PAPER 22

ON THE MAGNETIC FIELDS OF NOVAE AND SUPER-NOVAE

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ABSTRACT

This paper is a development of the hypothesis, suggested earlier by the author, namely that novae possess a large general magnetic field. This hypothesis explains the following facts: (*a*) effects of the retardation of matter in novae before light maximum, (*b*) a preferential ejection of matter from novae in two diametrically opposite directions during an outburst, and (*c*) formation of rings and equatorial belts after light maximum, observed in N Aql 1918 and N Her 1934. These rings and belts are formed due to the fact that the general magnetic field of new stars deflects condensations of continuous ejection (the diffuse-enhanced and Orion spectra) towards the equator.

Magnetic fields inside novae must be 'tangled'. This explains (*a*), as well as the difference between cases (*b*) and (*c*).

The structure of envelopes, ejected by novae, must reflect the presence of tangled magnetic fields. According to G. A. Shajn this is confirmed for super-novae, the envelopes of which may be studied in detail.

Proceeding from the existing numerous spectroscopic data the author in a series of his papers [1, 2, 3, 4] came to the conclusion that in each nova, during its expansion before light maximum, considerable forces are present, which are directed to its centre and exceed gravity considerably in the case, when the mass of the nova is equal to the solar mass. In order to explain the origin of these forces a hypothesis was proposed by the author (in his early papers [1, 2]), in which large masses were postulated for novae. Later on, however, several facts showed that this hypothesis must be rejected, because of a number of difficulties. In connexion with this the author suggested [3] the hypothesis that magnetic fields are the principal source of retardation phenomena in the expanding nova before light maximum. As it is known (see, e.g. [5]) the conducting medium (ionized gas) becomes 'viscous', when magnetic fields are introduced. Moreover, the 'intertwining' (entangelment) of the magnetic lines of force, which is connected with the turbulent motions of ionized gases, increases this effect.

As a result of this the star, when being in a strongly turbulent state and possessing a magnetic field may be compared to a 'ball' of elastic threads.

There exist two possibilities in the problem of magnetic fields in novae: (*a*) the magnetic field of a nova is constant; it exists in the star before the outburst and after the latter, (*b*) the magnetic field arises during the outburst.

As we shall see further the first possibility is realized in novae, though the process of the outburst itself must lead to a strengthening of the magnetic field in the expanding star.

Let us now consider several arguments speaking in favour of the hypothesis about large magnetic fields in novae. It is natural to assume that the magnetic field of each nova is similar to the field of a dipole. This means that the influence of such a field on the motion of gases ejected from a nova must be non-isotropic.

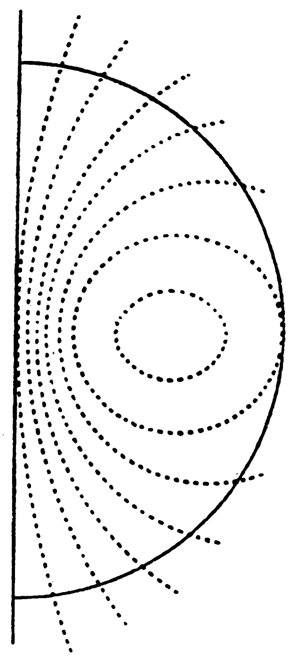

Fig. 1. A possible scheme of the distribution of the magnetic lines of force inside the nova.

First we shall consider the primary phase of the outbursts of the nova—the expansion of the latter before light maximum. If the magnetic field of the nova is of a dipolar character we must expect that the retardation of the moving (ionized) gases, ejected during the outburst, must be smallest in the polar directions, where the velocity vectors of gases and the magnetic lines of forces approximately coincide (Fig. 1). In other words, we must observe a preferential ejection of matter in two diametrically opposite directions.

