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THE RADIO SOURCES IN THE CYGNUS LOOP AND IC443*

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Within our Galaxy there are a number of nonthermal sources of radio emission. In the last few years a considerable amount of data has been collected about some of these sources, in particular the Crab nebula and the Cassiopeia A source. There is strong evidence now to suggest that all of the nonthermal radio sources emit by synchrotron radiation, or acceleration radiation as we shall describe it here. In this paper we want to discuss the physical conditions in two objects, the Cygnus loop and IC 443.

There is strong evidence in some cases, and a strong presumption in others, that all the objects of this kind in our Galaxy are supernova remnants. To determine the present physical conditions in these objects by using the theory of acceleration radiation, it is necessary to know the distance and size of the objects and the power spectrum and intensity of the radio emission.

The optical identification of the radio source in Gemini with the nebulosity IC 443 was first established by Baldwin and Dewhirst [1]. The radio data for this object are more detailed than for the Cygnus loop, whose probable identification with a radio source was demonstrated by Walsh and Hanbury Brown [2]. On the other hand, the optical data for the Cygnus loop are better than for IC 443. Minkowski [3] has observed radial velocities in the Cygnus loop that indicate a systematic expansion of a thick shell. He has derived a distance of 770 parsecs by using the radial velocity in conjunction with Hubble's measurement of an outward expansion of 0.″03 per year. This distance gives a diameter of 40 parsecs for the optical object. After studying the appearance of IC 443 Minkowski has suggested that it is probably a similar object at a greater distance, and that it has approximately the same linear diameter, which places it at a distance of about 2000 parsecs. He finds it probable that both sources, and other similar nebulosities—such as S 147 (listed by Shaĭn and Gaze) and those coincident with the radio sources HB 9 and HB 21 [4]—are the remnants of type II supernovae. The initial expansion velocities have been decelerated by interaction with the interstellar material.

Despite its greater distance, as observed at the earth IC 443 is a stronger radio source than the Cygnus loop. Although we accept here the postulate that it is of similar size and at a similar stage of expansion to the Cygnus

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* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

loop, we must bear in mind the possibility that it might have undergone more or less rapid deceleration, and be at a different stage in its development.

Whitfield [5] has determined the power spectrum of IC 443 by comparing it with the Cassiopeia A source; it has the form

$$P(\nu) \propto \nu^{-x}, \tag{1}$$

where $x = 0.55$, and $P(\nu)$ is the power emitted at frequency ν. The flux density at 100 Mc/s is 500×10^{-26} watts $\mathrm{m}^{-2}(\mathrm{c/s})^{-1}$. Then the total power P emitted at the source is given by

$$P = k \int_{\nu_1}^{\nu_2} \nu^{-0.55}\, d\nu \text{ ergs/second}; \tag{2}$$

where

$$k = \frac{4\pi(770 \times 3 \times 10^{18})^2 \times 5 \times 10^{-24} \times 10^7}{10^4} (\text{erg/second})^{-1},$$

and ν_1 and ν_2 are the assumed low- and high-energy cut-offs. Taking $\nu_1 = 10^7$ and $\nu_2 = 10^{10}$ c/s, we have

$$P = 4 \times 10^{33} \text{ ergs/second}. \tag{3}$$

There are no data on the power spectrum of the Cygnus loop, but let us assume that it is nonthermal and has the same form as that of IC 443. Then, by using the power measured by Walsh and Hanbury Brown at 92 Mc/s to determine k, we find that

$$P = 2.5 \times 10^{32} \text{ ergs/second}. \tag{4}$$

The equations for acceleration radiation by an electron or positron with energy E ergs in a magnetic field of H gauss are [6, 7]

$$\nu = 4.19 \times 10^6 H \left(\frac{E}{mc^2}\right)^2, \tag{5}$$

$$P(\nu) = 1.58 \times 10^{-15} H^2 \left(\frac{E}{mc^2}\right)^2, \tag{6}$$

and, as is well known, these do not give a unique solution for H and E. We write Eq. (6) in the form ([7] and other papers)

