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ON THE THERMAL RADIO EMISSION OF THE CYGNUS LOOP

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SUMARIO

Cuando el resto de la explosión de una supernova choca con el medio interestelar, se produce una nebulosa de muy alta temperatura cuya periferia es una región de gran densidad. Este modelo del resto de una supernova, que nos ha permitido interpretar la evidencia óptica de la nebulosa filamentosa en el Cisne, permite a su vez calcular la densidad de flujo en 960 Mc/s que debiera observarse en la tierra. Suponiendo que la emisión radioeléctrica de la nebulosa del Cisne es producida por transiciones hiperbólicas (free-free), en la película de alta densidad que envuelve a la nebulosa, este flujo térmico es igual a 220×10^{-26} watts m^{-2} $(c/s)^{-1}$, el cual coincide muy satisfactoriamente con los $(265 \pm 50) \times 10^{-26}$ watts m^{-2} $(c/s)^{-1}$ encontrados por Harris. Se concluye que alrededor de los 1 000 Mc/s la mayor parte de la emisión de esta nebulosa es térmica, y que probablemente su estado evolutivo actual caracteriza, aproximadamente, la transición entre restos térmicos y no térmicos.

It is generally accepted nowadays that the discrete nonthermal galactic sources of radio emission are supernovae remnants*; it is not so clear, however, if a supernovae remnant remains always a nonthermal source or, at some time, towards the end of its life it becomes a thermal source. Thus, the spectral index of the Cygnus Loop $x = -0.10 \pm 0.15$ found by Harris (1962) suggests at first sight —as it has been pointed out by Harris himself and by Parker (1964)— that most of the flux at 960 Mc/s is of thermal origin; other remnants, suspicious of being thermal, can be found in the paper by Harris:

The purpose of this note is to point out that a model (Poveda 1964a, b) of supernovae remnants of type II, inspired only by the optical evidence, implies a thermal radio emission which is in accord with current measurements of the flux density from the Cygnus Loop and that, therefore, its radio flux is mostly thermal at 1 000 Mc/s.

Independently of whether one describes the evolution of a supernova remnant by means of a shock wave propagating in the interstellar medium (Shklovsky 1962, Heiles 1964), or as a spherical piston of hot gas pushing against the interstellar gas, one is bound to accept that the boundary of such a remnant is a thin region of high density. This is so because, as the remnant expands, the incoming atoms of the interstellar medium will penetrate a mean free path before they become ionized, but, since the magnetic field of the remnant is tangential at its boundary, once the incoming atoms become ionized they get trapped very near the surface, spiralling with a very small Larmor radius ($\sim 10^{9}$ cm). This surface trapping increases considerably the electron and ion density at the periphery of the remnant, but without a detailed analysis it is impossible to predict precisely the equilibrium density. Certain consequences of this hypothetical high density region** can be checked against some observations concerning the so called filaments in the Cygnus Loop (and similar nebulae like S 147 etc.).

In fact, since the interstellar medium is not rigorously uniform, the skin of the remnant cannot be a spherical shell, but a rather irregular one; in a first approximation we may describe it as an irregular polyhedron, the faces of which ought to have the same linear dimensions as the irregularities of the interstellar gas. When the faces of the remnant happen to lie perpendicular to the plane of the sky, they will be seen like bright, long and narrow filaments (whose diameters are equal to the skin thickness) and these will lie along an annular region.

We have proposed elsewhere (Poveda 1964a, b) that the so-called "filaments" in the Cygnus Loop are nothing else than the projections of some of the sides of the high density skin which envelops) (without interruption) the expanding remnant. It can easily be shown that if the filaments were really so, with the electron densities, temperatures and diameters as found by Osterbrock (1958) or Parker (1964), they would be barely detectable in the best $H\alpha$ photographs. On the other hand, if the filaments are really sheets with a depth comparable to their length, their surface brightness will be 140 times larger, i. e. comparable to the surface brigthness of an H II region with an emission measure around 14 000; obviously when observing the central parts of the remnant projected on the plane of the sky, the skin will appear as a very faint glow in the best $H\alpha$ photographs, comparable to the brightness of an H II region with an emission measure of 100, because now its geometrical depth will be of the order of its width ($\sim 7 \times 10^{-3}$ pc.).

