20. NON-STABILITY IN CLOSE BINARY STARS

V. A. KRAT
Pulkovo Observatory, Leningrad, U.S.S.R.

Those eclipsing binaries whose components are non-stable stars deserve particular attention not only owing to the fact that in such cases the physical properties of the stars may be studied in greater detail, but also since the mechanism of the ejection of gases from the atmospheres of the components may then be established with some certainty.

According to our cosmogonical views [1], stars forming a close pair must have originated simultaneously because if their origin from diffuse matter did not occur at the same time, then the second component, while having not yet acquired the properties of a real star, would be torn to pieces by the tidal forces of the main star and dissipate under the influence of its emission. It should be noted that the 'black sphere' temperature of the region in which the second star is formed will be about two times less than the surface temperature of the main star.

The stage of non-stability plays the part of a jump in the evolution of a star. In the course of cosmogonically short periods of time of the order of 10^5 or 10^6 years, a non-stable star undergoes larger changes than those that would take place in ordinary stable stars in the course of 10^8 or 10^9 years [2].

Ejection of gases from the atmospheres of the components of eclipsing variables was discovered by O. Struve. The phenomenon of non-stability in eclipsing variables was considered until recently as being something extraordinary; ejection of gases had been found only in the cases of a few white super-giants (β Lyr) and cooler giants (RX Cas and SX Cas). At present no systems are known to us that have two stable hot super-giants as components, except Y Cyg. The non-stability of white super-giants was recently studied by A. N. Dadaev [3] in the systems of AO Cas and β Lyr. According to N. M. Goldberg-Rogozinskaya [4], u Her, an eclipsing star with a rather regular light curve, is also non-stable. The non-stability of the secondary star in the system of U Cep, discovered by O. Struve, and that of the secondary (a typical sub-giant) in V505 Sgr, discovered by A. V. Sofronizky [5], is of utmost importance. This fact testifies that not only giant stars may be unstable.

Still more interesting is a study by K. Kaltchaev, who investigated systems in which both components are sub-dwarfs: UX UMa, AK Her, AG Vir and RW CrB. Kaltchaev established with certainty that these stars are real sub-dwarfs. This confirmed our former statements that sub-dwarfs are never found in binaries together with stars belonging to other sequences of the H–R diagram and thus of a different age. All sub-dwarf systems studied by Kaltchaev were found to be unstable. A very important feature of the instability of close pairs is the fact that the non-stability is caused by the circumstance that the surface of one star is very near to the internal critical Roche surface. In all cases in which instability has been established, the photosphere of one of the components touches Roche's internal surface. The system of UX UMa, for which the spectroscopic observations suggest the presence of an extended atmosphere around one of the stars, is the only exception. Spectroscopic observations show that the velocity of ejection is very great in all the systems investigated, being of the order of 100 km./sec.

The rapid decrease of the mass of a non-stable star indicates that the process of ejection began comparatively recently (10^5 or 10^6 years ago) and was preceded by an expansion of the star up to the dimensions of Roche's critical configuration. Thus, the instability of binary systems appears to be a proof of the expansion of the stellar envelopes in the process of their evolution. Such stars could initially be stable stars in which the equilibrium of the outer layers was afterwards disturbed. We believe that white super-giants pass a certain stage in their evolution in which they are stable stars. Thus, for example, the O-type systems of Y Cyg and AO Cas are extremely similar in mass and spectral type; they might be regarded as being in different stages of their evolution, one of them being stable (Y Cyg) and the other non-stable (AO Cas). It is observed, as a rule, that only one star of a binary system is non-stable; the other star does not show any signs of non-stability.