This is fully confirmed by observations [6]. We have in mind:

(*a*) The well-known fact of the doubling of emission bands in the spectra of the majority of novae (see [6], Table 1; N Sgr 1954, which is not included in this table, also displayed double emission lines). In the cases in which there is no doubling of emission bands we may expect that the polar axis of the star is nearly perpendicular to the line of sight. Many observational facts convince us that the doubling of emission lines is not due to the phenomena of self-reversal and that we have two polar condensations (polar caps) in the expanding principal envelope, which are moving in two diametrically opposite directions;

(*b*) The so-called 'doubling' of novae, which was observed visually for N Pic 1925 and N Her 1934. In these cases two condensations in the expanding principal envelope, together with the nova itself, were located approximately on one common axis. In the spectra of these stars a doubling of emission lines was observed too, which confirms directly the conclusion that the doubling of emission lines in the spectra of other novae reflects also the presence of two condensations in the principal envelope of these stars (but not the presence of rings—toroids, which also give double emission lines).

It is of interest to note that the nebulosities which surrounded these two stars had an oval form; the just mentioned condensations were located on the large axis of the oval. Therefore the velocities of ejected matter were the greatest along the polar directions. This confirms also the statement that the retardation of ejected matter is the least in these directions.

Photographically the phenomenon of the 'doubling' was observed in N Aql 1918 [7], where only the one condensation and a very dense one was visible; this corresponded to spectroscopic observations. The latter indicated that the 'violet' maximum in the emission bands of this star was noticeably stronger, than the 'red' one.

We have pointed out that in the polar directions the retardation of the moving ionized gases must be smallest. However, even in these directions it cannot be zero. As it has been shown by A. Kipper [8] magnetic lines of force in any star must be 'intertwined', if the magnetic field strength inside the star is greater than one gauss. This 'intertwinement' must play a great part in the phenomena of retardation. The significance of this must be greatly increased during the expansion of the star. The motion of the ejected ionized gases in the non-homogeneous magnetic dipolar field* of the star (this field decreases rapidly in strength from the centre of the star) must be accompanied by induced electric currents (due to the law of induction) and therefore by corresponding magnetic fields. And since the process of the expansion of the star is of a strongly turbulent character these magnetic fields must be partly 'intertwined'. It seems that these fields play the principal part in the general retardation phenomena in novae. The source of energy of this induced magnetic field is the energy of the outburst;† therefore the strength of this field may exceed very greatly the strength of the original dipolar field.

The presence of an 'intertwined' magnetic field in the expanding nova

* It seems that the source of this dipolar field is in the innermost parts of the star.

† The retardation phenomena in expanding novae show that the kinetic energy is being transformed here into the magnetic energy.

means that the retardation of matter must take place in all the radial directions, including the polar ones, though in the polar directions it must be the least. Moreover, the presence of such a field means that 'electromagnetic viscosity' exists not only in the radial directions, but in all other directions too. This explains why in spite of the divergence of magnetic lines of force we observe relatively compact, dense, polar condensations, 'polar caps', which produce double maxima in emission bands. Such a compactness was, e.g. strongly displayed in the case of N Aql 1918, see [7].

The viscosity in the process of expansion of the nova before light maximum is very important, because the expansion itself is a continuous

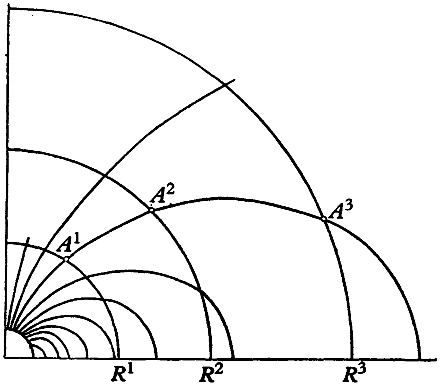

Fig. 2. The figure shows how the condensations, ejected after light maximum for the nova, are deflected to the equatorial plane of the star.

process. However, after light maximum this situation is radically changed. It is known [9, 10] that after light maximum a new ejection of matter begins from novae, but now in the form of separate gaseous condensations. These condensations, different in size, absorb the light from the star and produce the diffuse-enhanced and the Orion spectra of novae. The mean velocity of condensations which produce the diffuse-enhanced spectrum is approximately twice as great as the velocity of the principal envelope. The velocity of condensations, which produce the Orion spectrum is greater than the velocity corresponding to the diffuse-enhanced spectrum or is equal to it.

