11. ON THE CAUSES OF STELLAR BURSTS

L. E. GUREVITCH AND A. I. LEBEDINSKY
Physico-Technical Institute, Leningrad, U.S.S.R.;
University, Moscow, U.S.S.R.

The phenomena taking place as a result of a nova outburst indicate that a shock wave is propagated to the surface of the star. It may be the result of an explosion in the interior of the star. The hypothesis that peripheral thermo-nuclear explosions cause the outbursts of novae, and perhaps also those of nova-like stars, was advanced in 1947 [1]. By 'peripheral' we mean some spherical layer which we shall name the *A* layer.

A thermo-nuclear explosion in the central parts of the star is impossible under ordinary conditions because the star possesses the property of 'self-adjustment', which prevents an explosion in its interior. If as a result of a gradual increase in the activity of the central energy sources, the excessive heat has sufficient time to become distributed uniformly throughout the star, then, according to the virial theorem, an expansion of the star results. This leads not to a heating, but to a cooling of the central parts of the star. As will be explained later on, a peripheral explosion is not only possible but is even inevitable in certain evolutionary stages of some stars.

The hypothesis of a peripheral explosion is confirmed by the observational data on the asymmetry of envelopes ejected by the novae. Such asymmetry was clearly present in the cases of Nova Pictoris 1925 and Nova Herculis 1934, which resembled multiple stars some time after the outbursts. A central explosion in a spherically symmetric star develops without any violation of the central symmetry and must therefore cause the ejection of a spherical envelope. Conversely, as the result of a peripheral explosion the star becomes asymmetric, and an asymmetric envelope is ejected. This occurs owing to the fact that the explosion, which took place at some point of the *A* layer, propagates in the form of a detonation wave throughout that layer during a period of time comparable with the time required for the passage of the shock wave from the *A* layer to the surface of the star.

The velocities with which the envelopes are ejected by novae exceed the value appropriate for the region of the star where thermo-nuclear explosions, due to hydrogen being converted into helium, would be expected.

This circumstance has been explained both qualitatively [2] and quantitatively [3] by the increase of W, the velocity of the shock wave propagated in a sphere of outwardly decreasing density, when the front of the wave advances from the interior to the peripheral parts of the star. In a spherically symmetrical star $W^3 r^2 \rho = \text{constant}$, where ρ is the density previous to the explosion at a distance r from the centre of the star.

A peripheral thermo-nuclear explosion can take place, as was shown by us [4], when a star reaches a stage of its evolution when, as a consequence of hydrogen exhaustion in its central part, an isothermal region of such large dimensions is formed that the star passes from the condition where nuclear reactions provide its main source of energy, to the regime of gravitational contraction. Evolution of a star in this stage consists of contraction, accompanied by a gradual heating of its whole mass including its outer parts where some hydrogen remains.

When the transition of the star from the regime of nuclear energy sources to the regime of gravitational contraction is taking place, the star passes into the condition of instability, in which outbursts are possible. To explain this, let us investigate the most simple case (in the mathematical sense), where the outer parts where hydrogen is still present have become thin and their lower boundary lies at a depth z_A, which is small compared to the radius of the star R. In this case, the temperature T_A at a depth z_A is determined by the formula

$$T_A \propto z_A \propto \left(\frac{M_e}{R^2}\right)^{4/17} (gF)^{2/17}, \tag{1}$$

where M_e is the mass of the outer region, while g and F are the acceleration of gravity and the flux density of radiation on the surface of the star.

For a random increase of the energy source, F will increase along with it. This will also increase T_A according to (1). An increase of T_A will also intensify the energy output of the nuclear reactions in the A layer, which will in turn cause further growth of F and T_A. For a random decrease of F, the depth z_A, and at the same time also the temperature T_A will decrease, and this will lead to a decrease of the nuclear reactions and to a further fall of F. Such a state is unstable, as it may be proved, and will inevitably lead to an explosion.

Previous to the onset of non-stability, the depth z_A is large and relation (1) is incorrect. An occasional change of the flux of energy will cause a change of the temperature in the opposite direction. This will again re-establish the normal flow of thermo-nuclear energy. It is quite probable that this non-stability was formally discovered, without its physical significance being noted, by Chandrasekhar and Henrich [5]. They suggested that when the isothermal region of a star reaches a definite critical dimension the equilibrium equations become incompatible.

A slow evolutionary heating of the star causes a gradual temperature increase in the A layer, which continues up to some critical value T_k. At this stage, the radiative transport of energy cannot keep up with the output of the thermo-nuclear sources and a continuously increasing heating of the A layer begins. Over a period of time, which we shall name the induction period, the temperature at the lower boundary of the A layer will grow from the value of T_k to a value of T_i. At this stage, the thermonuclear sources in the A layer will be so intense that a discontinuity in the pressure will be formed. The shock wave, which carries a part of the energy to the surface, causes a strong heating of the gas masses lying above the A layer.

An examination of the kinetics of the outburst process [4] permits the following estimates: T_k is about 2×10^7 degrees, and T_i is about 8×10^7 degrees. The induction period in the case of a typical nova continues for several thousands of years, and in the case of outbursts of super-novae, for millions of years. But only immediately before the outburst—approximately a week before in the case of novae—the heat emission in an A layer will increase to such an extent that a super-adiabatic temperature gradient will be reached at the outer boundary of the A layer. This cannot cause a mixing of matter, because a considerably longer time is necessary for convection to develop, as may be shown.

