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Corresponding Member of the Academy of Sciences of the USSR V. L. GINZBURG, L. M. OZERNOI,

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Abstract

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Corresponding Member of the Academy of Sciences of the USSR V. L. GINZBURG, L. M. OZERNOI,
S. I. SYROVATSKII

ON THE EMISSION MECHANISM OF THE GALAXY 3C 273-B

The extragalactic radio source 3C 273-B, identified ([1]) with an emission star-like object of 12th magnitude, is a representative of a new type of metagalactic object discovered quite recently. The exceptionally high luminosity ($M_v = -26^m.5$) of this galaxy* is combined with a very small size ($D \simeq 4 \cdot 10^{16}$ cm; such an estimate follows from observations of irregular changes in brightness over a week ([3],[4])). Together with the peculiarities of the spectrum ([5]), this points to a very unusual nature of the object.

In this connection it is of interest to ascertain the possibility that the continuous optical emission of the galaxy 3C 273-B is due to the magnetobremsstrahlung mechanism. Adopting this assumption, which has already been expressed in the literature, we shall discuss the corresponding energy requirements and some observational consequences.

According to ([5]), the optical spectrum $I_\nu \sim \nu^{-\alpha}$ of the object 3C 273-B in the interval between $\nu_1 = 3.6 \cdot 10^{14}$ Hz and $\nu_2 = 9.1 \cdot 10^{14}$ Hz has a negative spectral index $\alpha = -0.28$. Therefore the index of the energy spectrum of the electrons $N(E) \sim E^{-\gamma}$ must be $\gamma = 2\alpha + 1 = 0.44$. Under stationary conditions such a character of the spectrum indicates a continuous escape of electrons from the emitting region with a strong field. Indeed, for the concentration of electrons $N(E)dE$ in the stationary case the continuity equation in energy space must be satisfied:

$$-\frac{\partial}{\partial E}(b(E)N(E)) = q(E). \tag{1}$$

Here $b(E) = -dE/dt$, and $q(E)dE$ is the number of electrons with energy in the interval $\{E, E+dE\}$, supplied by the sources. For both magnetobremsstrahlung and Compton losses $b(E) = \text{const}\cdot E^2$, and, consequently, for $N(E) = \text{const}\cdot E^{-\gamma}$ the power of the sources is

$$\int Eq(E)\, dE = (\gamma - 2)\int b(E)N(E)\, dE.$$

Obviously, for $\gamma < 2$ the power of the "sources" is negative and for $\gamma < 1$ even exceeds the losses in absolute magnitude. The use of the stationarity condition is based on the following arguments. The galaxy 3C 273-B has already been photographed for 76 years ([3],[4]), and the decrease in brightness amounts to, or more precisely does not exceed, $0^m.2$ per century ([3]). If this decrease is real, then for an exponential law of luminosity variation it diminishes by a factor of e in 550 years. Obviously, this value is a lower limit to the age. Meanwhile, as will be seen below, the characteristic loss time of the emitting electrons is considerably smaller.

Thus, the electrons must leave the emitting region. This imposes restrictions on its effective size l. Namely, l cannot appreciably

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* The object 3C 273-B is probably not a cluster of stars, but a "superstar" ([2]). Therefore, for lack of established terminology, we use the term "galaxy" with respect to it only in a conventional sense.

exceed the displacement of a relativistic electron over the characteristic loss time T.

Somewhat arbitrarily, we shall assume that $l = cT/3$, i.e., the electrons escape with an average velocity $v \simeq c/3$ (probably the size l is still smaller). Then, taking into account synchrotron and Compton losses, we have

$$l = \frac{cT}{3} = \frac{c}{3}\left(\frac{4}{9}\frac{e^4 H^2}{m^3 c^5}\frac{E}{mc^2} + \frac{4}{3}c\sigma_0 w_\phi \frac{E}{m^2 c^4}\right)^{-1}, \tag{2}$$

where H is the magnetic-field strength, E is the electron energy,

$$\sigma_0 = \frac{8\pi}{3}\left(\frac{e^2}{mc^2}\right)^2 = 6.65 \cdot 10^{-25}\ \mathrm{cm}^2$$

is the Thomson cross section, and w_ϕ is the radiation energy density.

