FLARE STARS AS A POSSIBLE SOURCE OF COSMIC X-RAY RADIATION

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T. A. GURZADYAN

FLARE STARS AS A POSSIBLE SOURCE OF COSMIC X-RAY RADIATION

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There is reason to believe that, in certain cases, late-type flare stars may be possible sources of cosmic X-ray radiation. We have in mind the fact that in some flares the emission line 4686 Å of doubly ionized helium appears. This obviously indicates that, at the moment of the flare, in the atmosphere of the given star there is either ionizing radiation (shorter than 228 Å) of sufficient power—if the ionization of helium is caused by photons—or particles of equivalent energy (electrons)—if the ionization is caused by collisions. In both cases it is difficult to assume that the spectrum of the ionizing agent breaks off immediately beyond the limit 228 Å; most likely it can extend into the region of soft X-rays (shorter than 100 Å).

In ([1]) an attempt was made to show that the phenomenon of continuous emission, or a flare in late-type dwarf stars, may be caused by the transformation of infrared quanta of the star’ s own photospheric radiation. The transformation itself occurs by virtue of the inverse Compton effect—the collision of infrared quanta with the so-called fast electrons, whose energy is not much greater than their own energy ($E > 5 \cdot 10^5$ eV). Such electrons appear above the photosphere as a result of the ejection of intrastellar matter outward. Elsewhere ([2]) it was shown that this same process—the transformation of infrared quanta—may be the cause of excitation of the emission lines of hydrogen, helium, and other elements in flare stars. As an example, Fig. 1 gives curves of the energy distribution in the continuous spectrum of a flare star of type M5 ($T = 2800^\circ$ K) for values of μ^2 equal to 50 and 100, where μ is the dimensionless energy of a fast electron ($\mu = E/mc^2$). As can be seen from this figure, in the case most favorable for excitation of the 4686 HeII line, i.e., at $\mu^2 = 100$, the continuous-emission spectrum in fact extends rather far beyond the ionization limit of doubly ionized helium ($\lambda < 228$ Å) and reaches the region of soft X-rays. It is therefore of interest to consider the problem of the generation of X-ray radiation by flare stars.

Fig. 1. Theoretical spectrum in the far ultraviolet during a flare of an M5-type star ($T = 2800^\circ$ K)

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Fig. 2. Theoretical spectrum in the X-ray range during a strong flare of an M5-type star ($T = 2800^\circ$K)

Figure 2: Fig. 2. Theoretical spectrum in the X-ray range during a strong flare of an M5-type star ($T = 2800^\circ$K)

The meaning of the inverse Compton effect, as is known, is that when a quantum collides with an electron whose energy is equal to μ, the frequency changes from ν' to ν, with

$$\nu \simeq \nu' \mu^2. \tag{1}$$

It follows from this relation that, for large values of μ, from any infrared quantum of frequency ν' one can obtain a quantum of the X-ray range with frequency ν. Therefore, if there is a sufficient supply of infrared quanta in the spectrum of a given star, and if there is some number of fast electrons above the photosphere, X-ray quanta may arise in quantities accessible to detection.

Fig. 2. Theoretical spectrum in the X-ray range during a strong flare of an M5-type star ($T = 2800^\circ$K)

Let us first write the law of distribution of energy in the X-ray region of the spectrum. In the general case, for an arbitrary frequency ν, this law has approximately the form[1]

$$I_\nu(\tau, \mu) = B_\nu(T) e^{-\tau} + \frac{1}{4\pi} \mu^2 B_{\nu'}(T) \tau e^{-\tau}, \tag{2}$$

where $I_\nu(\tau, \mu)$ is the intensity of the radiation of frequency ν emerging from the layer of electron gas; T is the effective temperature of the photosphere; τ is the effective optical thickness of the electron-gas layer: $\tau = \sigma_e N$, where $\sigma_e = 6.65 \cdot 10^{-25}$ cm^2 is the Thomson scattering coefficient; N is the number of fast electrons per 1 cm^2 of the layer ($\tau = 0$ at the surface of the photosphere or at the base of the electron-gas layer). $B_\nu(T)$ and $B_{\nu'}(T)$ are Planck functions, and in the second case the substitution $\nu' = \nu/\mu^2$ must be made.

For sufficiently large values of μ, or for $\nu \gg \nu'$, we have from (2)

$$I_\nu(\tau, \mu) \simeq \frac{1}{4\pi} \mu^2 B_{\nu'}(T) \tau e^{-\tau}. \tag{3}$$

Substituting the value of $B_{\nu'}(T)$, we find for the distribution law of the radiation intensity in the X-ray range

$$I_\nu(\mu) \sim \mu^2 \frac{(\nu/\mu^2)^3}{\exp\left(\frac{h}{kT}\frac{\nu}{\mu^2}\right) - 1}. \tag{4}$$

Let us note that in this case, although the absolute value of the intensity depends on τ (with $I_\nu(\tau, \mu) = \max$ at $\tau = 1$), the distribution of energy with frequency itself does not depend on τ.