$$-\frac{dE}{dt} = k_1 H^2 E^2 .$$

The number of particles of given energy, $N(E)$, is given by

$$N(E) = k_2 E^{-n},$$

where $n = 2x + 1$ (cf. Eq. (1)), so that for these two sources we have $n = 2.1$. Thus

$$P = k_1 k_2 \int_{E_1}^{E_2} E^{-n+2}\, dE ,$$

where E_1 and E_2 are the critical energies associated with the frequency cut-offs ν_1, ν_2 and are determined by Eq. (5). The total energy contained in the emitting particles, ε_e, is given by

$$\varepsilon_e = \int_{E_1}^{E_2} N(E)E\,dE$$

$$= \frac{P}{k_1} \frac{\int_{E_1}^{E_2} E^{-n+1}\,dE}{\int_{E_1}^{E_2} E^{-n+2}\,dE},$$

where k_1 is known from Eq. (6) and P for each source is given by Eqs. (3) and (4). Thus ε_e is proportional to $H^{-3/2}$.

Values of ε_e for a range of values of H are plotted in Figs. 1 and 2, for the Cygnus loop and IC 443, respectively. Burbidge ([7] and elsewhere) has shown that it is probable that the emitting particles in radio sources are secondary electrons and positrons produced as the end products of the decay of mesons resulting from collisions between accelerated protons and the stationary atoms in the gas. In this case, taking into account the proton/electron mass ratio and the probable multiple-meson production factor, the total proton energy, ε_p, is about 100 ε_e. Values of ε_p are also plotted in Figs. 1 and 2.

The magnetic energy, $\mathscr{M}$, for the same range of H values, is plotted in each figure on two assumptions: either the emission comes from a fairly thin expanding shell, or, more likely, it comes from the whole sphere delineating the optical sources (the same diameter of 40 parsecs was taken in both cases).

In past work ([7] and elsewhere) it has been postulated that the most probable physical conditions may be those giving the minimum energy requirements, which, as may be seen from from Figs. 1 and 2, are the conditions giving equipartition between magnetic and particle energy. However, it is worth noting that in the Cygnus loop the compression of interstellar matter postulated by Minkowski as the agent for decelerating the outward motion from the supernova explosion might well compress and increase the interstellar magnetic field ($\sim 10^{-5}$ gauss) to a value of 10^{-4} gauss. At $\log H = -4$, Fig. 1 shows that

$$\varepsilon_p = 10^{48}\text{ ergs}.$$

The energy density of primary cosmic radiation near the sun is taken as 1 ev/cm^3, and if the same value holds near the Cygnus loop, then a sphere of radius 40 parsecs would contain a total energy of

$$\varepsilon_p = 1.5 \times 10^{48}\text{ ergs}.$$

We wish to point out that, with a cosmic-ray energy density of the same average value as near the sun, any local compression that increases the galactic magnetic field by an order of magnitude may give rise to an observable radio source. In the case of IC 443, however, if the assumed distance is correct, a field of $H = 5 \times 10^{-4}$ would be required to explain the radio

