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POLARIZATION AND THE RADIATING MECHANISM OF THE CRAB NEBULA

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Photo-electric measurements made in Leiden in the first part of 1955 and extended by one of us at the Observatoire de Haute Provence in October 1955, show that the light of the Crab nebula is strongly polarized. The presence of polarization was first suggested by Vashakidze [2] and was firmly established by photo-electric measures by Dombrovsky [3] in 1954. The present observations, which are much more detailed, show that 17 % of the light coming from the central part, with a mean radius of 0ʹ.8, is linearly polarized. It may be seen that over the entire bright part of the nebula the polarizations are sensibly parallel, while in the outer parts they tend to be oriented at random.

As is well known from the observations by Baade and Minkowski, the Crab nebula consists of two parts of entirely different nature, namely, an 'amorphous' mass which emits continuous radiation and is rather strongly concentrated towards the centre, and a great number of emission filaments which form a thick, irregular shell surrounding the bright amorphous part. These filaments radiate like ordinary emission nebulae. It is the amorphous mass which emits the polarized light. A closer analysis indicates that wherever a small volume of this mass can be isolated from its surroundings, the light coming from such a volume is totally polarized.

These facts give strong support to the theory advanced by Shklovsky [4] that the continuous light comes from electrons of extremely high energy spiralling in a magnetic field. Plates recently obtained by Baade with the 200-inch Hale telescope through a polaroid screen and through filters to eliminate the emission shell, give a still stronger confirmation of this theory. They show a great amount of detailed structure in the 'amorphous mass'. Whenever the structure runs parallel to the direction of the analyzer, it disappears; this indicates that the light is 100 % polarized and that the structural features represent concentrations of magnetic lines of force.

Radiation by electrons moving in large orbits under the influence of a magnetic field has been first observed in synchrotrons. We propose, therefore, to call it synchrotron radiation. It is strongly concentrated in the direction in which the electron moves, and is totally polarized with the electric vector parallel to the radius of curvature of its orbit.

Consideration of the energy density of the electrons required to explain the observed radiation sets a lower limit to the magnetic field. An upper limit is set by the condition that the electrons must not loose a large fraction of their energy in one circuit through the nebula. From these considerations we find that the average field strength should be near 10^{-3} gauss. The median energy of the electrons emitting the optical radiation is estimated to be 2×10^{11} eV. The orbital radii are of the order of 10^{12} cm., which is very much smaller than the radius of the nebula (3×10^{18} cm.).

The electrons emit radiation over a very wide range of frequencies, extending far beyond the frequencies used in radio-astronomical observations. The relative strength of the radiation emitted at various wavelengths is determined by the field strength and by the numbers of electrons with different energies. As Shklovsky has pointed out, an energy spectrum like that of cosmic rays reproduces approximately the observed ratio of radio-frequency to optical radiation. It is tempting to suppose that the radio-frequency radiation of the Crab nebula is due to the synchrotron mechanism. It may be noted that the idea that the radiation of radio stars might come from particles of cosmic-ray energies caught in a stellar magnetic field, is due to Alfvén and Herlofson [5], who had suggested this as early as 1950.

If we want to compare the observed ratio of radio-frequency to optical radiation with the ratio computed from some assumed energy spectrum the comparison should be based on the radiation emitted from the same volume, rather than from the entire nebula. Measurements by Baldwin have indicated a large size for the radio source. A similar though somewhat smaller difference in scale was found from observations of an occultation of the Crab nebula by the Moon, recently made by Seeger at a wavelength of 75 cm. These accurate measurements show that the scale of the radio source is 1·7 times that of the optical source. In the following comparison this factor has been taken into account.

