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Figure 1

Figure 1: Figure 1

Abstract

Full Text

Astronomy

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ON THE LUMINESCENCE OF LONG-PERIOD VARIABLE STARS

(Presented by Academician V. A. Ambartsumian on 18 I 1962)

The theory of stellar pulsations is not in a position to explain many phenomena observed in long-period variables. In general, there are no facts that testify sufficiently convincingly to the applicability of the pulsation theory to them. It is therefore expedient to seek another mechanism for the variability of the brightness of these stars.

As is known, continuous emission is observed in the spectra of a number of variable stars, which is not explained by the thermal mechanism of radiation. V. A. Ambartsumian came to the conclusion (1) that the emission arises as a result of a very rapid release, in the outer layers of the star, of energy brought out from its interior, and suggested (2) that in some stars intrastellar energy may also be released beneath the photosphere. As is shown in the present note, the available data on rapid changes in the brightness of long-period variables make it possible to conclude that energy is released in the subphotospheric layers, in particular, of these stars. One may suppose that the cyclic brightness variations of long-period variables are also caused by the same reason.

Fig. 1. Changes in the brightness of the star R Leonis,
$a - m_{\lambda\,8500\ \text{Å}}$, $b - m_{\lambda\,9250\ \text{Å}}$

1. Observational data. Observations have recorded cases of rapid changes in the brightness of long-period variables both in the visible region of the spectrum and in its far infrared part. For example, in the star UX Cygni a decrease in brightness by 1.4 magnitudes in 12 min was noted (3). After some time the brightness increased to its mean value. As a subsequent study of old photographs of the star showed, even before this case similar jumps in brightness had occurred in it.

Extensive series of determinations of the brightness of long-period variables in different regions of the spectrum made by Getzler (4) (with effective wavelengths 8500, 9100, and 9250 Å) show that in almost all the stars studied there are brightness variations of 0.3-0.6 magnitude, occurring in only a few days. These variations cannot be explained by observational errors. They are observed at different wavelengths (although it is not always possible to establish the synchronism of the variations in two regions of the spectrum, since the observations were not made quite simultaneously). Therefore the reality of the brightness jumps is beyond doubt. As an example we shall cite

(graphic) data on changes in the brightness of the star R Leonis at two wavelengths, λ8500 and 9250 Å, at moments close to the epoch of one of the brightness maxima (Fig. 1). The amplitude of the cyclic brightness variations of this star is $2^m.4$ at λ8500 Å and $\simeq 2^m.0$ at λ9250 Å.

Changes in the visible brightness of a long-period variable do not sufficiently characterize changes in its luminosity, because the main part of the energy is radiated by the star in the far infrared region of the spectrum (near wavelength 10 000 Å). But fluctuations of the radiation in the region $\lambda\lambda$9000–9500 Å by 0.3 –0.6 magnitude (with an amplitude over the whole cycle of about 2 magnitudes), occurring in only a few days, i.e., in 0.01 of the period, indicate rapid changes in the star' s luminosity. These fluctuations occur near the mean brightness level for the given phase.

It is obvious that such entirely irregular and considerable changes in brightness cannot in any way be explained by the theory of pulsations. To this one may add that the period of a long-period variable does not remain constant, but undergoes irregular fluctuations reaching up to 10% of its value. There is also the known fact of a progressive change in the period of the well-studied star R Hydrae (see, for example, ([5])). Its period, from 1784 to 1914, decreased from 497 to 403 days, and after that again began to increase without any change in the other characteristics of the star. Such a phenomenon contradicts the pulsation theory. The pulsation period of a star is determined by its internal structure, which cannot change rapidly without a catastrophic disturbance of the equilibrium of the outer layers. In light of the facts indicated, the hypothesis of pulsations in its usual form appears inapplicable to long-period variables.

2. Estimate of the depth at which the release of energy occurs. The rapidity of the brightness changes noted above shows that the processes of energy release leading to these changes occur at a comparatively small depth, in the subphotospheric layers of the star. The greater the depth at which energy is released, the longer the outward escape of the energy continues.

It is difficult to find the dependence on time of the radiation flux emerging outward after the release of energy in the star at a given optical depth τ. To estimate τ from the observed time of increase in brightness, one may use the concept of the "mean time of escape of energy" from some level l. The formula for the mean escape time of energy released at a distance r_1 from the center of the star was obtained in the work of V. V. Sobolev ([6]). For $R - r_1 \ll R$, where R is the radius of the star, it may be written in the form

$$\bar{t}(r_1) = \frac{3\tau + 2}{R^2} \int_0^R (t_1 + t_2) \varkappa \rho r^2 \, dr, \tag{1}$$

where $\varkappa$ is the opacity coefficient; ρ is the density, t_1 is the mean time spent by radiant energy in the absorbed state, and t_2 is the mean time spent by radiation between two successive absorptions. Since

$$t_2 = \frac{1}{c\varkappa\rho}, \qquad \frac{t_1}{t_2} = \frac{3}{2}\frac{R^*}{\mu a}\frac{\rho}{T^3},$$

formula (1) may be transformed into the form

$$t(r_1) = \frac{2 + 3\tau}{cR^2} \int_0^R \left(\frac{3}{2}\frac{R^*}{\mu a}\frac{\rho}{T^3} - 1 \right) r^2 \, dr, \tag{2}$$

where T is the temperature, R^* is the gas constant, and the remaining notation is standard. In the very surface layers of the star ($r \simeq 1$),

$$\frac{3}{2}\frac{R^*}{\mu a}\frac{\rho}{T^3} \ll 1.$$

With depth this quantity grows slowly, but for a star of large radius ($R \simeq 10^3 R_\odot$) it cannot become very large in comparison with unity.