Since in this case an ejection of isolated condensations takes place, the role of electromagnetic viscosity must be negligible here, being essential only inside the condensations themselves. Therefore, these condensations must move independently one from another along the magnetic lines of force, see Fig. 2. This figure shows that the condensations ejected from the star after light maximum must be deflected to its equatorial plane. Therefore an equatorial belt must be formed in the principal envelope because

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the condensations have velocities greater than the velocity of the principal envelope and must overtake the latter after a certain lapse of time. An equatorial belt will be formed also in the case (N Aql 1918), when practically all the matter constituting the principal envelope is concentrated in its 'polar caps', while in the equatorial parts of this envelope there is practically no matter.

In the process of formation of the equatorial belt the following circumstances must be of great importance: (*a*) the remoteness of the principal envelope from the star; it changes with time, see Fig. 2; (*b*) the fact that at great distances from the star the influence of the dipolar magnetic field on the motion of condensations is very weak (magnetic field strength rapidly diminishes with distance).

Fig. 2 shows that the motion of condensations ejected from the equatorial parts of the star, is hindered due to a specific distribution of magnetic lines of force in these parts. When this factor is important, the amount of matter ejected in the equatorial directions, may be lowered. In these cases the equatorial belt will be divided into two parts, the 'southern' and the 'northern' ones. These parts may be called 'rings'. If (as it happens frequently), the velocities corresponding to the diffuse-enhanced and Orion spectra are different* condensations corresponding to both spectra will be deflected to the equatorial plane at a different rate (as in the case of a mass-spectrograph). This must lead to a rise of two pairs of rings, displaced symmetrically towards the equatorial plane.

These general considerations are confirmed by existing observational data on envelopes around N Aql 1918 and N Her 1934, see [6]. According to W. Baade [7, 11] the envelope of N Aql 1918 had a symmetrical system of rings and two polar caps. H. Weaver [12] has constructed a more exact model of the envelope, which surrounded N Aql 1918 and has found that actually both pairs of rings had velocities, which corresponded to the velocities obtained from the displacement of the absorption lines of the diffuse-enhanced and the Orion spectra. This shows that practically all the matter of the principal envelope is concentrated here in the polar caps and therefore condensations ejected after light maximum and deflected to the equatorial plane, were not retarded by the principal envelope.

It is of great importance that the equatorial rings around N Aql 1918 were characterized by strengthened emission in lines 6548 and 6584 (N II), while on the contrary the hydrogen emission was mainly concentrated in the polar caps [13]. This is in accordance with the fact that the

* The state of ionization and magnetization must also be different in both types of condensations.

Orion absorption spectrum of novae is characterized by strong absorption lines of nitrogen [9, 14].

In the same paper [6] a preliminary model (Fig. 3) of the envelope around N Her 1934 is constructed, which confirms also the above considerations. Existing spectroscopic observations of N Her 1934 and photographs of the nebula of this star in different wavelengths are used. An equatorial belt was also observed here in the same emission lines 6548 and 6584 (N II). The absence of separate rings in this case is easily explained by the fact that in the spectrum of N Her 1934 (in contradistinction of N Aql 1918) several systems of the diffuse-enhanced and the Orion spectra were observed. In connexion with this an approximately continuous belt of noticeable thickness was formed.

Additional facts on other novae confirm the above considerations [6].

