9. PHYSICAL PROCESSES IN NOVAE

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The present communication is devoted to some important problems connected with the interpretation of spectroscopic phenomena observed during the outbursts of novae.

It is known that the phenomenon of an outburst in its initial stages is connected with the expansion of the 'photosphere' and the 'reversing layer' of a nova. There are some reasons to expect that this process does not involve the most central parts of the star. The increase of the radius of the 'photosphere' of the star can be estimated from the equation:

$$M_v = \frac{29500}{T} - 5 \log R_p - 0{\cdot}08, \tag{1}$$

while the expansion of the 'reversing layer' can be studied by means of integrating the curve of radial velocities determined from the displacement of lines of the pre-maximum spectrum of the star:

$$R = R_0 + \int_{t_0}^{t} V\,dt. \tag{2}$$

From equations (1) and (2), A. Beer[1] concluded that the radius of the 'reversing layer' of Nova Her 1934 during its expansion had exceeded many times the radius of its photosphere. The author showed[2] that the same was true for each of seven novae which were observed previous to their light maximum.* The comparison of the velocities of expansion of the 'photosphere' V_p, estimated from equation (1), with the velocities V made it possible for the author[2, 3] to conclude that previous to the moment t_m of light maximum, the velocity gradient in the expanding envelope of the nova (at least up to the level where the optical depth $\tau \approx 1$) cannot be large. This is confirmed by the relative narrowness of the absorption lines in the pre-maximum spectrum of the star, previous to its light maximum.

The moment of light maximum t_m is an extremely important transitional stage in the process of the evolution of a nova. Appreciable changes in the

* The problem of applying formula (1) to novae has been considered by the author[2]. It was shown that this formula cannot give large errors.

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spectrum of the star begin immediately after light maximum [4]. (*a*) The pre-maximum spectrum of the star is replaced by the principal spectrum with a greater displacement. From its very beginning, the system of the principal spectrum appears to be detached from the system of the pre-maximum one (see Fig. 1). The intensity of the systems is represented in this Figure by the breadth of the corresponding strip. For Nova Per 1901,

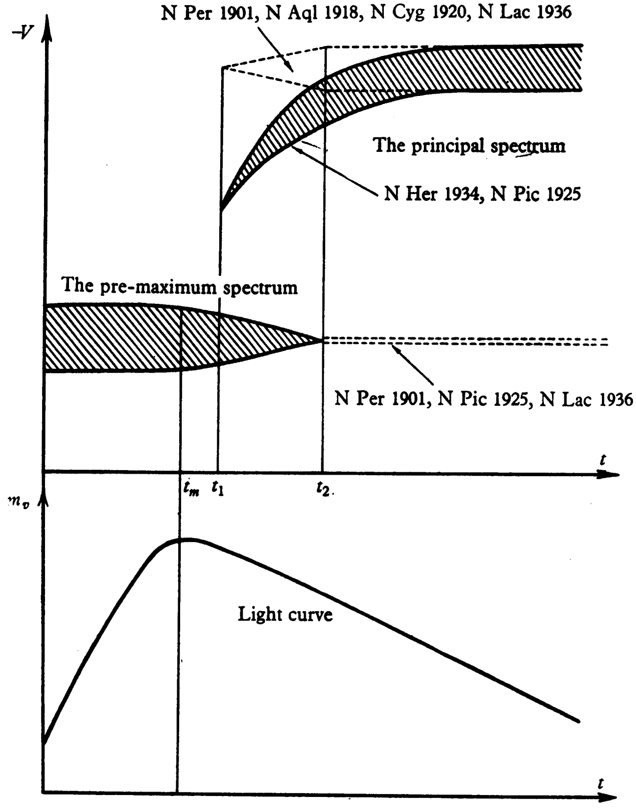

Fig. 1. The development of the principal absorption spectrum in a number of novae in the neighbourhood of maximum light.

Nova Aql 1918, Nova Cyg 1920, Nova Lac 1936 the variation of the displacement of the principal spectrum in the interval t_2–t_1 has been studied insufficiently. (*b*) Emission bands of the principal spectrum appear. (*c*) New systems known as the diffuse-enhanced spectrum and the Orion spectrum appear. Both these systems are accompanied by emission.