A hydrogen explosion will rapidly be halted or, as we express it, become degenerated, so that only a small portion of the hydrogen has time to become converted into helium. The cause of the degeneration of the explosion lies in the properties of nuclear reactions. Out of the two known reactions for the transformation of hydrogen into helium, only the carbon cycle leads to an explosion. The other reaction, the proton-proton cycle, cannot cause an explosion owing to its slowness. As was shown by us [4], the output of the thermo-nuclear source in the A layer must be comparable to the luminosity of the star at the time the critical temperature is reached. At the moment the explosion starts, it must exceed that luminosity by a number of orders of magnitude. The proton-proton reaction cannot produce such emission. The Bethe reaction, however, involves β-decays that take place during times of the order of some hundred seconds [6]:

$$N^{13} \rightarrow C^{13} + e^+,$$

the half-life being $9{\cdot}93 \pm 0{\cdot}03$ min., and

$$O^{15} \rightarrow N^{15} + e^+,$$

the half-life of which is 115 ± 1 sec. A possible path of the reaction

$$N^{13} + p \rightarrow O^{14} \rightarrow N^{14} + e^{+}$$

also involves β-decay, the half-life equalling $76{\cdot}5 \pm 0{\cdot}5$ sec. The velocity of the Bethe cycle at high temperatures is limited by the above processes. Therefore, in the course of time of one β-decay, every carbon or nitrogen nucleus may capture on the average only one proton. During this time a part x_c/x_H of the hydrogen abundance is converted into helium. Here, x_H and x_c are the atomic concentrations of hydrogen and carbon-nitrogen. At x_H about 1 and the ordinary value of x_c about 10^{-3}, this fraction equals 10^{-3}, so that the whole hydrogen abundance may be spent in a day. But the gases of the outer region, heated up to many tens of millions of degrees, cannot be at rest for a day. The outer region will inevitably reach during a time of the order of some tens of seconds a state of rapid expansion, accompanied, generally speaking, by disorderly convective motions. A considerable cooling is thus produced, and the explosion is stopped. Therefore, the amount of hydrogen that will have time to be transformed into helium during the outburst is of the order of the abundance of carbon atoms, namely 10^{-3}. While only a small amount of hydrogen burns away during the explosion, the same conditions are re-established afterwards. The explosion must, therefore, repeat itself after a certain lapse of time.

The sum of the observational facts makes it rather probable that outbursts of every nova are actually recurrent. The intervals of time between outbursts must be of the order of the time required for a pre-explosional heating. A strong outburst, causing an intense turbulent motion, cools the stellar gas after the explosion, so that the gas almost reaches temperature T_k. The intervals of time between such bursts are, therefore, comparable to the induction time. Minor outbursts cause a lesser cooling and the intervals between them are shorter. Thus, a possibility appears of explaining the correlation between the frequency of outbursts and their amplitudes.

The energy scale of an outburst is determined by the mass of the outer part of the star containing hydrogen, namely by the mass M_e. This mass has previous to the induction period a temperature less than T_k. An evaluation of this mass leads to the equation

$$M_e = 6{\cdot}5 \frac{R^4}{\sqrt{\mathbf{m}L}} \left(\frac{T_k}{10^7}\right)^{17/4},$$

where $\mathbf{m}$ is the mass, L the luminosity, and R the radius of the star before its outburst, expressed in solar units. The explosion does not involve the hydrogen as a whole, but only the innermost layers with masses equalling

$0{\cdot}16\ M_e$, as may be seen from calculations. Consequently, the energy of the explosion is

$$Q = \frac{q x_c R^4}{\sqrt{\mathrm{m}L}} \left(\frac{T_k}{10^7}\right)^{17/4}, \tag{2}$$

where q is the amount of energy emitted when a mass of hydrogen equal to the mass of the Sun is converted into helium.

As is seen from equation (2), outbursts on the energy scale of novae may occur only in the case of sufficiently dense dwarfs that possess masses and luminosities comparable to the Sun, and a radius of the order of less than $0{\cdot}1\ R_\odot$. According to Walker's data [7], Nova Herculis 1934 is a dwarf of that kind.

Outbursts on the scale of super-novae can take place during the first explosions, when the mass M_e constitutes a major part of the star. If x_c is greater than 2–3 %, then a hydrogen explosion may call forth a detonation of the reaction when helium converts into carbon. In this reaction β-decay is not involved, and it may therefore cause an explosion of the main mass of the star. At x_c less than 0·005, the temperature does not reach the value $T_i = 8 \times 10^7$ degrees. Expansion of the A layer therefore proceeds with a sub-sonic velocity and the shock wave is formed in the higher layers.

Along with the stellar outbursts resulting from the preceding internal causes, it has been shown by one of the authors [8] that outbursts caused by external factors and particularly by the accretion of interstellar gases containing deuterium are also possible.

As we have already seen, all the processes of the Bethe cycle proceed with extremely large velocities (except the processes involving β-decay that lead to the formation of C^{13} and N^{15}) when extremely high temperatures are attained in the A layer during the course of the explosion. The increase of thermo-nuclear emission is stopped and the explosion degenerates when a considerable part of the stable nuclei of C^{12}, C^{13}, N^{14} and N^{15} are converted into radioactive nuclei N^{13}, O^{15} and O^{14}, which later pass into C^{13}, N^{15} and N^{14} by β-decay. Therefore, as a result of outbursts, C^{12} and N^{14} must become converted into C^{13} and N^{15} and, consequently, the ratios $C^{13}:C^{12}$ and $N^{15}:N^{14}$ must be anomalously large in the atmosphere of stars in which explosions have taken place.

In some cool stars an anomalously high abundance of the isotope C^{13} has been discovered [9]. The observed value of the ratio $C^{13}:C^{12}$ reaches unity. From our point of view, this may be a consequence of the fact that these stars have experienced outbursts in the past. The possibility is not excluded that the ratio $N^{15}:N^{14}$ is also anomalously large in some of these stars. It should be extremely interesting to check this supposition by means of observations.

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