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Abstract

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G. A. GURZADYAN

ON THE GENERATION OF CONTINUOUS EMISSION IN COLD STARS

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The phenomenon of continuous emission, discovered by Joy (^{1}), is manifested, as is known, in a sudden and strong increase in the brightness of a star (a flare), chiefly in the ultraviolet region of the spectrum. This phenomenon is characteristic of low-temperature stars—of types G-K-M—and is not observed in hot stars. During a flare the brightness of a star usually increases severalfold, and sometimes by several tens and hundreds of times. A clearly expressed regularity is observed in the increase of the brightness amplitude toward short wavelengths, i.e., during a flare the star becomes bluer. In the U-rays, for example, the amplitude (Δm_U), according to Arp' s observations, reaches 6-7^m (^{2}), while the quantity $U - B$ reaches $-1^m, 5$ (^{7}). The duration of a flare, or of the process of continuous-emission release, in some cases is very short—from several tens of seconds to several tens of minutes—while in other cases it is measured in months and years. A typical representative of objects of the first type is the star UV Ceti, and of the second type—the T Tauri stars.

V. A. Ambartsumian (^{3}), who was the first to subject the facts connected with the phenomenon of continuous emission to a detailed analysis, showed that it cannot be of a thermal nature. V. A. Ambartsumian connects this phenomenon with the ejection of intrastellar matter into the outer layers of the star and the liberation there of intrastellar energy. In the present paper an attempt will be made to describe the properties of this matter and to find the mechanism leading to the release of continuous emission from this matter.

First of all, attention should be drawn to one interesting feature of the energy distribution in low-temperature stars, namely, that the number of quanta N_{pg} in the photographic region of wavelengths constitutes a very small fraction of the total number of infrared quanta N, and the ratio N_{pg}/N decreases with decreasing effective temperature of the star T (Fig. 1). The relative number of ultraviolet quanta N_U (in the range 3000-4000 Å) decreases still more rapidly with decreasing T; the ratio N_U/N, as calculations show, is about 3% for stars of type K5, about 0.2% for type M0, and about 0.02% for type M5.

Thus, in the infrared region of the spectrum of late-type stars there is an enor-

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

mous number of quanta (in comparison with quanta of the visible range), and therefore it is sufficient to effect the transition or transformation of only a few percent, or even fractions of a percent, of the infrared quanta into quanta of high frequencies in order to produce an enhancement of the short-wavelength region of the spectrum by many tens and hundreds of times. One may indicate a mechanism that could effect such a transformation: this is the scattering of electrons of intermediate energies ($\sim 10^6$ eV) on photons, i.e., the inverse Compton effect. As is known, in this case the frequency of the primary photon increases according to the relation

$$\nu \simeq \nu' \left(\frac{E}{mc^2}\right)^2 = \nu' \mu^2, \tag{1}$$

where ν' is the frequency of the photon before collision with the electron, and ν after the collision. This relation is valid to within a well-known factor of order unity, depending on the scattering angle.

We assume, therefore, that as a result of a flare above the photosphere there appear electrons with energies only slightly greater than their intrinsic energy, i.e., of the order of 10^6 eV (we shall call them "fast electrons"). These electrons may, in particular, be released from the material that is ejected from the stellar interior. The appearance of a sufficiently thick layer ($\tau \sim 1$) of such electrons above the photosphere should lead to a strong change in the original Planck spectrum of the radiation emerging from this layer of the photosphere; there will be a strong enhancement of its short-wavelength part and a weakening of the infrared. The total number of quanta in the spectrum of the star, of course, remains unchanged; only a kind of drift of quanta from the long-wavelength region of the spectrum into the short-wavelength region takes place; in this process the additional energy of the quantum is taken from the energy of the fast electrons.

Fig. 1. Distribution of the relative number of quanta in the spectra of stars of various spectral types

Fig. 2. Theoretical flare spectrum of an M0-type star for different values of the electron energy μ (thin lines). The bold line denotes the normal spectrum of an M0 star (i.e., for $\mu^2 = 0$, $\tau = 0$)

Proceeding from this concept, one may pose the problem of determining the radiation intensity in the flare spectrum $I_\nu(\mu, \tau)$, if the energy spectrum of the electrons μ and the Planck spectrum of the photospheric radiation $B_\nu(T)$ are known. For this it is necessary to formulate and solve the transfer equation together with the condition of radiative equilibrium. In the case of monochromatic electrons, when the energy of all electrons is the same and equal to μ, this solution has the form

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

where τ is the effective optical depth, over the entire surface of the star, of the medium for Thomson scattering processes, and $B_\nu(T)$ and $B_{\nu'}(T)$ are represented by Planck' s formula, only in the second case one must substitute $\nu' = \nu/\mu^2$, i.e.,

$$B_\nu(T) = \frac{2h}{c^2}\frac{\nu^3}{e^{h\nu/kT} - 1};$$

$$B_{\nu'}(T) = \frac{2h}{c^2}\frac{(\nu/\mu^2)^3}{e^{(h/kT)(\nu/\mu^2)} - 1}. \tag{3}$$

Expression (2) is nothing other than the theoretical spectrum of a flare. As an example, Fig. 2 gives curves of the relative energy distribution in the spectrum of a flaring star of type M0 ($T = 3600^\circ$) for various values of μ. The bold line ($\mu^2 = 0$) denotes the normal (Planck) spectrum of an M0 star. Already in this figure one clearly sees the increase of intensity in the short-wavelength region and its decrease in the long-wavelength region when fast electrons of one energy or another appear above the photosphere. Having constructed such curves for different values of T and μ, we can then, by ordinary methods, compute the amplitudes Δm_V, Δm_B, and Δm_U, i.e., the increase (or decrease) of the star' s brightness in the V-, B-, and U-rays in comparison with its normal brightness (when $\tau = 0$), and also determine the theoretical color indices in this system $B - V$ and $U - B$. The results of the calculations for stars of type M0, M5, and M6 are given in Table 1. In doing this, the curves of the relative sensitivities in the V-, B-, and U-rays were taken from (^{4}).