To explain the existence of light maximum, with which all these phenomena are intimately connected, obviously only two hypotheses A and B can be suggested [5, 6]. Two possibilities are foreseen by hypothesis A.

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Hypothesis A, first model. At the moment of its outburst the star throws off a spherical shell, which begins to expand in the form of an envelope, detached from the star (Fig. 2). At first the optical thickness of the envelope satisfies the inequality $\tau \gg 1$. As long as this inequality is realized, the brightness of the star increases. While moving away from the star the envelope becomes rarefied and its τ decreases. When $\tau \approx 1$ the moment of light maximum sets in, after which the brightness of the star begins to decrease.

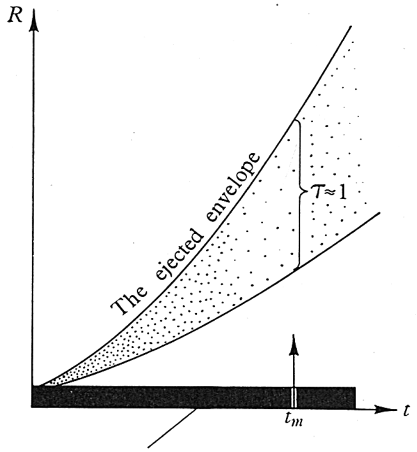

Fig. 2. A representation of the ejection of a shell by the nova under hypothesis A, first model.

This hypothesis meets considerable difficulties, as follows:

(*a*) It fails to explain the replacement of the pre-maximum spectrum by the principal spectrum, as well as all the peculiar properties which characterize this process.

(*b*) According to hypothesis A, immediately after light maximum $\tau < 1$ in the visual and the photographic regions of the spectrum. At the same time beyond the limit of the Balmer series, where the absorption coefficient is considerably greater, this inequality must be realized later. Thus, immediately after light maximum, a jump in intensity is expected to arise at the limit of the Balmer series. In other words $I(\lambda \leqslant 3647)$ would be considerably greater than $I(\lambda \geqslant 3647)$, which contradicts the observations [2]. (The normal intensity of the Balmer lines in the spectra of novae previous to light maximum suggests a quite normal hydrogen content in the second quantum state.)

(*c*) Let t_e be the moment of appearance of the emission bands in the spectrum of the star. At this moment, the inequality $\tau \ll 1$ must be realized

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in the optical range of the spectrum. Otherwise the red wings of the bright bands, which correspond to the receding hemisphere of the envelope, would be appreciably weakened, which contradicts the observations. Assuming now that hypothesis A is valid, then at the moment t_e and even somewhat earlier we would be able to see through the detached envelope the outer layers of the central star. On the other hand, it seems obvious that whatever is the mechanism of ejection, the temperature of these outer layers must be sensibly higher than that of the detached envelope (particularly of its outer layers). Otherwise it is difficult to explain the origin of the impulse gained by the outer layers of the nova at the moment of its outburst.

Thus it should be expected that at the moment t_e the observed temperature of the nova is essentially higher as compared with its temperature at the moment t_m, which is contradicted by the observations. The latter show that in the course of a short period of time $\Delta t = t_e - t_m$, the spectrum for all novae become later. Moreover, immediately after light maximum bands of CN were observed in the spectra of Nova Aql 1918 and Nova Her 1934. Emission bands connected with the principal spectrum which appear at the moment t_e correspond exactly to the same (relatively low) state of excitation and ionization that characterizes the principal absorption spectrum. Finally, in the course of the same period of time Δt, the colour temperature of the star usually decreases also. Only a few days after the time t_e we observe a slow decrease of temperature accompanied by a transition of the spectrum of the star towards earlier subdivisions.