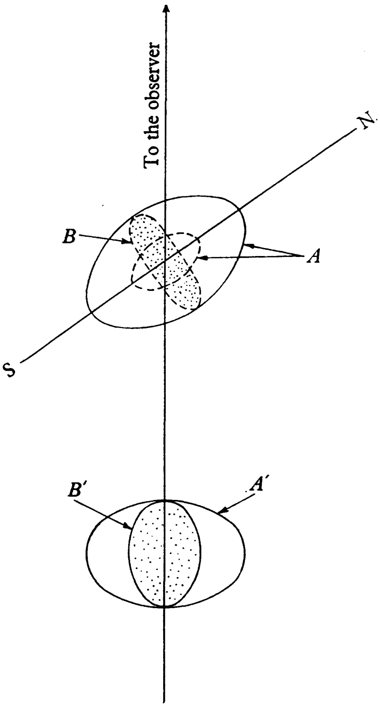

Fig. 3. The upper part of this drawing represents the structure of the envelope around N Her 1934, observed in the light of lines 6548 and 6584 (N II). *A*—is the principal envelope; *B*—is the equatorial belt. The lower part gives the projection of the envelope and of the equatorial belt on the plane perpendicular to the line of sight. *B′*—is the 'nitrogen belt' observed by W. Baade.

The problem of estimating the strength of magnetic fields which cause the retardation of gases in the expanding star before light maximum is very difficult. Three possibilities should be considered: (1) A magnetic field of a dipolar character. This field is produced in the innermost parts of the nova. (2) An 'intertwined' magnetic field existing in all the layers of the nova and even in its normal state [8], before the outbursts. Due to the expansion of the star the density of this field continuously decreases towards the light maximum. (3) A magnetic field which arises in the expanding new star before light maximum, due to the fact that the ionized masses of gas are moving in a non-homogeneous magnetic field of the dipole (see p. 196).

Probably this field (which is partly 'intertwined') plays the principal part in the process of retardation of the expanding new star. The strength of this field estimated according to the formula

$$\tfrac{1}{2}\rho v^2 \approx H^2/(8\pi) \tag{1}$$

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amounted for N Aql 1918 to 2000 gauss near light maximum [6]. The strength of this field must be different for different novae. This may be concluded from the fact that 'masses', which were estimated by the author from the retardation effects, depend on the luminosity of the nova in its 'normal' state before the outburst [14]. The greater the luminosity of the nova is, the greater is its 'mass'. Of all the obtained masses the largest is the 'mass' of N Aql 1918, the smallest 'mass' is the one of N Her 1934. One may think that the same correlation must be true for the strength of magnetic fields, because these fields 'replace' now the 'large masses' of novae.

The question which field plays the principal part in deflecting the condensations towards the equator is very difficult to decide. It may be the original dipolar field of the nova. On the other hand it is also possible that the part played by the induced magnetic field is more important, of course if the latter is sufficiently strong. It is known that at large distances any magnetic field is similar to the dipolar field.

From the above considerations it follows that as a result of the outburst, magnetic fields which are present in the outer layers of the expanding nova are carried out from the nova together with the principal envelope. These fields must be partly 'intertwined'. If super-novae also possess large magnetic fields, the structure of their envelopes must also reflect the presence of magnetic fields, which are carried out from the star. This is fully confirmed by the recent results of G. A. Shajn [15]. He arrived at the conclusion that the presence of a systematic distribution of matter in the nebulosities IC 443, S 151 and in the system of fibrous nebulosities near the regions NGC 6960–NGC 6992, all these facts speak in favour of the hypothesis that the magnetic fields governing this distribution are carried out into the outer space together with the matter during the outbursts of super-novae. The same conclusion may be drawn from the study of the polarization of light from the Crab nebulae [16, 17, 18, 19].

Some authors do not agree with the idea that the origin of the magnetic field in the Crab nebula is connected with the magnetic field of the super-nova. For example, J. Oort and Th. Walraven [17] find that the total magnetic flux through the Crab nebula is extremely large. However, it is necessary to take into account that this magnetic flux must correspond not to the initial dipolar field of the star but to the field which arises during the outburst and which is of induction nature.* As I have already indicated,

* This field may also be connected with shock waves in the star during its outburst. The source of energy of these shock waves is the energy of the outburst. An initial magnetic field is needed in this case too.

the source of energy of this induced magnetic field is the energy of the outburst and therefore the strength of this field may exceed very greatly (by many orders) the strength of the original dipolar field.

