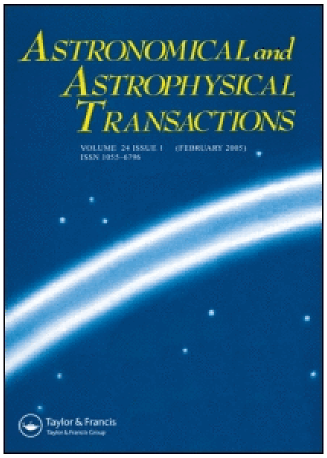

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COMPTON RADIATION OF THE CRAB NEBULA

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Usually radioemission from a compact source is considered as a radiation of the pulsar, and the observed spectrum is joined. In the model of radioemission presented here the frequency spectrum of a compact source and a pulsar described separately. The observed spectrum is a superposition of independent spectra of a compact source and a pulsar, with the indices $\alpha_c = 2.09$ and $\alpha_p = 3.5$. The pulsar spectrum continues to high frequencies beyond 100 MHz, with a cutoff at lower frequencies. The pressure of magnetic dipole radiation from a rotating pulsar with $\Omega = 33$ Hz sweeps up the plasma from the cavity around pulsar. The size of the cavity determines the size of the compact source, which have brightness temperature above 10^{12} K, and negligible reabsorbtion. Therefore radiating particles must be relativistic protons. The photons of the magnetic dipole radiation scatter on these protons, and trough inverse Compton effect their frequencies grow significantly. Compton radiation is observed as a radiation of the compact source. The radiating protons must have energies $10^{11} < E < 2 \times 10^{12}$ eV.

Keywords: Compact source; Radioemission; Magnetic dipole radiation; Pulsar; Scattering; Relativistic proton; Compton radiation

1 INTRODUCTION

In 1964 Hewish and Okoye discovered a low frequency compact source in Crab nebula. Radioemission from the source is observed at frequencies below 100 MHz, and is usually regarded as pulsar radiation PSR 0531+21 scattered on inhomogeneiteis of the interstellar medium. The broadening of the pulses due to scattering forms a sharp low frequency cutoff, and for PSR 0531+21 the cutoff is observed near 100 MHz. However, identification of radioemission from compact source at very low frequencies (5 MHz) as a continuation of the pulsar radiation is questionable and not established yet. The mechanisms of the pulsar radiation and continuous radiation of the compact source as well as the regions of their generation can be quite different. In this paper generation of radioemission of compact source outside the light cylinder is considered. The pulsar energy losses from magnetic-dipole radiation at the rotation frequency Ω is equal to (Ostriker and Gunn, 1969)

$$W_d = \frac{B_0^2 \Omega^4 R^4}{6c^3} \sin^2 \chi, \tag{1}$$

B_0 is the magnetic field on surface of the neutron star, R is the radius of the neutron star, χ, the angle between the rotation and magnetic dipole axes. In theory (Beskin *et al.*, 1989) the

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energy losses of a rotating pulsar include the radiation W_d and the current losses on surface of the neutron star W_c. The latter is

$$W_c = 0.4 \frac{B_0^2 \Omega^4 R^4}{c^3} i \cos^2 \chi \tag{2}$$

The pulsar in Crab nebula has $\chi = 90^\circ$ and $W_c = 0$. The luminosity of magnetic-dipole radiation at frequency $\Omega = 33$ Hz is equal to $L_\Omega = 5 \times 10^{38}$ erg s^{-1}. Because the frequency is very low, the electromagnetic waves can not propagate into the shell of the nebula surrounding the pulsar, and radiation pressure sweeps up the plasma from the cavity around pulsar. Rees and Gunn (1974) have shown that in Crab nebula the cavity radius is not more 5×10^{17} cm, and outer regions low frequency radiation is absorbed on the shock front. Photons of the magnetic-dipole radiation scatter in the cavity relativistic electrons or protons from and receive energy through inverse Compton effect. Their average frequency is equal to

$$\nu = \frac{4}{3}\Omega\left(\frac{E}{mc^2}\right)^2 \tag{3}$$

and they represent radioemission of the compact source.

2 RADIOEMISSION OF THE COMPACT SOURCE

A detailed study of the spectrum of the compact source were made by Bobeiko *et al.* (1979) at frequencies 16.7, 20, 25, 26.3, 38 and 74 MHz and Bovkoon and Zhouck (1981) at 12.6, 16.7, 20, 25 MHz. As result the spectrum was established.

$$S(\nu) = 936\left(\frac{\nu}{25\,\text{MHz}}\right)^{-2.09\pm0.04} \text{Jy} \tag{4}$$

Tokarev (1996) measured the fluxes at frequencies 5.6 and 8.9 MHz, and found them to be $15,400 \pm 2500$ Jy and 6800 ± 1200 Jy correspondingly. At 5.6 MHz the flux is 1.4 times lower than given by (4). This discrepancy is explained as due to absorption by the interstellar matter (Tokarev, 1996). It follows then, that the spectrum of the compact source (4) holds to very low frequency 5.6 MHz. The coordinates of the compact source were measured interferometrically (Vandenberg *et al.*, 1973; Mutel *et al.*, 1974), and found coincident with pulsar PSR 0531+21 in Crab nebula. The angle size of the source at 26.3 MHz was determined interferometrically $1.3^{+0.23}_{-0.13}$ arc sec (Mutel *et al.*, 1974). Bovkoon and Zhouk (1981) by mean of scintillations determined that at lower frequencies down to 12.6 MHz angle sizes increase inversely proportional to the square of the decreasing frequency. In Table I the ratios of the fluxes of the compact source $S(\nu)$ and the shell nebula $S_s(\nu)$ at frequencies 25 and 26.3 MHz measured in the period 1969–1982 are shown. The methods of measurements in table are indicated: J – interferometer, M – occultation by Moon, S_c – scintillation. It is seen that the fluxe ratio is practically invariant.