Hypothesis A, second model. Here the 'main burst' is followed by continuous expulsion of matter at a steadily decreasing rate. The matter ejected as a result of such a continuous process expands and its transparency increases. This model is shown in Fig. 3. The thick continuous curve represents the change of R_p for Nova Aql 1918 calculated [5] by means of equation (1) and roughly corresponds to the level with $\tau \approx 1$. Beyond this level outwards the matter is transparent. The temperatures used here are based on the spectral types of the star during its expansion. The density of shading corresponds to the density of matter. Before the outburst the value of R_p for Nova Aql 1918 did not exceed $0{\cdot}4 R_\odot$. This model retains the first difficulty of the first model, whereas the second and third difficulties no longer exist. But at the same time a new difficulty arises. From elementary calculations and from Fig. 3 it may be concluded that for times before light maximum the velocity of matter (thin lines A–A in Fig. 3) must be much greater than the velocity V_p. This contradicts available data [3].*

* Especially if we take into consideration the influence of interstellar absorption upon M_v of formula (1); this was not done in reference 3.

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There are, finally, two more extremely serious difficulties with hypothesis A. (*a*) It is quite obvious that the moment of light maximum is of a purely optical character in the case of both models. But as we have already pointed out, this moment has a great physical meaning and sharply defines two totally different stages in the evolution of the nova. Thus, McLaughlin [4] and the author [6, 7] showed that the diffuse-enhanced spectrum is the result of continuous ejection of matter from the outer

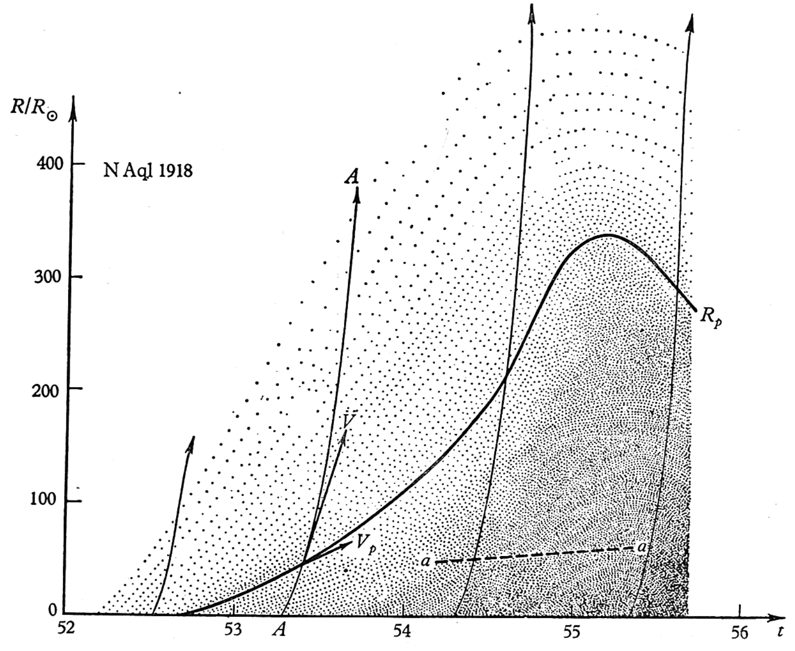

Fig. 3. A representation of hypothesis A, second model, in which the main outburst is followed by a continuous ejection of matter at a steadily decreasing rate. The specific data are those for Nova Aquilae 1918.

layers of the star; the latter are located at a very great distance from the centre of the contracting nova. (The Orion spectrum is of a quite similar origin, although the matter is ejected in that case from somewhat deeper layers.) This process does not have anything in common with the 'explosion', which is manifested in the form of a star expanding before light maximum. It is quite clear that in the latter case, the source of explosion is located very deep, in the main body of the star.

(*b*) In the first model the envelope is detached at the initial moment of the outburst, whereas in the second model there is a continuous ejection of matter, which decreases appreciably towards the moment of light maximum. All this contradicts observation. The observations show that it is

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the displacement of the principal spectrum, but not the displacement of the pre-maximum one, which corresponds to the expansion velocity of the nebulosity observed later (note particularly the cases of Nova Per 1901, Nova Her 1934 and Nova Pic 1925). As long as this nebulosity contains the main mass of matter ejected by the nova as a result of the outburst, an important conclusion can be drawn: that the envelopes of novae are

