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Abstract

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ASTRONOMY

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ON THE NATURE OF DISCRETE SOURCES OF X-RAYS

Discrete sources of X-rays of cosmic origin have recently been discovered (1,2). Moreover, one of the three sources found, within the accuracy of the observations (the angular resolution of the apparatus was (1,2) about 5°), coincides with the Crab Nebula. Since the angular dimensions of this nebula are $5'$, it is quite obvious that, as yet, there can be no question of proof that the X-ray source is in fact located within the Crab. Such an assumption is, however, natural. Moreover, a still more far-reaching hypothesis is being discussed in the literature: that the source of the X-ray radiation in the Crab and in other known cases is neutron stars (1–4). Indeed, a neutron star with a surface temperature of the order of 10^7 °K will emit enough thermal X-ray radiation to be detected in experiments of the type (1,2), even if the distance to the star is thousands of parsecs (we note that the possible high luminosity of neutron stars in the X-ray region was pointed out even before the experiments (1,2), in article (5)).

Establishing a connection between X-ray sources and hot neutron stars would be of great importance. To test this hypothesis, it is obviously necessary to increase as much as possible the angular resolving power of X-ray "telescopes," but along this path one cannot hope to distinguish a distant neutron star (radius $\sim 10^6$ cm) from a substantially more extended source, say, with a radius of 10^{16} cm. It is therefore important to make use of the circumstance that the spectrum of the X-ray radiation of a neutron star should be a blackbody spectrum (one can hardly expect, in this case, the appearance of separate lines, and the bremsstrahlung of electrons arising in transitions in a continuous spectrum will dominate, i.e., in astrophysical terminology, in free-free transitions). In addition, in this case there are no grounds to expect any polarization of the radiation.

Since at the present time neither spectral, nor still more the very difficult polarization measurements in the X-ray region have been carried out, we wished to discuss one more possible hypothesis on the nature of X-ray sources; this hypothesis would not be refuted even if these sources had very small angular dimensions.

Namely, let us consider a source of magnetobremsstrahlung radio emission (for example, the envelope of a supernova) in which relativistic electrons fill a volume V_0, and the mean magnetic-field strength is $H = H_0$. Suppose now that, in a small part or parts of the source with total volume $V_1 \ll V_0$, the field reaches sufficiently large values $H_1 \gg H_0$. Then regions with such a strong field can already give magnetobremsstrahlung X-ray emission.

Before discussing the possibility of the appearance and the nature of regions with a strong field, let us estimate the values of H_1 and V_1.

The flux of magnetobremsstrahlung radiation from a source located at a distance R is equal to (see $^{(6)}$)

$$F(\nu) = 1.35 \cdot 10^{22} a(\gamma) \frac{K_e V H^{(\gamma+1)/2}}{R^2} \left(\frac{6.26 \cdot 10^{18}}{\nu} \right)^{(\gamma-1)/2} \frac{\text{erg}}{\text{cm}^2 \cdot \text{sec} \cdot \text{Hz}}, \quad (1)$$

where V is the volume of the source, H is the field strength, and it is assumed that the energy spectrum of electrons in the source has the form $N_e(E) = K_e E^{-\gamma}$.

Let us apply this formula to the aforementioned parts of the source with volumes V_0 and V_1. Then

$$\frac{F(\nu_1)}{F(\nu_0)} = \frac{V_1}{V_0} \left(\frac{H_1}{H_0} \right)^{(\gamma+1)/2} \frac{K_{e,1}}{K_{e,0}} \left(\frac{\nu_0}{\nu_1} \right)^{(\gamma-1)/2}, \quad (2)$$

where the electron spectra in both parts of the source are assumed to differ only in the factors K_e, but not in the exponents γ.

For the Crab Nebula we shall adopt the following values (see, for example, (^{6})): the radio-emission flux at frequency $\nu_0 = 10^8$ Hz is $F(\nu_0) = 1.7 \cdot 10^{-20}$ erg/cm^2 • sec • Hz, the volume $V_0 = 6.6 \cdot 10^{55}$ cm^3, the field $H_0 = 1.4 \cdot 10^{-3}$ oersted, and the exponent $\gamma = 2\alpha + 1 = 1.7$ (spectral index $\alpha = 0.35$).

To estimate the field H_1, let us take into account that electrons with energy E radiate mainly at a frequency ν determined by the relation

$$E = 4.7 \cdot 10^2 \sqrt{\nu / H_\perp} \text{ eV}, \quad (3)$$

where $H_\perp$ is the field projection perpendicular to the electron velocity. Without making, for simplicity, a distinction between $H_\perp$ and H, we see that for electrons with a given energy E the emitted frequency ν is proportional to H, i.e. $\nu_1/\nu_0 = H_1/H_0$. In the Crab there are electrons with energy reaching $E \sim 3 \cdot 10^{11}$ eV, and the magnetobremsstrahlung spectrum with $\alpha \simeq 0.35$ extends to optical frequencies*. Therefore, taking $\nu_0 \lesssim 5 \cdot 10^{14}$, we see that X-ray radiation ($\nu_1 = 10^{18}$ Hz, $\lambda_1 = c/\nu_1 = 3$ Å) will arise if the field $H \gtrsim 3$ oersted. For definiteness, let us choose the value $H_1 = 10$ oersted. According to (2), for the indicated values of $F(\nu_0 = 10^8 \text{ Hz})$, H_0, and H_1 we obtain

$$F(\nu_1 = 10^{18}\text{ Hz}) \simeq 10^{18}\frac{V_1}{V}\frac{K_{e,1}}{K_{e,0}}\frac{\text{erg}}{\text{cm}^2 \cdot \text{sec} \cdot \text{Hz}}. \tag{4}$$