Therefore,

$$\bar{t} \approx \frac{R}{c}\left(\tau + \frac{2}{3}\right). \tag{3}$$

The time elapsing from the moment of energy release to the moment when the intensity of the emergent radiation is maximal must be close to the mean time of energy escape. Thus, from observations it follows that $\bar{t} = 10^5$—10^6 sec. Then from (3), putting in it $R \approx 10^{13}$ cm, we find that $\tau = 10^2$—10^3. Layers with such values of τ have a radius substantially smaller than the radius of the star, since the opacity of the outer layers of a long-period variable is small. However, one may suppose that even if the condition $R - r_1 \ll R$ is not satisfied, formula (3) gives the correct order of magnitude of τ.

Let us note that in photographic observations it is difficult to record very rapid changes in a star' s brightness, and it is possible that in some cases energy may also be released at smaller depths. Nevertheless, the absence of the veiling of the absorption spectrum by continuous emission shows that the release of energy occurs in subphotospheric layers. This energy cannot emerge directly outward; it is transformed into thermal energy and is carried into the atmosphere of the star partly in the form of thermal radiation and partly in the form of a shock wave.

During rapid changes in the luminosity of a star, its spectrum and, in particular, the absorption spectrum do not change appreciably. Apparently the outer layers of the atmosphere, in which the absorption spectrum is formed, are little affected by the short-term release of energy beneath the photosphere of the star. The "inertia" of the spectrum is most probably connected with the small value of the density of the atmosphere, as a result of which the various physical processes in it proceed comparatively slowly.

3. **On the character of the cyclic changes of brightness.** The cyclic changes of the mean brightness, which constitute the main peculiarity of long-period variables, can be connected, just as the rapid changes are, with the liberation of energy in the subphotospheric layers of the star. Earlier we found (^{7}) that, simultaneously with the increase in brightness after the moment of minimum, a shock wave propagates through the atmosphere of the star. It is precisely shock waves that produce the partial ionization of hydrogen in the envelope and the appearance of bright hydrogen lines in the spectrum. Subsequently, when the ionized layers shine out, bright lines of metals also arise (^{8}).

It was also established (^{7}) that the quantity $p_2 r^2$, where p_2 is the pressure behind the wave front and r is the distance of the front from the center of the star, increases rapidly with increasing brightness. After the moment of maximum brightness this quantity falls sharply.

It may be assumed that the increase of pressure in the inner layers of the stellar atmosphere and the increase of the mean brightness are explained by one and the same cause, namely by the heating of the subphotospheric layers of the star when additional energy is released in them. What is meant here is that the process of energy release is not continuous, and the mean intensity of this process changes, bringing about cyclic changes in the brightness of the star.

If we assume that the shock wave propagating through the envelope of the star arises as a result of an increase of pressure in the subphotospheric layers during their instantaneous heating, then from the observed velocity of the gas behind the wave front one can estimate the temperature T_0 of these layers. Let the wave be strong and stationary; then

$$w = \sqrt{3p_2/4\rho}, \tag{4}$$

where $\rho = \eta\mu m_{\mathrm{H}}$ is the gas density and p_2 is the pressure, varying according to the law

$$p_2 = p_0(r_0/r)^2, \tag{5}$$

Here r_0 is the radius of the heated layer. We shall take the total number of ions and electrons per unit volume, n, to depend on the radius in the following way:

$$n = n_0(r_0/r)^l. \tag{6}$$

Since $p_0 = n_0kT_0$, from (4), with the aid of (5) and (6), we find

$$w^2 = \frac{6.3 \cdot 10^7}{\mu} \left(\frac{r_0}{\overline{R}}\right)^{2-l} T_0, \tag{7}$$

where $\overline{R}$ is the radius of the layer to which the observations of the velocity from the bright lines refer. For $r_0/\overline{R} \simeq 1$, $\mu = 1/2$, and the observed velocity $3 \cdot 10^6$ cm/sec, for T_0 we obtain values of order 10^5. This value is approximately 10 times greater than the temperature that should exist in the subphotospheric layers of the star in the case of radiative equilibrium. It is possible that the radius of the layer in which the energy is released is substantially smaller than the radius of the star; then the temperature T_0 is correspondingly larger.

The energy of the shock wave, expended to a considerable extent on the excitation of atoms that subsequently radiate in lines, is 10^{34}–10^{35} erg/sec, whereas the additional energy released during the epoch of enhanced brightness of the star and converted into radiation is close to 10^{37} erg/sec. Consequently, only an insignificant part of all the energy released in the subphotospheric layers is converted into the energy of the shock wave.

Under the action of the shock wave, the atmosphere of the star expands. After the moment of maximum brightness the shock wave disappears; under the force of the star' s gravity the inner layers are decelerated and then move in the opposite direction. In this way there arises a picture resembling pulsations of the inner layers of the atmosphere. In its outer layers, however, conditions may be created under which part of the matter is ejected into space.

In conclusion we note certain circumstances which, in our opinion, support the assumption made above concerning the character of the changes in brightness of long-period variable stars. According to V. A. Ambartsumian' s conclusion ([1]), the presence of technetium in the atmospheres of long-period variables of class Se testifies to processes of decay of intrastellar matter in the outer layers of these stars. In some irregular variables—red giants with bright lines in their spectra —apparently close in nature to long-period variables, strong variable magnetic fields are observed ([9]). In a number of cases the radiation of these stars is polarized to a considerable degree ([10], [11]). It is possible that the polarization of the radiation is connected with the presence of relativistic electrons in the atmospheres of these stars. Systematic investigations of long-period variables in this direction have not been carried out, but they are very desirable.

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