Let us assume that the total energy of the relativistic electrons is $W_e = \frac{H^2}{8\pi}V$, where V is the volume of the emitting region. Under these conditions the total energy of the electrons and field is close to the minimum. In this case (see [6], p. 115)

$$W_e = 0.19\left[A(\gamma,\nu)\frac{L_\nu}{4\pi}\right]^{4/7}(6D^2 l)^{3/7}, \tag{3}$$

where $L_\nu = 4\pi F_\nu R^2$ is the spectral luminosity at frequency ν, D is the linear size of the optical source, l is the thickness of the emitting layer ($l \ll D$, $V = \pi D^2 l$), and R is the distance to the source. The electron intensity is here chosen in the form $I_e(E) = \frac{c}{4\pi}N(E) = K_{eE}^{-\gamma}$. It should be kept in mind, however, that the use, for $\gamma < 2$, of the coefficients $A(\gamma, \nu)$ from [6] corresponds to the assumption of a power-law character of the electron spectrum over a very wide energy interval. To obtain the minimum value of W_e, let us assume that all the radiation of an electron with energy $E = E_m(\nu)$ occurs at the frequency ν, and that the power-law electron spectrum extends only from energy $E_m(\nu_1)$ to $E_m(\nu_2)$, where

$$E_m(\nu) = mc^2\sqrt{\frac{4\pi mc}{3eH_\perp}\frac{\nu}{0.29}} = 5.1 \cdot 10^2\sqrt{\frac{\nu}{H}}\ \text{eV} \tag{4}$$

is the energy of electrons whose spectral emission maximum falls at the frequency ν.

In this case, in $A(\gamma, \nu)$ one must put $y_2(\gamma) = y_1(\gamma) = 0.24$ and $a(\gamma) = 0.31(0.24)^{(\gamma-1)/2}$.

In accordance with the data [1,3,5], we put * $R = 1.6 \cdot 10^{27}$ cm, $L_\nu(\lambda = 5600\text{Å}) = 3.5 \cdot 10^{-26}\, 4\pi R^2 = 1.1 \cdot 10^{31}$ erg/sec · Hz (the same result is obtained if one takes the optical luminosity $L = 1.3 \cdot 10^{46}$ erg/sec and $\Delta\nu \sim 10^{15}$), $D \simeq 4 \cdot 10^{16}$ cm. For these values

$$W_e = 4.4 \cdot 10^{42} l^{3/7}\ \text{erg}, \qquad H = 1.5 \cdot 10^5 l^{-2/7}\ \text{oersted}. \tag{5}$$

For the synchrotron radiation in the frequency interval considered, the responsible electrons have energy

$$E_m = 1.3\nu^{1/2} l^{1/7}\ \text{eV}. \tag{6}$$

At the surface of the object the energy density of the photon radiation is $w_\phi = 5.4 \cdot 10^{13}$ eV/cm^3. Using (5) and (6), and solving (2) with respect to l for $E = E_m(\nu_2)$, we find

$$l = 2.6 \cdot 10^{11}\ \text{cm}, \qquad V = 1.3 \cdot 10^{45}\ \text{cm}^3, \qquad W_e = 3.5 \cdot 10^{47}\ \text{erg},$$

$$H = 82\ \text{oersted}, \qquad E_m(\nu_1) = 1.1 \cdot 10^9\ \text{eV}, \qquad E_m(\nu_2) = 1.7 \cdot 10^9\ \text{eV}. \tag{7}$$

* In the Einstein-de Sitter model the photometric distance to 3C 273 is 5% smaller, and the optical luminosity is 40% smaller than the values given. We shall neglect these differences, since the accuracy of the observational data is insufficiently high. Let us note, in particular, that the value of D given is most

likely an upper limit. Therefore a number of the following numerical estimates are necessarily of an approximate character.

In this case the Compton losses are approximately 3 times smaller than the magnetic-bremsstrahlung losses.