As we indicated earlier [1], white super-giants are non-stable stars which in the course of their evolution enter into the stage of unsteady stars (probably Wolf-Rayet stars). The instability of these stars is caused by the lack of equilibrium of their outer layers through the so-called corpuscular instability. By corpuscular instability is understood a state of the stellar atmosphere in which the atoms may dissipate at thermal velocities. Corpuscular instability sets in either as a consequence of a low gravity in the atmosphere of a star, or in consequence of a high temperature. In the atmospheres of white super-giants both factors are present. Such stars must be corpuscularly unstable, as are the majority of super-giants and red giants. It should be noted that any star that reaches the critical Roche surface during its expansion must automatically become corpuscularly unstable. The ejection starts in this case from the zone of the internal critical point.

Corpuscular instability causes a disturbance of the equilibrium of the gaseous masses near the surface of the star. The cause of such a disturbance is the enormous inertia of the luminosity of a star. The luminosity of a star, owing to the slowness of the energy transfer through the gaseous layers, does not correspond to the activity of its present energy sources. A star suddenly deprived of energy sources will still maintain its luminosity for about 10^6 or 10^7 years. The loss of mass by a star at the surface will therefore lead to no change of the luminosity of the star during an interval of time of less than 10^6 or 10^7 years, even if the activity of the energy sources has changed. The evolution of the star during this interval of time takes place under contradictory conditions of constant luminosity and decreasing mass. It is easy to show that in the case of constant luminosity the process of ejection will be a self-accelerating process. At an initial moment at some equipotential surface $R=R_0$ near the boundary of the star let there exist hydrostatical equilibrium: that is, let the condition

$$\frac{1}{\rho}\,\mathrm{grad}\,P=g \tag{1}$$

be fulfilled, where ρ is the density, and P is total pressure. In a first approximation the gas pressure is

$$P=\frac{R}{\mu}\rho T, \tag{2}$$

where μ is the average atomic weight, T is the absolute temperature, and g is the acceleration, representing the sum of the Newtonian acceleration and centrifugal acceleration. Starting from the surface $r=R_0$ and calculating r in the direction towards the centre of the star, we can assume, by neglecting the second component of the acceleration, that

$$g\approx\frac{G\mathbf{m}}{R_0^2}, \tag{3}$$

where $\mathbf{m}$ is the mass of the star. During a time interval dt the mass $d\mathbf{m}$ will be lost from the atmosphere of the star through dissipation. The left side of the equation (1) will then be changed as follows:

$$d\left(\frac{1}{\rho}\,\mathrm{grad}\,P\right)=\frac{R}{\mu}\,T(d\,\mathrm{grad}\ln T+d\,\mathrm{grad}\ln\rho). \tag{4}$$

Since in any model of a stellar atmosphere, $\ln\rho$ is always undergoing a greater change than is $\ln T$ (on the boundary in particular), it is advisable to take in the right side of the equality (4) the member with d grad $\ln\rho$ only. But when ejection of matter takes place, d grad $\rho > 0$ and therefore

$$d\left(\frac{1}{\rho}\operatorname{grad} P\right) > 0. \tag{5}$$

At the same time, if the mass changes by $d\mathbf{m}$, then $dg < 0$. The left side of the equation (1) will exceed the right one, and the star will begin to expand. It is also obvious that if the process is reversed and the star accumulates mass, then d grad $\ln\rho$ must decrease and g grows, and a disturbance of the equilibrium will lead to a compression of the star.

Owing to the slowness of the change of velocity v on the surface $r < R_0$ with time, the ejection can be considered as a stable process, the parameters of which undergo a gradual change with time. In this case the change of the kinetic energy in the stream equals the change of the potential energy, and the change of the internal energy of the gas can be neglected in a rough approximation. It will be easy then to calculate the increase of the velocity of the stream for a given change of mass. As was shown in reference 1, even for deliberately lowered estimates of the decrease of the mass of corpuscularly unstable stars, the ejection which goes on initially with the thermal velocity of the order of 10 km./sec., will after 10^6 years reach the value of 10^2 or 10^3 km./sec. The star will become a typical Wolf-Rayet star. A permanent decrease of temperature and pressure in the central regions of the star owing to the weakening of the thermonuclear reactions will stop the process of expansion. At this stage the star will be a red super-giant or giant and will lose mass only by dissipation. Probably the process of expansion will be replaced by contraction which might stop only in the case when the star acquires equilibrium. Judging by the fact that in the Wolf-Rayet stage and then in the red giant stage the star might decrease in mass by several times, this new state of equilibrium will correspond to that of a main sequence star [2].