Figure 2 shows curves of N_λ, found on the basis of formula (4), representing the number (in arbitrary units) of X-ray quanta per unit interval of wavelengths arising during a flare of an M5-type star. It follows from this figure that already at $\mu^2 = 300$,

i.e., at electron energy $E \sim 10^7$ eV, an appreciable part of the star' s infrared quanta is shifted into the soft X-ray region ($\lambda \sim 50$ Å). For $\mu^2 = 1000$ ($E \sim 1.6 \cdot 10^7$ eV) the maximum of the X-ray radiation is already at $\lambda \sim$ 10–20 Å, while for $\mu^2 = 3000$ ($E \sim 2.8 \cdot 10^7$ eV) this maximum is near $\lambda \sim 5$ Å.

What, after all, is the theoretical radiative capacity of a flaring star, say of type M5, in the X-ray range, bearing in mind the considerations set out above? After all, in the final analysis the possibility of detecting this star as an X-ray source at the moment of its flare depends only on this.

Table 1

Power of X-ray radiation N_R and of the X-ray-quantum flux N_r reaching the Earth during a flare of stars of types M6–G1

T, °K	N_f, quanta/sec	N_R ($\alpha = 0.01$), quanta/sec	N_r ($\alpha = 0.01$), quanta/cm^2 · sec
2500 M6	$\cdot 10^{43}$	$0.8 \cdot 10^{41}$	1.8
3000 M2	1.4	1.4	3.1
4000 K0	3.3	3.3	7.5
5000 G1	6.6	6.6	14.5

The power of the star' s X-ray radiation during a flare depends above all on the total number of infrared quanta N_f emitted by the star in one second. We have:

$$N_f = 4\pi R_*^2 \int_0^\infty \frac{B_\nu(T)}{h\nu}\, d\nu = 4\pi R_*^2 \frac{2}{c^2} \int_0^\infty \frac{\nu^2 d\nu}{\exp(h\nu/kT) - 1} = 4\pi R_*^2 C T^3 \text{ quanta/sec}, \tag{5}$$

where R_* is the radius of the star,

$$C = \frac{2}{c^2}\left(\frac{k}{h}\right)^3 \int_0^\infty \frac{x^2 dx}{e^x - 1} = 4.65 \cdot 10^{10}.$$

Let only a fraction α of the total number of infrared quanta N_f be shifted into the X-ray region as a result of the inverse Compton effect. Then for the total power of the star N_R in the X-ray range we shall have

$$N_R = \alpha N_f = \alpha 4\pi R_*^2 C T^3 \text{ quanta/sec.} \tag{6}$$

In the third column of Table 1 are given the values N_R, calculated with the aid of (6), for different values of the stellar temperature T, on the assumption that only 1% of the total number of infrared quanta passes into the region of X-ray radiation, i.e. $\alpha = 0.01$. In the calculations it was assumed that $R_* = 0.4 R_\odot \approx 3 \cdot 10^{10}$ cm for all four types of stars.

As follows from the data of this table, on average $N_R \sim 10^{41}$ quanta/sec for stars of types M2—M6. To obtain some idea of how large or small this power is, let us compare it with the total flux of X-ray quanta emitted by the solar corona. The total energy emitted by the solar corona in the X-ray range (at $\lambda \sim 20$ Å) at a coronal temperature $\sim 10^6$ °K is, according to Elwert (^{3}), $I_\odot \approx 5 \cdot 10^{25}$ erg/sec, or $N_\odot \approx 5 \cdot 10^{34}$ quanta/sec. It follows that the power of X-ray radiation during a flare of late-type stars, even for $\alpha = 0.01$, is a million times greater (see Table 1) than the power of the Sun' s X-ray radiation.

Denoting by r the distance of the flaring star from us, for the flux of X-ray quanta N_r reaching the observer on Earth we shall have

$$N_r = N_R / 4\pi r^2 = \alpha C (R_*/r)^2 T^3 \text{ quanta/cm}^2 \cdot \text{sec.} \tag{7}$$

According to Arp (^{4}), individual flaring stars of the UV Ceti type are found in a zone around the Sun with a radius of about 20 pc. Let us take pos-

to this, $r \approx 6 \cdot 10^{19}$ cm. The last column of Table 1 gives the values of N_r, calculated with the aid of (7): on average one obtains $N_r \sim 3$ quanta/cm^2 • sec for stars of late types and for $\alpha = 0.01$. This quantity lies within the sensitivity limits of the best modern X-ray detectors used to detect point or extended sources of cosmic X-ray radiation.

As is known, the best-studied flare stars are located at a distance of only 7 pc from the Sun (^{5}). Then the estimate of N_r made by us may be increased by almost an order of magnitude.

Are there any practical possibilities for testing the hypothesis advanced here? Leaving aside the theoretically possible, most direct, but as yet difficult-to-implement method of testing this suggestion—launching a rocket with X-ray detectors on board beyond the Earth' s atmosphere at the moment of a flare of some star—one may point to the following indirect possibility.

The point is that, according to the concept set forth above, X-ray radiation can appear in late-type stars only at the moment of their flare; at other times this radiation will be absent. Therefore, by carrying out a regular survey of the sky in the X-ray range, a kind of "X-ray patrol," with the aid of specialized Earth "X-ray satellites," we shall be able to detect variables among them, if, of course, such exist. And although the variability of some X-ray source of cosmic origin may also be caused by other reasons, nevertheless with sufficiently high probability it will be possible to assert that they may also be flare stars.

Byurakan Astrophysical Observatory
Academy of Sciences of the ArmSSR

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