At the same time, according to (²), $F(\nu \sim 10^{18}\text{ Hz}) \simeq 2 \cdot 10^{-9}$ erg/cm^2 • sec • Å $\simeq 6 \cdot 10^{-27}$ erg/cm^2 • sec • Hz, and, consequently, $V_1 K_{e,1}/V_0 K_{e,0} \sim 6 \cdot 10^{-9}$. With $K_{e,1}/K_{e,0} \sim 1$, it follows that $V_1 \sim 4 \cdot 10^{47}$ cm^3.

Since the volume V_1 is 8–9 orders of magnitude smaller than the volume of the nebula V_0, the assumption of the existence of regions with a strong field does not seem inadmissible to us. In particular, the field energy in the region V_1 in our example is approximately three times less than the field energy in the region V_0.

Of course, the region with the strong field must be connected in some way with the remnants of the supernova. In all probability, the object in question here must be a collapsed star, i.e. a neutron star or a star approaching the gravitational radius. During collapse the magnetic field of the star must increase very strongly, as a result of which the star acquires a powerful magnetosphere (⁷). From the estimates given in (⁷), it is easy to see that for stars with mass $M \sim M_\odot$, initial radius $r_0 \sim r_\odot \sim 10^{11}$ cm, and field $H_0 \sim 1 \div 100$ oersted, the volume of a dipole-type magnetosphere with field $H \gtrsim 10^2$ is considerably smaller than the required volume V_1 (see above). However, in the collapse of a star of greater mass, and also with the detachment of a regular or turbulent envelope (⁸), or with the rotation of the star (⁹), the appearance of a magnetosphere with radius $10^{15} \div 10^{16}$ cm (we mean distances or dimensions at which the field is $H \sim 10 \div 100$ oersted) already appears possible. In addition, taking into account the inhomogeneity of the magnetic field may noticeably change the estimate of the volume V_1. Finally, the presence of additional acceleration of particles in the region

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* We proceed here from the assumption that in the Crab there are very few electrons with energies $E \gg 3 \cdot 10^{11}$ eV. This circumstance, however, has not yet been reliably established. If there are sufficiently many such electrons, then they, of course, can produce appreciable magnetobremsstrahlung radiation even in a field $H \sim 10^{-3}$ oersted.

near the star would lead to $K_{e,1}/K_{e,0} \gg 1$. On the other hand, it must be kept in mind that in a field $H \sim 10$ oersted an electron with energy $E \sim\sim 5 \cdot 10^{10}$ eV, when moving across the field, loses half its energy in a time $t \sim 100$ sec. During this time the electron will travel a distance of only 10^{11}–10^{12} cm. Therefore the volume V_1 cannot be spherical. Rather, one should consider a spherical layer (say, a layer with radius $r \sim 10^{17}$ cm and thickness $l \sim 10^{12}$ cm, so that $V_1 \simeq 4\pi r^2 l \sim 10^{47}$ cm^3) or else a turbulent region of still larger size, but with large "fluctuations" of the field strength.

On the basis of the foregoing, and taking into account the approximate nature of the estimates, it seems to us that the assumption of a magnetobremsstrahlung nature of the X-ray radiation of the Crab Nebula, and probably of other discrete sources as well, is admissible and so far contradicts nothing. But, of course, at present there are no grounds for preferring this hypothesis to, say, the assumption of the existence of a hot neutron star.

If the source is sufficiently distant, then, as already indicated, one cannot hope to distinguish, by angular dimensions, an X-ray-emitting magnetosphere from a neutron star—in both cases the angular dimensions will be very small (for example, for an emitting region of size $r \sim 3 \cdot 10^{16}$ cm located at a distance $R \simeq 3.4 \cdot 10^{21}$ cm, corresponding to the Crab, the angular size of the source is only about $2''$). Therefore the differences in the spectrum are more characteristic—in the case of a magnetosphere the spectrum is not thermal, and under the simplest conditions its spectral index $\alpha = (\gamma - 1)/2$ coincides with the index for radio emission (see (1), (2)). In addition, polarization of the magnetobremsstrahlung X-ray radiation may be expected, although because of averaging over the directions of the magnetic field the observed resultant polarization of the entire source may turn out to be quite small.

Thus, quite definite ways can be indicated for clarifying the question of the nature of discrete sources of X-ray radiation, and the identification of these sources with neutron stars will be reliable only if other possibilities are excluded, in particular the magnetobremsstrahlung model discussed above.

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