion obeys a power law, and that the number of relativistic particles does not increase during the expansion.

The second assumption implies that the general structure of the field remains constant.

$$H = H_o \left(\frac{r_o}{r}\right)^2 \qquad (1)$$

where H_o is the field strength at radius r_o, and H that at radius r.

The relativistic electrons will lose energy during the expansion, through the Fermi mechanism. The rate of loss is

$$\frac{dE}{dt} = -\frac{V}{r} E$$

where V is the velocity of expansion. Therefore,

$$E = E_o \left(\frac{r_o}{r}\right) \qquad (2)$$

All electrons lose energy in the same ratio. Thus, if the electrons are distributed initially in energy, according to

$$N(E) = K_o E^{-\gamma} \qquad (3)$$

where N(E) is the density of electrons with energy E, then γ will remain constant, but the K term will vary as

$$K = K_o \left(\frac{r_o}{r}\right)^{\gamma - 1} \left(\frac{r_o}{r}\right)^{3} \qquad (4)$$

The flux S_ν from a synchrotron source (see page 7) is given by

$$S_\nu(r) \,\alpha\, (\mathrm{Volume}) \times (H_\perp)^{\frac{\gamma + 1}{2}} \; K\nu^{\frac{1 - \gamma}{2}}$$

$$\alpha\, S_\nu\,(r_o) \left(\frac{r_o}{r}\right)^{2\gamma}$$

and, if there is no deceleration of the expansion rαt, and therefore

$$S_\nu(t) \,\alpha\, S_\nu(t_o) \left(\frac{t_o}{t}\right)^{2\gamma} \qquad (5)$$

Equation (5) shows that the radio flux from a nebula of this type will decrease with time, but that the spectral index $\alpha = \frac{\gamma - 1}{2}$ will be constant. Moreover, the flux from sources with steeper spectra (i.e. γ large) will decrease much more rapidly than for those sources with flat spectra; we would therefore expect to see no old, large remnants with steep spectra. Thus, the theory predicts, in a qualitative way, the correlation found by Harris.

Since the spectrum of the flux from Cas A is so steep, the theory would predict that its flux is rapidly decreasing. It can easily be shown from equation (5) that, in one year the decrease ΔS_ν will be

$$\frac{\Delta S_\nu}{S_\nu} = \frac{2\gamma}{250} \approx 2\%$$

After this prediction was made in 1960, observers checked back over their records and found that the flux from Cas A was indeed decreasing, at a rate of about one per cent (cf. Heeschen and Meredith, 1961).

Shklovsky's theory is not completely satisfactory, especially for the older remnants, because there clearly has been interaction between the expanding shell and the general interstellar medium. In two more recent papers, van der Laan (1962 a,b) has attempted to include the effects of this interaction. He proposes that supernovae might evolve along one of two paths:

(a) The radiation of the nebula initially is due to internally generated relativistic particles and magnetic field. The time decay of the emission will be proposed by Shklovsky. As the expansion proceeds, however, the ambient cosmic rays and magnetic fields will be compressed, and a shell will form. The shell will, of course, also radiate at radio wavelengths. As the expansion proceeds, the radiation from the shell will exceed that from the inner spherical region, and a shell source of emission is left. The source is weak with a spectral index like that of the galactic background radiation.

(b) The process is as described above, except that the particles in the final shell are not cosmic rays which have been swept up, but rather are particles that were generated in the original outburst, and have been trapped in the expansion. The volume emissivity in this case can be much greater than that of (a), and the spectral index need not be that of the background radiation. The object will still appear as a shell source, however.

The theory of van der Laan has been successful, at least qualitatively, in that a number of shell sources are now known to exist. Quantitative verification must await the completion of further high-resolution studies of supernovae remnants.

In order to illustrate the type of information which may be obtained from radio observations of supernovae remnants, the measured volume emissivity in IC 443 will be used to estimate the magnetic field strength and relativistic electron density.

