POSSIBLE MECHANISM OF FORMATION OF THE SPECTRA OF COSMIC X-RAY SOURCES

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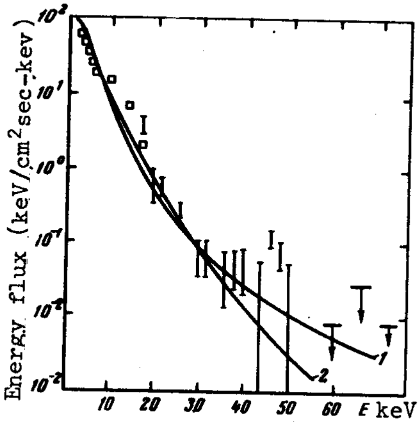
Submitted 9 September 1969
ZhETF Pis. Red. 10, No. 9, 441 - 444 (5 November 1969)

By now there are quite many experimental data on the spectra of x-ray sources [1 - 4]. Various models have been proposed to explain these spectra [2, 5, 6], but all encounter certain difficulties. If it is assumed that the x-ray spectra are the result of plasma bremsstrahlung, then it must be proposed that there are several plasma layers with different high temperatures, $(40 - 100) \times 10^6$ °K. The hypothesis that the radiation is of bremsstrahlung origin does not explain all the available experimental data (for example, the spectrum of Sco-XR-1). It is difficult to explain within the framework of these models the optical and x-ray sources of these sources [3, 5, 6] in a unified manner. The absence of radiation in individual lines likewise contradicts the thermal models [4].

In all the proposed models it is assumed in essence that the radiation spectrum is an equilibrium spectrum in a medium. We wish to call attention to the fact that, for example, the spectrum of Sco-XR-1 is surprisingly similar to the nonequilibrium spectrum of the hard γ radiation with energy of the order of several MeV, resulting from deceleration of gamma quanta



Experimental and theoretical spectra of the x-ray source Sco-XR-1: 1 - x = 32, λ_0 = 0.1; 2 - x = 19, λ_0 = 1.

in a medium (see the figure). As is well known, the slowing-down spectrum of the gamma quanta is of the form

$$dI(E) = AE^{-1}\tau^{-3/2}(E)\exp[-x^2(4\tau(E))^{-1}]\,dE \quad . \tag{1}$$

Here I(E) is the energy flux, x the optical thickness of the medium relative to pure Thomson scattering, and $\tau(E)$ is the so-called slowing-down length, given by:

$$\tau(E) = \frac{1}{3}\int_{\lambda_0}^{\lambda}\left[\frac{\sigma_0}{\sigma(\lambda)}\right]^2 \frac{d\lambda}{[1-\mu(\lambda)]^2} \tag{2}$$

λ_0 and λ are the wavelengths of the incident and scattered gamma quanta, respectively, in units of the Compton wavelength of the electron, $\sigma(\lambda)$ and σ_0 are the Compton and Thomson scattering cross sections, and $\mu(\lambda)$ is the mean cosine of the scattering angle. Let the energy of the initial quanta be $\sim$5 MeV, corresponding to $\lambda_0 \sim 0.1$. Then in the soft x-ray region (energy on the order of several keV) we have $\lambda >> 1$, $\sigma(\lambda) = \sigma_0$, $\tau = (\lambda - \lambda_0)/3 = \lambda/3$. It is easily seen from (1) that in this case the spectrum will have an exponential character. Starting with an energy 20 - 30 keV, the Compton cross section decreases rapidly and τ increases accordingly. The spectrum of the quanta therefore "softens" and assume the form shown in the figure. Within the framework of this model, it is easy to determine the optical thickness of the medium and the initial energy of the quanta from a comparison with the experimental spectrum.

If we assume such a mechanism of spectrum formation, then the question of the source of the gamma radiation arises. Such a source may be, for example, synchrotron radiation of relativistic electrons. This assumption is natural, since it is assumed now that the synchrotron radiation may be the source of hard x-rays with a power-law spectrum. On the other hand, it does not require too high a density of the relativistic electrons. By specifying the experimentally determined x-ray flux for Sco-XR-1 and using the known formulas for synchrotron radiation, we estimated the density and the energy of the relativistic electrons with a power-law spectrum, leading to the emission of gamma quanta with energy $\sim$1 MeV, for two models: 1) a neutron star with a magnetic field H $\sim 10^9$ G [8], and 2) a star with radius $\sim 10^{11}$ cm and a field H $\sim 10^4$ G. In the former case we obtain for the density of electrons of energy ε a value $n(\varepsilon) \leq 10^{-2}$ cm^{-3} at $\varepsilon \sim$ 150 MeV, and in the second $n(\varepsilon) \leq 10^{-4}$ cm^{-3} at $\varepsilon \sim$ 10 GeV. The distance to the source was assumed to be 100 psec. We note that the upper limit of the density of the relativistic electrons in the second model is only two orders of magnitude higher than the corresponding density of electrons with energy larger than 1 GeV from a solar flare, and is many orders of magnitude larger than the density needed to explain the exponential part of the Sco-XR-1 spectrum as being due to bremsstrahlung [3].

We thus propose as a model for the Sco-XR-1 x-ray source a relativistic-electron emitter in a magnetic field, surrounded by an optically thick shell of cold plasma with temperature T $\sim 10^4$ °K. From a comparison of the experimental spectrum with the calculated one (see the figure) we find that the optical thickness of the cold plasma is x = 32, and the initial gamma-quantum energy is E_0 = 5 MeV. This yields for the cold-plasma concentration near a source of radius 10^{11} cm a value $N_e = 5 \times 10^{14}$ cm^{-3}. As to sources with power-law spectra, they can be explained within the framework of our model by simply assuming that they have optically thin shells. The theoretical and experimental [3] fluxes in the optical region can be readily reconciled by taking into account the soft part of the synchrotron spectrum, which is transformed into optical radiation. Indeed, as follows from [2], the slowing-down length of the optical quanta, for which $\lambda \gg 1$, does not depend on the initial energy λ_0^{-1}, and equals $\lambda/3$. Therefore the flux (1) in the optical region is proportional to the total area of the initial γ-ray spectrum. In the x-ray region ($\lambda \leq 10$) the slowing-down length depends strongly on the lower limit λ_0, and consequently on the hard part of the initial spectrum. A quantitative agreement is obtained within the framework of our model by stipulating that the gamma-quantum spectrum be sharply cut off in the hard region at E > 5 MeV, and that the flux of quanta with energy $\gtrsim$ 1 MeV be approximately 1/30th of the total flux. Such an agreement can be obtained, in particular, when the initial γ-ray spectrum lies in the interval 0.1 - 5 MeV; such quanta can be produced by relativistic electrons with energy 10 - 100 GeV in a magnetic field $H \sim 10^4$ G if the exponent of the electron power-law spectrum equals 3 in this interval.

The authors thank D. A. Varshalovich and N. A. Silant'ev for a useful discussion of the work.

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