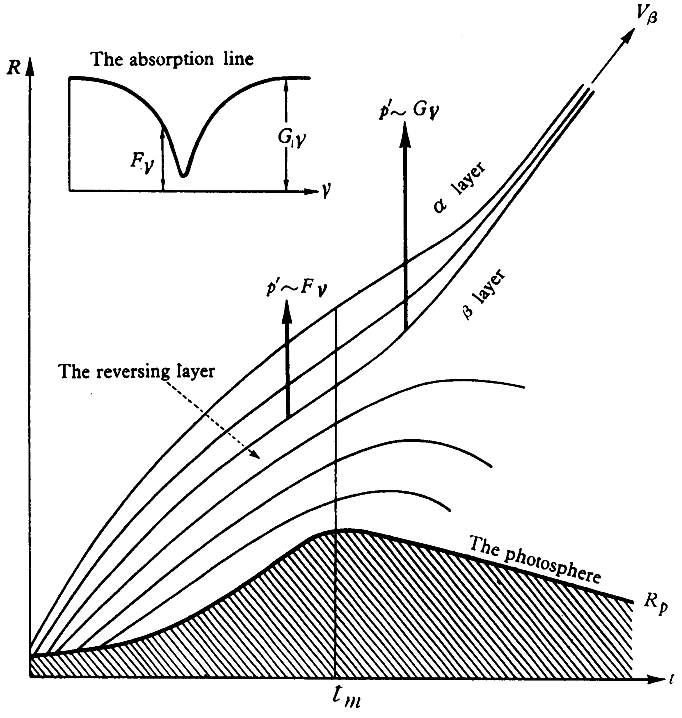

Fig. 4. A representation of hypothesis B, in which the outer parts of the extended reversing layer of the nova, as the star contracts, continue to rise in the form of an envelope.

detached after light maximum, when the principal spectrum is appearing. Moreover, because we can see the birth of the principal envelope itself (the appearance of an extremely weak principal spectrum at the very beginning) it means that the latter originates inside the extended reversing layer of the nova, which is transparent for the frequencies of the continuous spectrum.

The difficulties of hypothesis A force us to consider hypothesis B.

Hypothesis B. It is supposed that the 'photosphere', which determines the brightness of the nova, has its greatest dimensions at the moment of light maximum, after which the contraction of the photosphere begins,

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followed by a decrease of brightness of the nova. From the point of view of this hypothesis the matter which forms the 'photosphere' remains with the star.* The outer parts of the extended reversing layer of the nova leave the star in the form of an envelope. As was shown by the author in references 6, 8, 9, and 10, hypothesis B permits one to explain the process of replacement of the pre-maximum spectrum by the principal spectrum.

This process can be easily understood from Fig. 4. The rise of a large velocity gradient in the inner parts of the extended reversing layer of the star near the moment t_m makes these parts transparent even for the frequencies of absorption lines. This leads to an almost sudden increase of selective radiation pressure upon the internal parts of the envelope, which is in a state of detachment and has a small gradient of velocities. As a result of this a new β layer is formed which moves away from the star. This β layer creates absorption lines of the principal spectrum. The 'old' envelope with a small gradient of velocities decreases in thickness. This envelope, called the α layer, corresponds to the pre-maximum spectrum. When the β layer reaches the outer parts of the α layer, the latter disappears and the pre-maximum spectrum disappears with it. There remains only the completely detached principal envelope, which can be observed later in the form of a bright nebulosity. This mechanism offers a possibility of estimating the thickness ΔR of the envelope which is being detached. It is obvious that

$$\Delta R = \int_{t_1}^{t_2} |V_\beta - V_\alpha| \, dt. \tag{3}$$

The moments t_1 and t_2 are fixed in Fig. 1. Computations show [6] that for Nova Her 1934 we have $\Delta R \approx 60\ R_\odot$ for metallic lines, and $\Delta R \approx 100\ R_\odot$ for hydrogen lines.

The above mechanism explains furthermore all the peculiar properties which characterize the replacement of the pre-maximum spectrum by the principal spectrum, namely:

(*a*) The formation (after light maximum) of subsidiary absorption systems with displacements that are larger than the displacement of the principal spectrum.

(*b*) The increase of displacement of the principal spectrum at the interval $t_2 - t_1$ (see Fig. 1).

(*c*) The existence of a very weak pre-maximum spectrum after light maximum. This weak spectrum was observed for Nova Per 1901, Nova Pic 1925 and Nova Lac 1936. A special investigation carried out by the

* A few possible cases of the motion of matter in hypothesis B are considered in reference 6, pp. 116–20.