If the average field strength is 10^{-3}, the electrons responsible for the optical radiation will lose by this radiation half of their energy in 180 years. There are indications that new high-energy electrons are being injected into the nebula by the central star in sufficient amount to make up for the radiation losses. If we assume that the energy spectrum of the injected electrons is like that of the primary cosmic rays we find that this gives a ratio of radio frequency to optical radiation that is about thirty times higher than the observed ratio. In order to obtain the observed ratio we have to take a somewhat less steep energy spectrum. The following distribution will reproduce the observed ratio:

$E > 15{\cdot}5 \times 10^9$ eV.	$n_0(E) \sim E^{-2\cdot3}$
$1{\cdot}55 \times 10^9 < E < 15{\cdot}5 \times 10^9$	$n_0(E) \sim E^{-1\cdot3}$
$0{\cdot}155 \times 10^9 < E < 1{\cdot}55 \times 10^9$	$n_0(E) \sim E^{-0\cdot3}$

$n_0(E)$ is the number of electrons of energy E injected into the nebula per unit of time. The above exponents are algebraically about 0·5 higher than the exponents that have been assumed for cosmic rays.

Using the spectrum just given we obtain the following radiation per unit of frequency:

ν	$J(\nu)$
10^8	$1{\cdot}19\alpha$
10^9	$1{\cdot}88\alpha$
10^{10}	$2{\cdot}16\alpha$

α being a constant. The emission varies little over this range, in agreement with available observations. The small increase between $\nu = 10^8$ and 10^9 can easily be made to disappear by a slight increase in the slope of the energy spectrum at low energies.

The average strength of the magnetic field probably decreases in the outer parts of the nebula. If we have an energy spectrum like that indicated above, the optical radiation will decline more rapidly with decreasing magnetic field than the radio emission. We have computed that with constant electron density the following relation will hold between light-emission, u_l, and radio emission, u_r:

$$u_l = a u_r^{3\cdot2},$$

where a is a constant. If the electron density should decrease proportionally with the magnetic field H, the exponent of u_r would be 1·9.

We can thus understand why the optical radiation decreases more rapidly with increasing distance from the centre. There are indications that in the outer regions the optical radiation diminishes still more rapidly relative to the radio emission than indicated by the above expressions. This may indicate that the highest-energy particles are escaping from these parts.

The theory predicts that the radiation emitted at radio frequencies should also be polarized. The observation of such polarization is hampered by two circumstances. In general we can only observe the radiation of the radio source as a whole. Because of the wider distribution of the radio emission the contribution of the outer parts, where the resultant optical polarization is practically zero, outweighs that of the polarized central part. We have estimated that the resulting polarization of the entire radio source will not exceed 1 %. Except at centimetre waves this polarization will, moreover, be largely effaced by Faraday effects in the filamentary shell. We estimate that at 20 cm. the electric vector of polarized light passing through this shell will be turned over an average angle of the order of 10 radians.

An attempt to measure polarization at 22 cm. wave-length was made by Mr Westerhout at Kootwijk [6]. He found that the polarization must be smaller than 1%.

It is not unlikely that many other radio sources radiate by the same process. The conditions required are a mechanism for producing high-energy particles and a magnetic field. In most sources the magnetic fields or the particle energies are apparently insufficient to give observable optical radiation of the type discussed. In Virgo A (M87), however, the bright wisp near the centre of the nebula may radiate by the same process as the Crab nebula. The fact that the radio source is very much larger than the luminous wisp would be due to the fact that weak magnetic fields extend through the entire volume of this galaxy. Measurements of optical polarization of the wisp are still inconclusive.

If the radio emission is due to the synchrotron mechanism the distribution of radio emission through a radio source may show little resemblance to that of optical radiation. Striking differences of this kind have indeed been observed in several sources.

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Discussion

Baade: I am quite relieved to hear that the Crab nebula does not have to have a large mass. Its mass has to be fairly small as it is a supernova of type I, i.e. a star belonging to population II. There are other objects in which polarization might be expected, as the mechanism of radiation may be the same, e.g. in M87.

Oort: We have attempted to measure polarization in the jet of M87 in Leiden, but it is very difficult to measure with a small telescope.

Hanbury Brown: Should we expect any component of circular polarization?

Oort: No, the theory predicts strictly linear polarization.