It is interesting to observe that the process of mass accumulation on the surface of the star leads to the same result but to a reverse order of the processes of evolution. First, a contraction of the star will take place. T and P will grow in the centre of the star, causing an increase in the rates of thermo-nuclear reactions. After a short period of time (equalling the time required for the contraction, starting on the surface, to reach the centre), an expansion of the internal and, afterwards, the external layers of the star will occur.

It is also interesting to note that the gas stream flowing from the zone of the internal critical point of the critical Roche configuration is, contrary to

Kuiper's view [6], asymmetrical and can surround the second star only at low velocities. In most cases it dissipates soon after its emergence from the zone of the internal critical point. This follows from theoretical deductions: the stream must possess a small angular momentum, corresponding to that in the critical point region. It also follows from observation that a decrease of light in the stream always causes asymmetry in the light curve out of eclipse. The well-known periastron effect, expressed by the differences in the maxima of the light curve and formerly attributed to the change of the phase effect when a star is moving in its elliptical orbit, is now almost always connected with the stream from the components. The new interpretation of the mechanics of the ejection of gas from non-stable stars makes it possible to explain the variation of the period of β Lyr by the loss of mass, and to estimate the age of that system as about 10^6 years [2].

In conclusion, we shall attempt to give a new cosmogonical interpretation of the H–R diagram based mainly upon data obtained from studies of eclipsing variables.

The evolution of massive stars proceeds from the stage of stable hot super-giants through the stage of Wolf-Rayet stars and red giants to the main sequence (thus approaching solar-type stars). The mass decreases according to the law

$$\frac{d\mathbf{m}}{dt} = 4\pi R^2 \rho_0 v_0, \tag{6}$$

where v_0 is the rate of ejection, ρ_0 is the density at the surface of the star, and R is the radius of the star. As soon as v_0 and R begin to grow progressively in the Wolf-Rayet stage, the derivative $d\mathbf{m}/dt$ reaches a maximum. In the giant stage, it decreases rapidly and reaches zero in the stage of solar-type stars. We do not believe an evolution along the main sequence to be possible. E. R. Mustel showed recently [7] that solar-type stars lose mass at a rate of the order of 10^{16} grams/year. Stars of small mass in their initial stage of development are not met among the eclipsing variables known to us. Perhaps only the system of YY Gem, in which the spectra of the components have emission lines typical of the T Tau variables (which, according to Ambartsumian, form T-associations and are therefore very young stars), may be thought of as young non-stable stars of small mass. The process of expansion of the initially stable star transforms it into a sub-giant. The loss of mass by the star might reach its largest value in that stage of the star's evolution. For stars of small mass, sub-giants may play in a number of cases the role of Wolf-Rayet stars. The process of contraction makes the sub-giant evolve into a star belonging to the second part of the main sequence, according to Parenago; i.e. into a star with comparatively large density and mass less than the solar mass. If the energy source of such stars is the proton-proton reaction, then their further transition into the sub-dwarf stage [1] will be altogether natural. According to Kaltchaev, sub-dwarfs are stars of small mass and radius, and large density by comparison with main-sequence stars (the main characteristics of main-sequence stars were taken from Parenago's data). It is obvious that main-sequence stars transformed into sub-dwarfs were also objects of small mass and a still greater density, because when the amount of helium increases, the opacity of the star increases also and expansion takes place. The fact that all eclipsing variables composed of sub-dwarfs are found to be unstable suggests that the cause of their instability is the passage of a main-sequence star into the sub-dwarf phase, the star expanding and becoming unstable after it has reached Roche's limiting figure. We can, therefore, believe that in this case the instability of the star does not suggest its youth but rather its comparatively old age. Non-stability can arise in various stages of stellar evolution.

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