For comparison, let us consider the energy requirements for the relativistic electrons of components A and B of the radio source 3C 273, the magnetic-bremsstrahlung nature of whose radio emission is beyond doubt. Table 1 gives the spectral indices and sizes of both components from ([7]), as well as the calculated spectral flux densities of the radio emission of the individual

Table 1

Source	φ	D, cm	α	$F_{960\ \text{MHz}}$, $\frac{\text{erg}}{\text{cm}^2\ \text{sec} \cdot \text{Hz}}$	L_p, $\frac{\text{erg}}{\text{sec}}$	W_e, erg	H, Oe
A nucleus	$2''$	$1.6 \cdot 10^{22}$	0.9	$1.25 \cdot 10^{-22}$	$2.5 \cdot 10^{43}$	$1.2 \cdot 10^{57}$	$1.2 \cdot 10^{-4}$
A halo	$6''$	$4.8 \cdot 10^{22}$	0.9	$1.25 \cdot 10^{-22}$	$2.5 \cdot 10^{43}$	$4.9 \cdot 10^{57}$	$4.6 \cdot 10^{-5}$
B nucleus	$0''.5$	$4 \cdot 10^{21}$	0	$2.0 \cdot 10^{-22}$	$2.3 \cdot 10^{43}$	$1.0 \cdot 10^{56}$	$2.7 \cdot 10^{-4}$
B halo	$7''$	$5.6 \cdot 10^{22}$	0	$0.5 \cdot 10^{-22}$	$2.3 \cdot 10^{43}$	$1.3 \cdot 10^{57}$	$1.9 \cdot 10^{-5}$

components from data on the total flux ([8]) and the spectral data ([7]). In the last three columns are given the radio luminosities $L_p = 4\pi R^2 \int_{\nu_1}^{\nu_2} F_\nu d\nu$ (in all cases $\nu_1 = 10^8$ Hz and $\nu_2 = 3 \cdot 10^9$ Hz were adopted), the energy of the relativistic electrons, and the mean value of the magnetic-field strength. We emphasize that these estimates for the total energy are minimal (in particular, here, as in ([5]), the energy of the proton-nuclear component of cosmic rays has not been taken into account). The characteristic cooling time for the nucleus of radio source B is $T_p \simeq W_{e,\text{nucleus}}/L_p \simeq 10^{13}$ sec, and for the halo of both sources $T_p \simeq 3 \cdot 10^{14}$ sec.

For the optical source the cooling time is $T_o \simeq W_e/L \simeq 30$ sec, even if only the losses to optical radiation $L = 1.3 \cdot 10^{46}$ erg/sec are taken into account. Thus, in the case of a magnetic-bremsstrahlung nature of the optical emission of the galaxy 3C 273-B, an almost continuous generation of relativistic electrons with characteristic energy (7) must occur. Taking into account Compton losses, the escape of electrons from the region emitting optical frequencies, and also optical radiation outside the interval $\nu_1 \leq \nu \leq \nu_2$, the injection power of relativistic electrons will probably be not less than 10^{47} erg/sec. For example, over a time $T \sim 10^3$ years this corresponds to an injected energy $W > 3 \cdot 10^{57}$ erg. Such an energy release is by no means unusual for radio galaxies. At the same time, the need to provide the indicated injection power imposes substantial requirements on "superstar" models.

The optical emission of the galaxy 3C 273-B is unpolarized ([9]). Therefore it might perfectly well also have a non-magnetic-bremsstrahlung nature*. If the radiation of the object is bremsstrahlung (free-free and free-bound transitions), then, owing to the features of its spectrum, it cannot be regarded as blackbody radiation ([5]). There are, however, various other possibilities. We shall now merely note that a sphere with diameter $D = 4 \cdot 10^{16}$ cm will radiate $L = 10^{46}$ erg/sec if its effective temperature is $T_{\text{eff}} \simeq 13\,700^{\circ}$. As stated, the radiation apparently cannot be considered blackbody, but the value of T_{eff} given here, from our point of view, does not exclude the possibility of a bremsstrahlung mechanism for the object' s radiation. At the same time, the character of the spectra of other star-like extragalactic sources makes the hypothesis of a bremsstrahlung nature for their radiation considerably less probable (this remark belongs to I. S. Shklovsky).