In general when an old remnant has grown considerably, its shape will be more dependent on the irregularities of the interstellar medium because, the larger the remnant, the more likely that it has met large variations in density from one part of its boundary to another. Thus an old remnant should

* The radio source at the galactic center is, of course, quite a different problem.

** Which for brevity we shall call "skin".

have the shape more of an amoeba than of a sphere; also the density in the skin should vary over its surface. However, in spite of its irregularities there must exist continuity of the skin, for if we assume that for some reason the remnant is to break into two or more separate pieces, each one of them will expand in all directions (since the temperature, and the pressure are much larger inside the remnants) until they blend again into a single mass. With the above interpretation of supernovae remnants, we can readily estimate the thermal radio emission from the skin of the Cygnus Loop, under the simplifying assumption that we are dealing with a spherical remnant, and that the electron density in the skin is equal to the densities of the typical "filaments" studied by Osterbrock. We thus take the following set of parameters from Osterbrock and Parker:

$$N_\varepsilon = 2 \times 10^2 \qquad T_\varepsilon = 1.7 \times 10^4 \ {}^\circ K$$

$$R = 20 \ pc \qquad \Delta R = 1.8'' = 2.1 \times 10^{16} \ cm \ (= 7 \times 10^{-3} \ pc)$$

hence the volume of the skin $= 4 \pi R^2 \Delta R = 9.50 \times 10^{56} \ cm^3$.

The thermal emission per unit volume is given by (Allen 1962).

$$j_\nu / 4\pi = 5.44 \times 10^{-39} \ Z^2 g \ T_\varepsilon^{-1/2} \ N_\varepsilon \ N_i \ ergs \ cm^{-3} \ s^{-1} \ (c/s)^{-1} \ sterad^{-1}$$

which for 960 Mc/s becomes:

$$j_{960} = 5.45 \times 10^{-37} \ T_\varepsilon^{-1/2} \ N_\varepsilon \ N_i \ ergs \ cm^{-3} \ (c/s)^{-1} \ s^{-1}$$

thus the thermal emission from the whole remnant at 960 Mc/s is: 1.75×10^{23} ergs s^{-1} $(c/s)^{-1}$ which at the assumed distance of 770 pc produces a flux density at the earth of: 220×10^{-26} watts m^{-2} $(c/s)^{-1}$; this is to be compared with the flux density observed by Harris of $(265 \pm 50) \times 10^{-26}$ watts m^{-2} $(c/s)^{-1}$. The agreement between these two figures strongly suggests that most of the emission at 960 Mc/s is of thermal origin. The present interpretation of the Cygnus Loop also explains in a natural way the corre lation between the surface brightness in radio frequency and the optical features of the Loop, that is, those regions in which the irregularities of the interstellar medium have led to a large number of pieces of the skin perpendicular to the plane of the sky will be optically brightest and also more prominent in radio emission, since the latter is also proportional to the depth of the emitting region.

The possibility that a relevant part, if not most of the radio emission from the Cygnus Loop, is of thermal origin has been considered before by both Harris and Parker. Unfortunately their discussions only succeeded to explain around 3 — 5 per cent of the observed fluxes, a very small fraction to be of any consequence. It appears that the reason for this failure lies in the attempt to derive the radio flux, from the observed brightness of the Loop in $H\alpha$ while most of the $H\alpha$ flux remains below the level of detection because of the very small probability that a piece of the skin will be perpendicular to the plane of the sky.

In conclusion, a physically plausible model —which describes the evolution of a supernova rem nant and which explains in a natural way the brightness and surface distribution of the filaments in the Cygnus Loop— predicts a thermal flux density at 960 Mc/s in good agreement with the observations, strongly suggesting that most of the radio emission from the Cygnus Loop is thermal and that probably this nebula marks approximately the transition between thermal and non thermal remnants.

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