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author [9] has shown that all the other mechanisms which were suggested to explain the replacement of the pre-maximum spectrum by the principal spectrum involve very serious difficulties.

It is not possible to agree with the suggestion of McLaughlin [4] that the replacement of the pre-maximum spectrum by the principal spectrum is connected with the increase of the radiation pressure caused by a sudden increase of temperature of the star. We have seen above that there is no increase of temperature immediately after light maximum. Moreover, for some stars (for example, Nova Her 1934) the replacement of the pre-maximum spectrum by the principal spectrum took place even before the appearance of the emission bands.

From all that has been said above, it follows that from the spectroscopic point of view, hypothesis A meets a number of extremely serious difficulties which do not exist in B. Hypothesis B permits one also to explain the replacement of the pre-maximum spectrum by the principal spectrum. Such a replacement was observed in all the seven novae 'caught' before maximum and it ought to be considered as a fundamental law in the spectroscopic evolution of every nova [4].

Let us now examine the consequences which follow from hypothesis B. If this hypothesis is valid, then in this case the photospheric matter must remain with the star. Assuming that the nature of forces which retain the photosphere is gravitational, we can estimate then the minimum masses of novae. In fact, we may consider that the velocity V_p of the photosphere, which can be derived from equation (1), is less than the parabolic one for the level R_p. Extremely large masses are obtained in this case [5], which are greater, the greater the luminosity of the nova previous to its outburst. Of all the obtained masses the largest is the mass of Nova Aql 1918, for which $\mathbf{m} \approx 1700\,\mathbf{m}_{\odot}$, and the smallest mass is the one of Nova Her 1934, for which $\mathbf{m} = 7\,\mathbf{m}_{\odot}$.

The cases in which displacement of the pre-maximum spectrum diminished with time also gave large 'masses' of novae. It is true that a number of authors have raised the question that probably there was no real deceleration of matter here, but simply a certain movement of some 'effective' absorbing level in the reversing layer of a nova. However, a critical investigation of this problem made the author arrive at the conclusion [11] that in certain cases there had been a real deceleration of moving matter. Then again the 'masses' reach several hundred solar masses.

In this connexion the following facts may also be mentioned. R. F. Sanford [12] discovered that the absorption lines of the type-gM3 component of the recurrent Nova T CrB show orbital motion with a period of

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about 230 days and a semi-amplitude of 21 km./sec., while the emission bands in the spectrum of the nova itself do not show any periodic variations. This case, for the present unique in the history of stellar spectroscopy, may be explained by the fact that the mass of T CrB exceeds considerably the mass of its giant satellite. Further, it seems of interest to note that the 'masses' of novae, estimated by means of the above-mentioned methods, are proportional to the masses of the envelopes ejected by the novae. The values of the masses of the envelopes were determined by I. Kopylov [13] for a number of stars by means of the same method.

The introduction of large masses for novae is connected, however, with extremely serious difficulties:

(*a*) The emission bands observed in the spectra of post-novae do not show the presence of large gravitational displacement expected in this case.

(*b*) According to recent data, Nova Her 1934 is an eclipsing variable [14] and it may be concluded that its mass is small.

Taking into account all these difficulties let us consider some other possible forces of a non-gravitational character. In this connexion we may indicate the forces under the influence of which the prominences of the surge type are moving. For example, for the surge that was observed over the chromospheric flare of 8 May 1951 [15], decelerations were registered which were very large compared with gravitation. The existence of such forces which act in the direction towards the centre of the star and which exceed the force of gravitation, must, therefore, be considered as a fact, which follows directly from observations! Hence the necessity of introducing these forces (obviously of an electro-magnetic nature) cannot be considered as a difficulty of hypothesis B. Moreover, the phenomenon of surges ejected and then returned to the Sun with accelerations exceeding gravitation is very similar to the phenomenon of expansion of a nova. The only difference here is that the separate condensations forming the photosphere are moving radially in *all* directions.

