

# THE POSSIBILITY OF X-RAY EMISSION FROM COSMIC RADIO SOURCES

1964

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**Abstract**

**Full Text**

**Astronomy**

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## **THE POSSIBILITY OF X-RAY EMISSION FROM COSMIC RADIO SOURCES**

*(Presented by Academician V. A. Ambartsumian, 23 V 1964)*

In connection with the deployment of extra-atmospheric observations in the region of the far ultraviolet, the problem arises of making a preliminary estimate of the radiative capacity of celestial objects (galaxies, nebulae) in X-rays (1-100 Å).

The following mechanisms for the generation of X-rays in celestial bodies may be indicated: a) bremsstrahlung of relativistic electrons in the magnetic fields of the medium; b) bremsstrahlung of nonrelativistic electrons in the field of a proton (atomic nuclei); c) radiation in nuclear transformations. From a practical standpoint, the first two mechanisms are apparently of greatest interest.

In the case of bremsstrahlung by relativistic electrons, the generation of X-rays in the range 1-100 Å will be caused by electrons with energy of the order of  $10^{14}$ – $10^{13}$  eV at a magnetic-field strength  $H \sim 10^{-5}$ – $10^{-4}$  gauss. Assuming that the energy spectrum of the relativistic electrons responsible for the appearance of synchrotron radiation in the optical range does not cut off in the object under consideration and, at the present time, extends at least up to energies  $10^{14}$ – $10^{13}$  eV, we shall determine the spectrum and power of the X-ray radiation generated in this way (we shall call it “of synchrotron origin” ).

As the volume emission coefficient of the medium  $\varepsilon_\nu$  in X-rays of synchrotron origin, one may use the expression (1)

$$\varepsilon_\nu = C(\gamma)KH^{(\gamma+1)/2}\nu^{(1-\gamma)/2} \text{ erg/cm}^2 \text{ sec}, \quad (1)$$

where  $K$  and  $\gamma$  are the parameters of the energy spectrum of relativistic electrons:  $N(E) = KE^{-\gamma}$ , and the numerical values of the function  $C(\gamma)$  have been tabulated in (1).

Let us denote by  $\tau_\nu$  the total optical thickness of the object under consideration (for example, a radio galaxy) at frequency  $\nu$  of the X-ray range. Under the assumption that the matter absorbing the X-rays (atoms of interstellar hydrogen and helium, as well as dust particles) and the relativistic electrons are distributed uniformly throughout the entire volume, we can write for the intensity of the X-ray radiation emerging from the object,  $I_\nu$ :

Fig. 1

Figure 1: Fig. 1

$$I_\nu = \frac{\varepsilon_\nu}{a_\nu} (1 - e^{-\tau_\nu}) \text{ erg/cm}^2 \text{ sec}, \quad (2)$$

where  $a_\nu$  is the volume absorption coefficient at frequency  $\nu$  of the X-ray range;  $\tau_\nu = a_\nu 2s$ , where  $2s$  is the linear size of the object. For the total energy  $E_\nu$ , emitted by an object of volume  $V$  in all directions in one second, we have

$$E_\nu = 4\pi s^2 I_\nu = 4\pi V \frac{\varepsilon_\nu}{\tau_\nu} (1 - e^{-\tau_\nu}) \text{ erg/sec}. \quad (3)$$

Denoting by  $R$  the distance of the object under consideration from the Earth, we find for the observed X-ray flux  $F_\nu$  in the frequency interval  $\Delta\nu$ , also substituting the value of  $\varepsilon_\nu$  from (1),

$$F_\nu = \frac{V}{R^2} \frac{1 - e^{-\tau_\nu}}{\tau_\nu} C(\gamma) K H^{(\gamma+1)/2} \nu^{(1-\gamma)/2} \Delta\nu \text{ erg/cm}^2 \text{ sec}. \quad (4)$$

In the case when the object is completely transparent to X-rays ( $\tau_\nu = 0$ ), for the spectrum of pure emission we shall have

$$F_\nu = \frac{V}{R^2} C(\gamma) K H^{(\gamma+1)/2} \nu^{(1-\gamma)/2} \Delta\nu. \quad (5)$$

For discrete sources of cosmic radio emission (radio galaxies and supernova remnants) usually  $\gamma \approx 3$ . Then from (5) we find

$$F_\nu = \frac{V}{R^2} C(3) K H^2 \frac{\Delta\nu}{\nu} \text{ erg/cm}^2 \text{ sec}. \quad (6)$$

If we pass from the energy flux to the number of X-ray quanta  $N_\nu$  per 1 cm<sup>2</sup> in 1 sec, then we shall have:

$$N_\nu = \frac{F_\nu}{h\nu} = \frac{V}{R^2} C(3) K H^2 \frac{1}{h\nu^2} \Delta\nu = \frac{V}{R^2} C(3) K H^2 \frac{1}{ch} \Delta\lambda \text{ quanta/cm}^2 \text{ sec}. \quad (7)$$

It follows from (6) and (7) that, in the absence of absorption inside the object emitting X-rays, the observed energy intensity is inversely proportional to the frequency, while the observed number of X-rays in a unit wavelength interval is constant and does not depend on wavelength (see Fig. 1a and b).