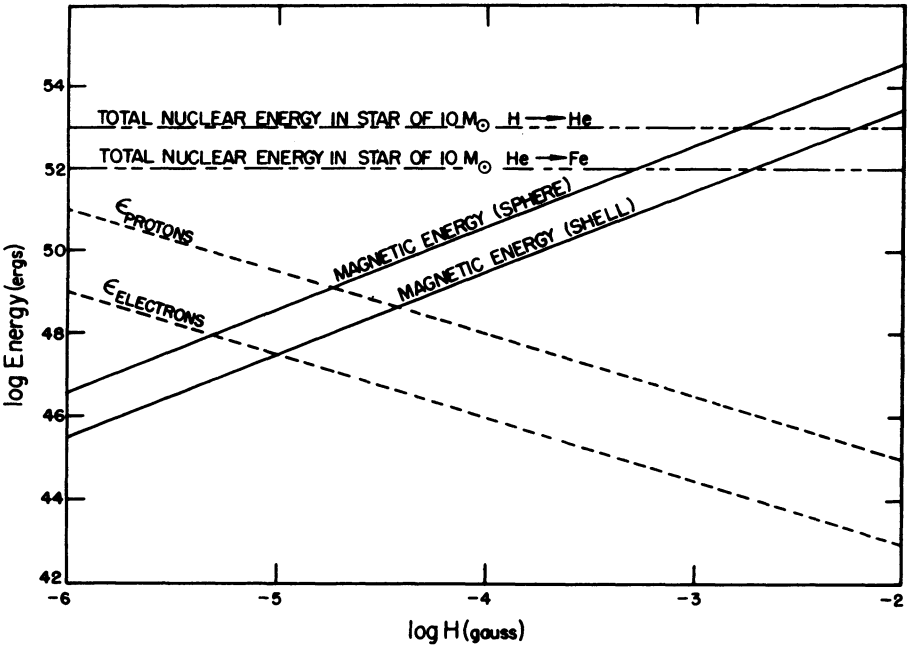

Fig. 1. Particle and magnetic energies in the Cygnus loop.

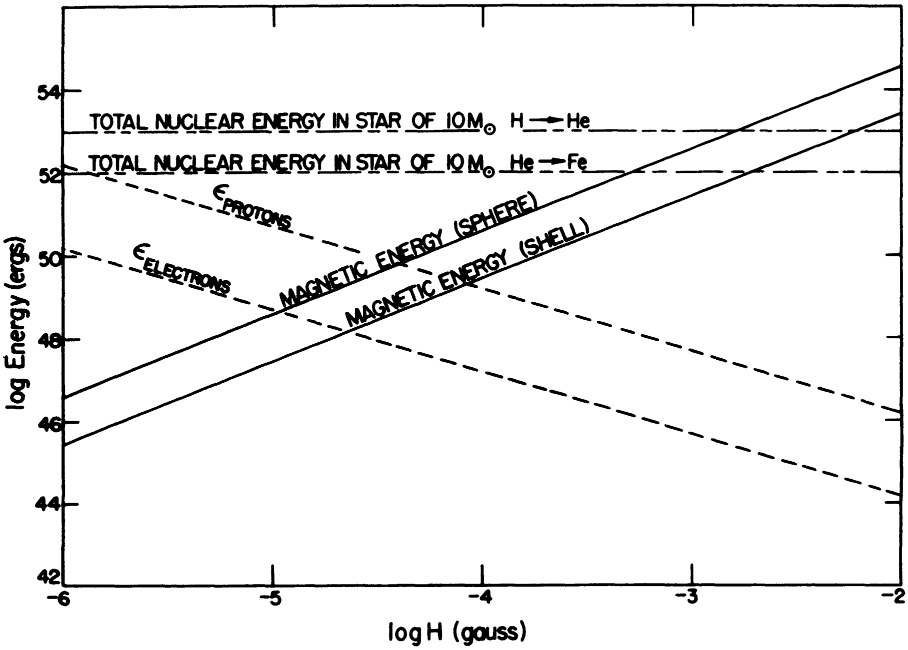

Fig. 2. Particle and magnetic energies in IC 443.

emission if ε_p is no larger than the cosmic-ray value. Approximate equipartition between ε_p and $\mathscr{M}$ for IC 443 occurs at

$$\varepsilon_p = 6 \times 10^{49} \text{ ergs} ;$$
$$H = 4 \times 10^{-5} \text{ gauss}.$$

Finally, since Minkowski has suggested type II supernovae as the origin of nebulosities like the Cygnus loop and IC 443, and since type II supernovae are thought to be the explosion of fairly massive (Population I) stars, we have shown in Figs. 1 and 2, for comparison with the magnetic and particle energies, the nuclear energy contained in a star of 10 solar masses. The upper line gives the energy available from the conversion of the whole mass of hydrogen to helium, and the lower line gives the remaining energy that would be released if the helium were totally converted to iron, beyond which point no further nuclear energy is available.

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