It is of interest to note that there exists another similarity between the outbursts of novae and the chromospheric flares. It is known that the appearance of a chromospheric flare on the Sun is accompanied in certain cases by a growth in the intensity of cosmic rays. On the other hand, there are some reasons to think [16] that the envelopes ejected from the supernovae and from the novae contain particles of very high energies. Thus, in both cases we have simultaneously: (*a*) a sharply non-stationary process, accompanied by ejection and consequent return of matter, (*b*) an appearance of forces that exceed gravitation, (*c*) the formation of high energy particles. Obviously, such an extremely complicated non-stationary process

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characterizes not only the novae and the chromospheric flares, but also many other phenomena in the atmospheres of the non-stationary stars.

The idea that the rise of the electromagnetic forces inside the expanding nova, which are directed to its centre, may be connected with the phenomena of the outburst itself, is supported by the following considerations. It is known that the outburst of a nova is accompanied by ejection of separate gaseous condensations that move radially with different velocities. Ionized gas clouds moving with high velocities pass through clouds with low velocities. This causes* the formation of electric currents, the directions of which are radial. These currents will be accompanied by magnetic fields with components perpendicular to the radius.

The main source of the magnetic fields must be the inner parts of the expanding nova, where all the processes connected with the explosion proceed most intensively. These magnetic fields will cause the retardation of the conducting gases of the photosphere and of the reversing layer. That the magnetic fields may be large, even at distances of several hundred stellar radii from the surface of the star, is evident in the case of AG Pegasi (see reference 17).

It is necessary to point out here that the magnetic fields thus formed (as well as the general magnetic field of the star which possibly existed before the outburst (see below)), must be greatly strengthened by further chaotic turbulent movements of the conducting gases. The 'interlacing' of the magnetic lines of forces will make the star resemble a ball of elastic threads and this will also cause retardation of radially moving gases.

It is possible that the initial general magnetic field of the star plays the principal role in the problem of retardation. Indeed, if before the outburst a nova possesses a general magnetic field, the retardation of ejected ionized matter will be the least in the polar directions, where magnetic lines of force are approximately radial. Accordingly, the quantity of ejected matter in these directions will be the greatest. This is in agreement with the fact that in many cases the main mass of matter is ejected during the outburst in two diametrically opposite directions. We have in mind Baade's polar caps for Nova Aql 1918, the two condensations in the nebula of Nova Her 1934, and generally the so-called 'doubling' of novae. Finally, we must indicate the symmetrical disposition of the two maxima in the emission bands in the spectra of the majority of novae. Table 1 illustrates this fact.

However, it must be stated at the same time that in spite of the very complex character of the phenomena of ejection before light maximum the expansion of each new star proceeds in *all* directions. In certain direc-

* Because of the different masses of electrons and ions and their different cross-sections.

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tions, however, the quantity of ejected matter is the greatest. The fact that for all the seven new stars that were 'caught' before light maximum, a replacement of the pre-maximum spectrum by the principal spectrum took place speaks in favour of this picture. Therefore the general concepts of the mechanism of expansion considered above must be retained.

Table 1. *Data on the Presence of Two Maxima in the Emission Bands of Novae*

Nova Per 1901	absent	Nova Mon 1939	absent
Nova Lac 1911	present	Nova Pup 1942	present?*
Nova Gem 1912	present	Nova Aql 1943	present
Nova Aql 1918	present	Nova Aql 1945	absent
Nova Cyg 1920	present	Nova Sgr 1947	absent
Nova Pic 1925	present	Nova Cyg 1948	absent
Nova Her 1934	present	Nova Ser 1948	present
Nova Sgr 1936	present	Nova Sco 1950 (1)	present
Nova Aql 1936 (1)	present	Nova Lac 1950	absent
Nova Lac 1936	present	η Car	present

* Present in He I, He II.

It is of interest to point out the following fact. Let us assume that the radio-frequency radiation from the envelopes ejected by super-novae is actually connected with the emission of radiation of the relativistic electrons in magnetic fields [16]. In this case we can consider that these envelopes in their *present* state are characterized by the presence of magnetic fields. On the other hand, magnetic fields in these envelopes must change with time extremely slowly. Therefore, magnetic fields must be present in these envelopes at the moment of their *detachment* from super-novae. It is possible that the same is true for novae.