**Fig. 1**

A characteristic feature of objects of the type of our Galaxy (from the standpoint of the structure of the interstellar medium) is their practical transparency in the region of short X-rays (1-10 Å). However, with increasing wavelength the optical thickness rapidly increases, reaching 100 at  $\lambda \sim 100$  Å; this is caused by the growth of absorption mainly by atoms of interstellar hydrogen and, to a lesser degree, by dust particles <sup>(2,3)</sup>. In the second column of Table 1 are given the values of  $\tau_\nu$  for our Galaxy, taken from <sup>(3)</sup>, for several wavelength values, under the assumption that the total number of neutral hydrogen atoms along the line of sight is equal to  $1.5 \cdot 10^{21}$  cm<sup>-2</sup> (the values of  $\tau_\nu$  for  $\lambda = 80 \div 120$  Å were found by extrapolation).

**Table 1**

Calculated number of X-ray quanta (quanta/cm<sup>2</sup> · sec · Å) arriving from M82 and the Crab Nebula

$\lambda, \text{Å}$	M82		Crab Neb- ula		$\lambda, \text{Å}$	M82		Crab Neb- ula	
	$\tau_\nu$	$N_\nu$	$\tau_\nu$	$N_\nu$		$\tau_\nu$	$N_\nu$	$\tau_\nu$	$N_\nu$
1	0	10.2	0	1.93	60	21.7	0.47	1.45	0.453
5	0	10.2	0	1.93	80	53	0.19	3.13	0.084
10	0.25	9.0	0.017	1.93	100	110	0.093	6.33	0.004
20	1.72	4.85	0.115	1.90	120	230	0.045	16.7	—
30	3.54	2.80	0.236	1.53					

Allowance for absorption both in the object itself and during the passage of X-radiation through our Galaxy sharply changes the picture presented in Fig. 1.

As an example, let us determine the expected number of X-ray quanta arriving at the Earth in 1 sec per 1 cm<sup>2</sup> from the well-known irregular galaxy M82. Since we do not have data on the distribution and amount of absorbing matter in this galaxy, we shall adopt for it the same values of  $\tau_\nu$  that were found for our Galaxy. No lesser difficulty is also presented by the determination of that effective volume in which the ...

generation of X-rays. Let us take it to be an order of magnitude smaller than the volume where, according to the data of Lynds and Sandage <sup>(8)</sup>, the remnants of the matter ejected from the center of this galaxy are distributed. Then we shall have  $V \approx 10^{66}$  cm<sup>3</sup>. Further, with distance modulus  $m - M = 27.5$  <sup>(8)</sup>, we find  $R \approx 10^{25}$  cm. Finally, substituting the value  $KH^2 = 1.7 \cdot 10^{-19}$  <sup>(4)</sup>, we find, using (4):

$$N_\nu = 10.2 \frac{1 - e^{-\tau_\nu}}{\tau_\nu} \Delta\lambda \text{ quanta/cm}^2\text{sec}, \quad (8)$$

where  $\Delta\lambda$  is expressed in angstroms. The third column of Table 1 gives the values of  $N_\nu$  calculated by this formula, computed for  $\Delta\lambda = 1 \text{ \AA}$ . In fact, expression (8) gives the observed spectrum of the X-ray radiation for M82 (without allowing for interstellar absorption in our Galaxy).

Analogous calculations have also been carried out for the Crab Nebula (Table 1). In this case, absorption of X-rays in our Galaxy is taken into account and absorption within the nebula itself is neglected. The total number of neutral hydrogen atoms in the direction of this nebula is estimated to be about  $N_H \approx 10^{20} \text{ cm}^{-2}$  <sup>(3)</sup>. Accordingly, the  $\tau_\nu$  values should be reduced by a factor of 15 compared with the values given in the second column of Table 1. Further, taking  $V = 5 \cdot 10^{55} \text{ cm}^3$ ,  $R = 3.7 \cdot 10^{21} \text{ cm}$ , and  $KH^2 = 1.08 \cdot 10^{-16}$  <sup>(5)</sup>, we find for the observed spectrum of the X-ray radiation of the Crab Nebula

$$N_\nu = 1.93e^{-\tau_\nu} \Delta\lambda \text{ quanta/cm}^2\text{sec}. \quad (9)$$

Figure 2 shows the curves of the theoretical X-ray spectra for M82 and the Crab Nebula. The dashed line represents the X-ray spectrum of M82 allowing for absorption in our Galaxy ( $N_H \approx 0.25 \cdot 10^{20} \text{ cm}^{-2}$ ). A noticeably slower decrease in the number of X-ray quanta in the interval 1–60  $\text{\AA}$  with increasing wavelength is seen in the case of the Crab Nebula. Both the galaxy M82 and the Crab Nebula, apparently, will be easier to detect in short-wavelength than in long-wavelength X-rays.