The power in ergs/sec/cps emitted by a high energy electron is, after Oort and Walraven (1956)

$$P(\nu) = \frac{\sqrt{3}\, e^3}{mc^2} H_\perp \frac{\nu}{\nu_c} \int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta)\, d\eta \qquad (6)$$

The volume emissivity from an assemblage of electrons is

$$J(\nu) = \int_0^{\infty} P(\nu)\, \phi(\nu_c)\, d\nu_c$$

$$= \frac{\sqrt{3}\, e^3}{2\, mc^2} \left(\frac{3\, e}{4\pi m^3\, c^5}\right)^{\frac{\gamma - 1}{2}} K\, H_\perp^{\frac{\gamma + 1}{2}}\, U(\gamma)\, \nu^{\frac{1 - \gamma}{2}} \qquad (7)$$

ergs/sec/cm^3/cps

where $U(\gamma)$ is a function given, for example, by Morrison (1961).

It is customary to assume that the field distribution and the angle of inclination of the particle trajectories are both random. Thus

$$J(\nu) = 1.35 \times 10^{-22}\, a(\gamma)\, (6.26 \times 10^{18})^{\frac{\gamma - 1}{2}}\, H^{\frac{\gamma + 1}{2}}\, K\, \nu^{\frac{1 - \gamma}{2}} \qquad (8)$$

where $a(\gamma)$ is a function given by Ginzburg and Syrovatskii (1964).

The intensity $I(\nu)$ and flux $S(\nu)$ are derived directly from the volume emissivity.

$$\left.\begin{aligned} I(\nu) &= J(\nu) \cdot \frac{d}{4\pi} \\ S(\nu) &= J(\nu) \cdot \frac{V}{4\pi R^2} \end{aligned}\right\} \qquad (9)$$

where d is the extent of the nebula in the line of sight

V is the volume of the emitting region

R is the distance to the nebula

The volume emissivity in the western part of IC 443 has a mean value of 2.6×10^{-36} ergs/cm^3/sec/cps at 1400 Mc/s. From equation (8)

$$KH^{1.40} = 1.8 \times 10^{-18} \qquad (10)$$

The density of relativistic electrons $\delta_E = \int N(E) \cdot E\, dE$

$$= K \int_{E_1}^{E_2} E^{1 - \gamma}\, dE$$

$$= 0.37\, KH^{-0.1} \qquad (11)$$

where the limits of integration E_1 and E_2 have been chosen appropriate to the frequency limits 10^7 and 10^{10} cps by means of the relation

$$E = \left(\frac{\nu}{2.08 \times 10^{18} H} \right)^{1/2} \tag{12}$$

From (10) and (11)

$$\delta_E = 6.6 \times 10^{-19} H^{-1.5}$$

The only way of obtaining the value of the magnetic field is by assuming the minimum energy condition, in which the magnetic energy density is equal to the particle energy density. Equipartition will be assumed to obtain between the field and the relativistic protons, whose energy density is of the order of one hundred times that of the electrons (Burbidge and Burbidge, 1959). Hence

$$\delta_P = 6.6 \times 10^{-17} H^{-1.5} = \delta_H = \frac{H^2}{8\pi}$$

from which $H = 6 \times 10^{-5}$ gauss

$$\delta_E = 1.4 \times 10^{-12} \text{ ergs/cm}^3$$

$$K = 1.5 \times 10^{-12} \text{ cgs}$$

$$N(E > E_o) = 1.2 \times 10^{-9} \text{ cm}^{-3}$$

with $E_o = 2.8 \times 10^{-4}$ ergs.

The value of the relativistic electron energy density found here is between one hundred and one thousand times that in the galaxy as a whole, showing that IC 443 is, in fact, a source of cosmic rays. It is less certain that such remnants can alone supply the entire population of cosmic rays in the galaxy. The total energy of relativistic electrons in IC 443 is 3 x 10^{46} ergs. If all of these particles can escape from the nebula, perhaps after expansion has proceeded, and if the rate of this type of supernovae is one in four hundred years, then the energy supplied in electrons is approximately 3 x 10^{36} ergs/sec. The energy loss of the galactic electrons is more difficult to estimate, but appears to be of order 2 x 10^{38} - 1 x 10^{39} ergs/sec, or a full order of magnitude greater than that supplied by nebulae of the IC 443 type. The total energy in Cas A is, however, about 1 x 10^{48} ergs; if all supernovae contain this much energy initially, they could support the observed galactic cosmic ray population.

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