* The opposite conclusion is, of course, incorrect, since magnetic-bremsstrahlung radiation, as a result of a number of causes ([6]), may be almost completely depolarized.

The fundamental question of the mechanism of the optical radiation of the galaxy 3C 273-B can in principle be solved in another way; indicating this way is the main purpose of the present note.

Namely, if the mechanism of the optical radiation of the galaxy 3C 273-B is magnetobremsstrahlung, then it must at the same time be a source of extremely powerful γ-radiation. Indeed, in the collision of a relativistic electron with energy $E \ll (mc^2)^2/\bar{\varepsilon}$ with photons of mean energy $\bar{\varepsilon}$, γ-rays are produced with mean energy

$$E_\gamma = \frac{4}{3}\,\bar{\varepsilon}\left(\frac{E}{mc^2}\right)^2. \tag{8}$$

If the mean photon energy is $\bar{\varepsilon} \simeq 2$ eV, then for $E \simeq (1 \div 3) \cdot 10^9$ eV γ-rays with energy $E_\gamma \simeq 10^7 \div 10^8$ eV are obtained (see also [10,11]). The total flux of γ-rays is equal to the Compton losses, i.e., in our case is approximately $5 \cdot 10^{45}$ erg/sec. Hence at the Earth the flux of γ-rays is $F_\gamma \simeq 5 \cdot 10^{45}/4\pi R^2 \simeq 1.6 \cdot 10^{-10}$ erg/cm^2 • sec. For γ-rays with mean energy $E_\gamma \simeq 10^7$ eV this corresponds to a photon flux

$$F_\gamma^* = \frac{F_\gamma}{E_\gamma} \sim 10^{-5}\,\frac{\text{photons}}{\text{cm}^2 \cdot \text{sec}}. \tag{9}$$

According to [10], the intensity of Compton γ-rays for $I_e(E) = K_{eE}^{-0.44}$ is

$$I_\gamma(E_\gamma) = \frac{2}{3}\sigma_0 w_\Phi K_e (mc^2)^{0.56}\left(\frac{4}{3}\bar{\varepsilon}\right)^{-1.28} E_\gamma^{-0.72}. \tag{10}$$

Hence, taking into account the radiation from the hemisphere facing us,

$$F_\gamma(E_{\gamma 1} \ll E \ll E_{\gamma 2}) = \frac{\pi D^2 l}{2R^2} \int_{E_{1\gamma}}^{E_{2\gamma}} I_\gamma(E_\gamma)\, dE_\gamma \simeq 5 \cdot 10^{-6} \, \frac{\text{photons}}{\text{cm}^2 \cdot \text{sec}}, \qquad (11)$$

where the adopted values are $E_{\gamma 1} = 2.7 \cdot 10^6$ eV and $E_{\gamma 2} = 10^8$ eV. The limits $E_{\gamma 1}$ and $E_{\gamma 2}$ correspond to the limits $E_1 = 5 \cdot 10^8$ eV and $E_2 = 3 \cdot 10^9$ eV (see (8)). Such an expansion of the electron-energy interval, compared with that used in (7), is intended to take approximate account of the contribution from electrons radiating light outside the interval of visible frequencies. The calculation (11) agrees with the estimate (9). The flux (11) must be regarded as very large. It suffices to say that the expected intensity of galactic γ-rays is $I_\gamma \lesssim 10^{-4}$ photons/cm$^2 \cdot$ sec $\cdot$ sterad (see [(10)]); for a γ-telescope with an aperture angle of 10° this corresponds to a flux $F^*_\gamma < 3 \cdot 10^{-6}$ photons/cm$^2 \cdot$ sec. The need to measure the γ-ray flux from the galaxy 3C 273-B appears obvious.

P. N. Lebedev Physical InstituteAcademy of Sciences of the USSR

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Note: Figure translations are in progress. See original paper for figures.