The fact that during the outbursts of novae some considerable inward forces must arise is confirmed by a number of subsidiary considerations. In particular, it is of interest to note that in Fig. 3 even the dotted line *a–a* corresponds to velocities exceeding the parabolic. The impression is that practically all the mass of the expanded envelope of Nova Aql 1918, including the region with $\tau > 1$, should have left the star, but this seems hardly admissible.

We have already pointed out that the source of matter which forms the diffuse-enhanced spectrum is localized in the external layers of the contracting nova. The source of the Orion spectrum is also located somewhere not very deep under the photosphere, but not in the main body of the star. Therefore it may be accepted that the processes of continuous ejection of matter after light maximum are connected with the internal instability of the outer layers of the contracting nova, but not with the continuous

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'explosions' in the main body of the star. It may be suggested that the source of such non-stability is the process of contraction of the star (after its light maximum) which leads to a transformation of the contraction energy into thermal energy and into energies of some other types. However, forces which greatly exceed gravitation at $\mathbf{m} = \mathbf{m}_{\odot}$ are required in order to provide a sufficiently rapid production of energy of contraction. It should be taken into account that sometimes the diffuse-enhanced spectrum of novae appears a few hours after light maximum.

The fact that after light maximum no jump of intensity at the limit of the Balmer series is observed [2] speaks in favour of an extreme non-stability of the outer layers of novae at this time (a Balmer jump due to recombination appears much later, as in the case of Nova Lac 1936, and is connected with the phenomena of fluorescence). This, as was shown by the author [18], may obviously be explained by the fact that the outer layers of a nova after its light maximum are in a relatively isothermic state, which requires random gas movements with supersonic velocities. The formation of emission bands of the principal spectrum [10, 19] is evidently connected with these processes. As we have seen, the temperature of the star up to the time t_e does not increase, but decreases slightly. Therefore, fluorescence of a thermal character must be excluded. It may be expected that the energy arising in the extended envelope as a result of atomic collisions* (and other processes) is absorbed by the principal envelope in its wide (ultra-violet) absorption lines. Following this, a re-emission of energy takes place in other lines as well.

Furthermore, it is of interest to point out that although the source of formation of the diffuse-enhanced and Orion spectra is the instability of the corresponding regions of the nova, the particular mechanism of the ejection of matter is similar in this case [7] to the ejection of prominences from the Sun. This emphasizes again the considerable role of the electromagnetic forces in the phenomenon of novae.

The author's computations show [7] also that atoms forming the diffuse-enhanced spectrum must be accelerated by selective radiation pressure in $L\alpha$. The intensity of $L\alpha$, estimated from the intensity of the observed $H\alpha$ line, is expected to be very high.

A very important problem in the physics of novae is the calculation of the mass m of the envelopes ejected by novae. This problem was first considered by V. Ambartsumian and N. Kozyrev [20].

The masses of envelopes are usually estimated from the intensity of emission bands created by the principal envelope. Recently (see above)

* Owing to collisions between gaseous clouds moving with different turbulent velocities.

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this method has been used by I. Kopylov [13]. He showed that there is a linear dependence between log m and the absolute visual brightness of the nova before its outburst. The brighter the star is before its outburst, the greater is log m.

Another method [21] of estimating the mass m is based on the observed accelerations of envelopes after light maximum. These accelerations $j > 0$ may be connected with the following forces: (*a*) the general and selective radiation pressure, or (*b*) the 'corpuscular' pressure. Atoms producing the diffuse-enhanced and Orion spectra have velocities larger than the velocity of the principal envelope. Overtaking the latter, they continuously communicate to it a part of their momentum.

Application of this method [21] gave values of m that are of the same order as the masses m calculated by other methods.

Let us consider briefly the problem of the origin of the outbursts of novae. It is clear that the novae possess some properties which distinguish them from other stars. It is possible that this is connected [22] with anomalies in the chemical composition of novae. The existing data indicate that many novae are characterized by a high content of the light elements O, C, N. Quantitative investigations are needed here.

The investigation of the outbursts of novae is of great importance from the dynamical and energetic point of view. The process of cooling of a nova during its expansion is especially interesting. The fact that the outer layers of the expanding nova emit radiant energy plays a very important part. This process, connected with the diffusion of light quanta in the envelope of a nova, has been considered recently by V. Sobolev [23].

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