The second problem is the problem of the diminishing of the field inside the nebula during its expansion. There are two possibilities here: (*a*) The ejected envelope (the nebula) is continuous in all directions. In this case the magnetic field strength decreases as r^{-2}, see Fig. 4 (*a*), (*b*) The envelope consists of separate condensations, and filaments, see Fig. 4 (*b*). In this case the magnetic field strength of these condensations will decrease

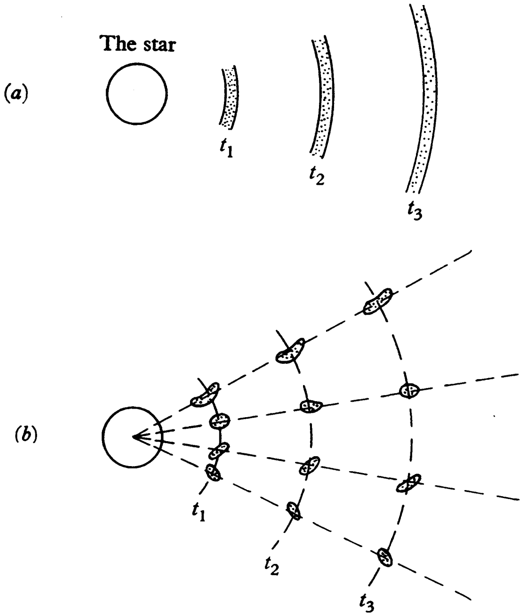

Fig. 4. Two possible types of expansion of the ejected envelope.

(during the expansion of the nebula) very slowly, especially if one takes into account the magnetic viscosity inside these condensations. One may think that in the Crab nebula the second case is realized because this nebula consists of separate filaments.

If novae and especially super-novae actually possess large magnetic fields, the above noted 'induction' mechanism may create in some way or other* particles of very high energies (cosmic rays), which may be released from the superficial layers of the expanding nova or super-nova. Owing to the pressure of magnetic fields in these layers the mechanism of

* For example, in the same way as in L. A. Artsimovich's experiments[20].

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Fermi may become very effective. It seems that all these processes must be localized in separate small volumes and have the character of fluctuations. It is also necessary to point out that this 'induction mechanism' can act very long even after the outburst of nova or super-nova. It is well known that the ejection of matter from novae is observed during a period of many years [21], in several cases twenty, thirty years and even longer. One may think that super-novae, which are more unstable, eject matter during whole centuries. At the same time in all these cases we deal with the motion of ejected gaseous ionized condensations across the magnetic lines of force in a strong non-homogeneous field of the star (the same is true for a more short-lived process—the process of ejection of condensations, producing the diffuse-enhanced and the Orion spectra). If this 'induction mechanism', which may be accompanied by the acceleration mechanism of Fermi, is valid, then novae and super-novae may be the sources of high-energy particles lasting for decades and centuries.

The results of this paper lead to the conclusion that the magnetic fields, which secure the observed radio emission from the envelopes, ejected by super-novae [22] and the relativisitc particles (which are also needed for this radio emission) have their origin in the general magnetic fields of super-novae themselves.

From the above it follows that further investigation of novae and super-novae is needed. A more thorough study of envelopes ejected by novae and super-novae is especially important. This study must include spectroscopic material, as well as direct photographs in different wave-lengths. Another problem is also important—the study of light polarization in emission lines of H, He, N, C, which are produced by the novae themselves (not by their envelopes). These emission lines, which appear in the spectra of novae several months after light maximum, are produced close to the surface of the nova [21] and it is possible that the influence of the magnetic field on the emitting atoms H, He, N, C may involve some polarization due to Zeeman effect. It is also of great interest to investigate the polarization of light from 'old' novae and 'old' super-novae (excluding their nebulosities).