TABLE I

Frequency, MHz	*$S(\nu)/S_s(\nu)$*	*Year*	*Method*	*Reference*
26.3	0.26 ± 0.11	1969	S_c	Cronyn (1970)
25	0.33 ± 0.07	1974	M	Bovkoon (1979)
25	0.31 ± 0.93	1977	J	Bobeiko *et al.* (1979)
25	0.33 ± 0.04	1980	S_c	Bovkoon and Zhouck (1981)
26.3	0.25 ± 0.06	1982	M	Weisenberger *et al.* (1987)

At 100 MHz and higher the pulsar spectrum is

$$S_p = 10\left(\frac{\nu}{100\,\mathrm{MHz}}\right)^{-3.5}\ \mathrm{Jy} \tag{5}$$

In the same period 1971–1981 variations of the intensity of the pulsars radiation were discovered at frequencies 74, 111 and 196 MHz (Rankin *et al.*, 1988). The difference between spectral indices and changeability of radioemission from the compact source and the pulsar is connected with different and independent energy spectra of relativistic particles in these objects. We assume the angular size of the compact source at 25 MHz to be 1 arc sec (Mutel *et al.*, 1974) and the distance to Crab nebula 2 kpc, and obtain the brightness temperature of the compact source to be $T_b = 1.3 \times 10^{12}$ K, with accounting the frequency dependence of the angular size we get

$$T_b = 1.3 \times 10^{12}\left(\frac{\nu}{25\,\mathrm{MHz}}\right)^{-0.09}\ \mathrm{K} \tag{6}$$

3 RESULTS

The lack of significant reabsorption at frequencies close and below 25 MHz in the observed spectrum (??), is inconsistent with synchrotron losses by relativistic electrons as a radiation mechanism of the compact source in Crab nebula. From this point of view synchrotron radiation by relativistic protons can be such a mechanism, first because it allows to obtain larger brightness temperatures $T_b > 10^{12}$ K (Kardashev, 2001), and second because the reabsorption coefficient by protons is much smaller than for electrons. In the Crab compact source the ratio between the reabsorption coefficients is $\mu_p/\mu_e = 3.5 \times 10^{-9}$, and so for radiation from protons self-absorption will be significant only below frequency 0.3 MHz. However, for the compact source the inverse Compton losses protons are more efficient than synchrotron, because energy density of the magnetic field much lower than energy density of the magnetic-dipole radiation. The latter is

$$u_\Omega = \frac{3L_\Omega}{4\pi r^2 c} = 1.8 \times 10^{-5}\ \mathrm{erg/cm^3}, \tag{7}$$

where $r = 1.5 \times 10^{16}$ cm is the radius of the compact source. For comparison the expected density of magnetic energy is only $u = H^2/8\pi < 10^{-10}\ \mathrm{erg\,cm^{-3}}$. The energy spectrum of relativistic protons is determined from (4) with spectral index $\gamma = 2\alpha + 1 = 5.18$

$$N(E)\,\mathrm{d}E = K_p E^{-\gamma}\,\mathrm{d}E. \tag{8}$$

The spectral emissivity of Compton radiation (Ginzburg, 1987) for photons scattered on relativistic particles with the spectrum (8) is found as

$$a_\nu = \frac{1}{3}\left(\frac{e^2}{m_p c^2}\right)^2 (m_p c^2)^{1-\gamma} K_p \frac{c u_\Omega}{\Omega}\left(\frac{4\Omega}{3\nu}\right)^{0.5(\gamma-1)}\ \mathrm{erg/cm^3\,s\,Hz\,sr}, \tag{9}$$

where m_p is the proton mass, $u_\Omega = N_{ph} h\Omega$ (7). The flux emitted by relativistic protons from the compact source is than

$$S_p(\nu) = 10^8 K_p\left(\frac{\nu}{\mathrm{MHz}}\right)^{-2.09}\ \mathrm{Jy}. \tag{10}$$

From (4) and (10) we obtain $K_p = 7.8 \times 10^{-3}$. From

$$n_p = \int_{E_{\min}}^{\infty} N(E)\,\mathrm{d}E, \tag{11}$$

the density of relativistic protons is determined as

$$n_p = \frac{2\Gamma(\gamma-1)}{\Gamma(\gamma+2)} E_{\min}^{1-\gamma} K_p. \tag{12}$$

If the lowest frequency in the spectrum (4) is $\nu_{\min} = 1\,\mathrm{MHz}$, from (3) we obtain $E_{\min} = 1.4 \times 10^{11}$ eV. In order to maintain the observed flux (4), the density of relativistic protons must have quite a high value $n_p = 6 \times 10^{-2}\,\mathrm{cm}^{-3}$. The frequency spectrum of the compact source with spectral index $\alpha = 2.09$ continues up to 100 MHz, and then breaks off, because of cutoff in the spectrum of relativistic protons at $E_{\max} = 1.4 \times 10^{12}$ eV as follows from (3).

4 CONCLUSIONS

In the discussed model radioemission of the compact source is due to inverse Compton losses of relativistic protons with energies $10^{11} < E < 2 \times 10^{12}$ eV on photons of magnetic-dipole radiation of the pusar. The observated spectrum represents a superposition of two independently spectra from compact source and the pulsar with different indices.

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