**Fig. 2**

This follows, in particular, from the data of Table 2, which gives the total number of X-ray quanta reaching the observer from M82 and the Crab Nebula in separate wavelength intervals.

**Table 2**

Calculated number of X-ray quanta  $N$  reaching from M82 and the Crab Nebula in separate wavelength intervals

Wavelength interval, $\text{\AA}$	$N$ , quanta/cm <sup>2</sup> · sec	
	M82	Crab Nebula
1–10	100	20
10–20	70	20
20–40	60	30
40–100	25	25

Thus, the expected emissive power of M82 and the Crab Nebula in X-rays is very small (compared with the Sun)—only a few tens of quanta per second per  $1 \text{ cm}^2$ . Nevertheless, it lies within the sensitivity limits of the best X-ray detectors. In particular, Giacconi et al. <sup>(6)</sup> were able to record an X-ray source of cosmic origin in the direction near the center of the Galaxy, the flux from which was equal to 5 quanta/cm<sup>2</sup>sec (in the region 2–8 Å).

The Crab Nebula is one of the strong sources of cosmic radio emission, while M82 is weaker than it by two orders of magnitude. At the same time, according to the estimates given above, both of these objects, estimates which are approximate in character, are equally accessible to a terrestrial observer in the X-ray range. This circumstance suggests that some sources of cosmic radio emission may simultaneously be sources of X-ray emission. Depending on the internal structure of these objects and on the concentration in them of relativistic electrons with energies  $\sim 10^{14}$  eV, the X-ray fluxes reaching the observer may undergo very large variations (the concentration of relativistic electrons with energy  $\sim 10^{14}$  eV is found from the estimates to be about  $6 \cdot 10^{-13} \text{ cm}^{-3}$  in the case of M82 and  $4 \cdot 10^{-13} \text{ cm}^{-3}$  in the case of the Crab Nebula).

The second mechanism of X-ray generation—bremsstrahlung of nonrelativistic (but fast) electrons in the field of a proton—acts most effectively at electron energies  $10^4$ – $10^2$  eV. Such electrons exist in the solar atmosphere (owing to the high temperature of the corona), and therefore this mechanism is the basic one in the generation of the Sun's X-rays <sup>(7)</sup>. As for galaxies and nebulae, the possibility of this mechanism operating depends above all on the concentration in them of electrons with energies  $10^4$ – $10^2$  eV. Let us estimate the order of magnitude of this concentration.

Denoting by  $q(v/c)$  the probability coefficient (effective cross section) for the emission, when a fast electron with relative velocity  $v/c$  passes by an atomic nucleus, of an X-ray quantum of frequency  $\nu$  in the interval  $\Delta\nu$ , we may write for the radiation power (number of quanta) in  $1 \text{ cm}^3$  in 1 sec

$$F_\nu = n_p n_e q(v/c), \quad (10)$$

where  $n_p$  is the concentration of thermal protons (atomic nuclei) in the medium, and  $n_e$  is the concentration of fast electrons (with energy  $10^4$ – $10^2$  eV). For the volume of a galaxy (or nebula)  $V$  and its distance from us  $R$ , we shall have, for the observed radiation power without allowance for absorption,

$$N_\nu = \frac{V}{4\pi R^2} n_p n_e q\left(\frac{v}{c}\right) \text{ quanta/cm}^2\text{sec}. \quad (11)$$

For the function  $q(v/c)$  we have <sup>(7)</sup>

$$q\left(\frac{v}{c}\right) = 0.608 \cdot 10^{-26} \frac{1 - e^{-2\pi\alpha Z/\beta}}{\beta^2} \frac{\Delta\nu}{\nu}, \quad (12)$$

where  $\beta = v/c$ ,  $\alpha = 1/137$ . Applying formulas (11) and (12) to the galaxy M82 with  $n_p \approx 1 \text{ cm}^{-3}$ , we find for the concentration of fast electrons the incredibly large value  $n_e \sim 10^6 \text{ cm}^{-3}$ , in order to register at least 4-5 quanta at wavelength  $\lambda \sim 100 \text{ \AA}$  in 1 sec per  $1 \text{ cm}^2$  and in the interval  $\Delta\lambda = 10 \text{ \AA}$ . For  $\lambda \sim 1 \text{ \AA}$ ,  $n_e$  is still larger—of the order of  $10^{11} \text{ cm}^{-3}$ . Approximately the same figures are obtained for the Crab Nebula as well.

Thus, it is unlikely that the mechanism of bremsstrahlung of fast electrons in the field of a proton plays a noticeable role in the generation of X-rays in radio galaxies, ordinary galaxies, and supernova remnants. In individual cases this mechanism may play some role in dense planetary and diffuse nebulae.

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Received  
18 V 1964

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