Finally we are going to discuss briefly the problem of the origin of magnetic fields of novae. Of course, this problem is a very complex one. However, it is necessary to point out that according to the recent article by M. Walker [23] N Her 1934 is an eclipsing variable with the shortest known period. Further, this is a reason to expect that in this binary the period of rotation of components in the system and the period of revolution coincide (as in the case of close binaries). Therefore N Her 1934 rotates very rapidly; in other words we have a very rapidly rotating dwarf. Besides it is necessary to note that the inclination of the orbit of N Her 1934 determined by M. Walker [23] and the inclination of the polar axis of N Her 1934 (obtained by the author, see Fig. 3) roughly coincides. At the same time the presence of magnetic fields is usually connected with rotation.

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Discussion

Spitzer: Would you explain again how the magnetic field of a super-nova is amplified by an explosion?

Mustel: The problem of strengthening of the field in hydromagnetics is a very complex one. In my communication I am considering the mechanism in which the strengthening of the field takes place, because of the fact that the ejected ionized gases are moving in the non-homogeneous dipolar field of the star. The source of this field is supposed to be located in the innermost parts of the nova. Of course this mechanism is connected with certain difficulties. It is possible that the non-homogeneity of the dipole field does not play any significant role here and that the strengthening of the field in the expanding star is connected only with the motion of ionized gases *across* the magnetic lines of force of the dipole (we do not speak here about the polar directions). In this case the strengthening of the field might follow from the fact that the gases crossing the magnetic lines of force are retarded, therefore the kinetic energy E of these gases is diminished. One may think that the lost energy ΔE must be mainly transformed into magnetic energy. A transformation of this energy ΔE into other kinds of energy is doubtful.

The decrease of velocity of the expanding gases in novae before light maximum follows from many spectroscopic facts (E. R. Mustel, *Symposium on Non-stable Stars*, 1957). This decrease is not accompanied by the heating of gases. The velocity of the reversing layer of N Her 1934 was diminishing all the time from the moment the star was discovered up to the moment of its light maximum (from 1300 km/sec to 300 km/sec) and the spectrum of the star changed from class B to class F.

In certain cases, however, it is possible (for example, in the case of the Crab nebula) that the magnetic field of the ejected envelope is actually the original magnetic field of the inner parts of the super-nova itself, this field being weakened by the nebula expansion. The magnetic flux in the superficial layers of the super-nova before the outburst cannot be very large, because this would violate the equilibrium of these layers.

In connexion with this the hypothesis (J. H. Oort and Th. Walraven, *Bull. Astr. Netherl.* **12**, 304, 1956), in which the phenomenon of the outburst of the super-nova arises from the equality between the magnetic energy of the internal parts of the star and the gravitational energy, is of great interest.

Schatzman: Have you to suppose that the ejection of matter at the beginning is spherically symmetric and that, later on, the magnetic field produces the rings and the polar caps, or is it necessary to suppose that the ejection of matter at the beginning was made of polar caps and rings?

Mustel: I suppose that the ejection of matter at the beginning and after light maximum is roughly spherically symmetric and that the magnetic field produces the rings and the polar caps. This supposition is quite justified. For example, the outburst of the nova is a sort of explosion and therefore the gases must be ejected practically in all directions. However, in reality we observe two polar caps. Further, the diffuse-enhanced and the Orion spectra were observed for each nova irrespective of the direction of its polar axis. This means that the ejection of corresponding condensations proceeds also in all directions. Nevertheless, after a lapse of time, we can see this matter only in the equatorial parts of the principal envelope and therefore the condensations are deflected to the equatorial plane of the envelope by magnetic fields. The most clear example is N Aql 1918. Its polar axis is near to the line of sight and in the spectrum of the star the strong diffuse-enhanced and the Orion absorption spectra were observed. However, after a certain lapse of time the corresponding condensations were concentrated in two pairs of equatoral rings. The identity of ejected matter was confirmed here by the equality of velocities inferred from displacement of both these spectra with the velocities inferred from the study of the corresponding equatorial rings.