Table 1

μ^2	$B - V$	$U - B$	Δm_V	Δm_B	Δm_U
M0 ($T =$ 3600° **K**), $\tau = 1$	**M0** ($T =$ 3600° **K**), $\tau = 1$	**M0** ($T =$ 3600° **K**), $\tau = 1$	**M0** ($T =$ 3600° **K**), $\tau = 1$	**M0** ($T =$ 3600° **K**), $\tau = 1$	**M0** ($T =$ 3600° **K**), $\tau = 1$
0	1.27	+0.45	–	–	–
2	0.82	−0.47	−0.2	0.0	1.0
3	0.44	−1.04	−0.1	0.6	2.1
4	0.32	−1.27	0.0	0.8	2.5

μ^2	$B-V$	$U-B$	Δm_V	Δm_B	Δm_U
5	0.21	-1.43	-0.1	1.0	2.8
10	0.04	-1.45	-0.3	1.0	2.8
20	0.25	-1.48	-0.6	1.5	2.4
M5 ($T =$ 2800° **K**), $\tau = 1$	**M5** ($T =$ 2800° **K**), $\tau = 1$	**M5** ($T =$ 2800° **K**), $\tau = 1$	**M5** ($T =$ 2800° **K**), $\tau = 1$	**M5** ($T =$ 2800° **K**), $\tau = 1$	**M5** ($T =$ 2800° **K**), $\tau = 1$
0	1.80	$+1.14$	–	–	–
2	0.79	-0.38	0.1	1.0	2.5
3	0.44	-0.87	0.8	2.2	4.2
4	0.20	-1.22	1.0	2.8	5.0
5	0.04	-1.33	1.1	2.9	5.4
10	-0.16	-1.57	1.0	3.0	5.7
20	-0.16	-1.63	0.6	2.5	5.3
M6 ($T =$ 2500° **K**), $\tau = 1$	**M6** ($T =$ 2500° **K**), $\tau = 1$	**M6** ($T =$ 2500° **K**), $\tau = 1$	**M6** ($T =$ 2500° **K**), $\tau = 1$	**M6** ($T =$ 2500° **K**), $\tau = 1$	**M6** ($T =$ 2500° **K**), $\tau = 1$
0	2.10	$+1.43$	–	–	–
2	0.96	-0.25	0.6	1.7	3.5
3	0.44	-0.86	1.4	3.1	5.5
4	0.12	-1.12	1.7	3.7	6.3
5	-0.06	-1.27	1.9	4.0	6.8
10	-0.23	-1.60	1.8	4.2	7.4
20	-0.31	-1.65	1.4	3.9	7.0

Let us make some comparisons with observations.

1. The theoretical amplitude of the brightness, as follows from the data of the table, reaches 7^m and more (in the U-rays). Such amplitudes, as indicated above, are observed (^{2}).

2. The brightness amplitude at a given value of μ increases toward short wavelengths (Table 1). This conclusion is also confirmed by observational data (^{2}). Johnson and Mitchell (^{5}) succeeded in obtaining rare electrophotometric records of the brightness variation in the V-, B-, and U-rays of one flare that occurred on the star 1306. From these curves the amplitudes in the V-, B-, and U-rays were determined: $\Delta m_V \simeq 0^m.7$, $\Delta m_B \simeq 1^m.7$, $\Delta m_U \simeq 3^m.7$. It turns out that such amplitudes

Fig. 3. Theoretical dependences of the ultraviolet amplitude of a flare of an M5 star for $\mu^2 = 2$ and $\mu^2 = 3$ on the wavelength. The dashed line represents the same dependence found from observations during a flare of the star 1306.

can be formed in the case of a flare of an M5 star at $\mu^2 \sim 2 \div 3$ and $\tau = 1$ (Fig. 3).

Figure 3: Theoretical dependences of the ultraviolet amplitude of a flare of an M5 star for $\mu^2 = 2$ and $\mu^2 = 3$ on the wavelength. The dashed line represents the same dependence found from observations during a flare of the star 1306

Figure 3: Figure 3: Theoretical dependences of the ultraviolet amplitude of a flare of an M5 star for $\mu^2 = 2$ and $\mu^2 = 3$ on the wavelength. The dashed line represents the same dependence found from observations during a flare of the star 1306

3. Under normal conditions the color of the star HII 1306 was: $B - V = +1^m,35$ and $U - B = +1^m,18$, while at the moment of the above-mentioned flare it became bluer: $B - V = +0^m,50$ and $U - B = -1^m,07$. Theoretically, color indices close to these can be obtained in a flare of an M5-type star, when $\mu^2 = 2,8$ and $\tau = 1$; in this case $B - V = +0^m,50$ and $U - B = -0^m,80$ (see Table 1).
4. The value of $U - B$ in some cases is less than -1^m. Thus, for example, for NX Mon we have $U - B = -1^m,35$ (^{6}), and for the star LHa22 still less: $U - B \sim -1^m,5$ (^{7}). This is in good agreement with the data of Table 1; the concept of transformation of infrared quanta permits the formation of a flare spectrum with a very large excess of energy in U-rays, down to values $U - B \sim -1^m,70$.

Byurakan Astrophysical Observatory
Academy of Sciences of the Armenian SSR

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