PAPER 21

# ON THE MAGNETIC FIELDS IN INTERSTELLAR SPACE AND IN NEBULAE*

G. A. SHAJN

*Crimean Astrophysical Observatory, Crimea, U.S.S.R.*

## ABSTRACT

Some aspects of the problem of magnetic fields in the interstellar space and in the nebulae are discussed in this paper. Our observational basis are the numerous photographs of the nebulae in H$\alpha$ and other rays, taken with high-speed 450 and 640 mm cameras.

The greatly elongated shape of many emission nebulae is interpreted as a result of three factors, the effect of the magnetic field, the macroscopic motions in these nebulae (including the tendency to expand) and the high electrical conductivity of matter. The expansion of nebulae is to be generally accompanied by the considerable decrease in brightness (roughly about $d^{-5}$), but if the expansion is only in one direction, owing to the presence of a regular magnetic field, the brightness decreases much more slowly (roughly about $d^{-2}$) and the nebulae remain visible for a longer time. The filamentary structure, which is very often inherent to the elongated nebulae, is, probably, an additional factor of a longer visibility of the nebulae under consideration. The great lengthening of nebulae may be reached in the period of the order of $10^6$ years.

In the dark nebulae the matter seems to be electrically conductive and the macroscopic motions of the order of 1–2 km/sec are present there, so that there are reasons to suggest that the magnetic field is also responsible for the elongated shape of many dark nebulae. One may prove that the observed elongated shape of dark and emission nebulae could not be caused by differential galactic rotation.

Some correspondence between the apparent orientation of many elongated dark nebulae in Persei-Tauri, Cygni, Sagittar, Oph.a.o. on the one hand, and that of the local magnetic fields in the same regions on the other hand, as derived from the polarization observations, may be considered as a serious argument in favour of that the interstellar magnetic field is an important factor responsible for the elongated shape of nebulae.

An attempt to interpret the elongated emission nebulae as single arcs, or bars—the remains of gigantic peripheral nebulae—leads to the conclusion that this hardly holds true, at least with respect to several most elongated ones. However, when accounting both the frequent occurrence of the peripheral nebulae and the effect of magnetic fields, we get more opportunities to interpret the observed diversity of configurations of the nebulae, particularly the elongated nebulae.

* Presented by Dr A. B. Severny.



https://doi.org/10.1017/S0074180900237777 Published online by Cambridge University Press

The structure of very elongated dark nebulae in Persei-Tauri, consisting of a number of mutually connected slightly elongated globules, seems to support the hypothesis of the magnetic field.

The high occurrence of the elongated dark nebulae oriented in addition predominantly at small and moderate angles with respect to the galactic equator, is interpreted as a result of a high efficiency of the controlling action of the interstellar magnetic field on the motion of matter in nebulae. We have to see in this very high occurrence of such nebulae also an argument in favour of the presence there of sensible macroscopic motions. The action of the magnetic field seems to be very efficient also with respect of emission nebulae, notwithstanding that the number of the observed elongated nebulae is not great.

It seems to be probable that in the emission nebulae there is an inner magnetic field of the order of $10^{-5}$ gauss, the variations being large within the observed nebulae, as well as within a single nebulae. Some correspondence between the structural features of the nebulae IC 1396 and Coal Sack and the orientation of polarization seems to be another fact in favour of the presence of an inner magnetic field. Practically, all bright emission nebulae, larger than $5'$ have filamentary characteristics and it is suggested in connexion with this that some nearly always operating factor, probably an inner magnetic field, is responsible for this widely spread phenomenon. The inner magnetic field does not seem generally to be a very important factor in the problem of stability of nebulae, although in some cases it may be very efficient in this relation in the more dense central and other regions.

The well-known strange peculiarity of planetary nebulae—the weakening of the brightness along the major axis, or at its ends, may be interpreted in the terms of the hypothesis of a magnetic field. There is some analogy in this with the uneven and systematic distribution of matter in some large peripheral nebulae, particularly in some shells, probably the remains of the very old super-novae or novae. One may suggest that in both cases the magnetic field of the central star, which had some influence on the primary conditions of the motion of the shells caused to some extent the observed peculiar distribution of matter and probably the magnetic field in the observed shells of the super-novae and novae in question, as well as in the planetary nebulae. The filamentary structure as revealed in the shells of former and sometimes in planetary nebulae is probably connected with the magnetic field.

The filamentary structure seems to be inherent not only to the majority of emission nebulae but also to a number of dust nebulae, both the reflexion and dark ones. The occurrence of the filamentary structure in the emission and dust nebulae consisting both of matter of high electrical conductivity and having at the same time such different temperature, $\sim 10{,}000^\circ$ and $\sim 100$ °K, respectively, suggests that the structure in question is conditioned by the very nature of magneto-hydrodynamics.

The high occurrence of the elongated nebulae in the Galaxy and in the galaxies in general, oriented predominantly probably along the spiral arms, is to be considered as a fundamental characteristic of the spiral galaxies. One may suggest that the magnetic field is efficient enough to control to some extent the motion and distribution of diffuse matter in the Galaxy, hindering the



https://doi.org/10.1017/S0074180900237777 Published online by Cambridge University Press

dissipation of matter and contributing to the maintenance of the spiral structure of galaxies with respect to the gas-dust population as well as probably to some classes of stars. The diffuse matter dissipated in such a manner along the spiral arms may be responsible, at least partly, for the almost continuous emission background as revealed in the low latitudes in the last years.

While below 10° (by latitude) the elongated dark nebulae have predominantly small and moderate inclination to the galactic equator, there is no such tendency for small angles in the elongated nebulae within latitudes of 10–21°. When confronting this with small and very great dispersion in the angles $\theta'$ for the plane of vibration within latitudes from 0 to 10° and from 10 to 25°, respectively (as revealed from the polarization observations), a conclusion is made that the elongated shape of dark nebulae below 10° is conditioned by the known regular magnetic field, while within the latitudes 10–21° by the local fields.

I

Some points of the problem of magnetic fields in the interstellar space and in the bright and dark nebulae are discussed in this paper. Our observational basis are the numerous photographs of the nebulae in H$\alpha$ and in other rays taken with high-speed 640 and 450 cameras of the Simeis observatory, in Crimea. Remarkable formations, systems of filaments, striae and strips were revealed on our photographs in 1950 and later. A striking example of such a system, as long as 11°, is met in Cygni. There are also other very elongated emission nebulae near $\xi$ Persei, 10 Lacertae, $\eta$ Canis Maj, $\alpha$ Orion and others. In 1952 we suggested that this phenomenon has a relation to the magnetic field and later on we obtained a number of independent arguments in favour of this supposition [1-7]. The strongly elongated shape of many emission on nebulae is interpreted as a result of three factors, the effect of the magnetic field, the macroscopic motions in these nebulae and the high electrical conductivity of matter. In fact, the study of the larger and brighter emission nebulae leads us to the conclusion that the preferential outward motion of matter seems to be an outstanding feature of some nebulae [8]. There are also very serious reasons to adopt from the theoretical point of view that the emission nebulae are expanding with sound velocity of 10–15 km/sec (L. Spitzer [9] was the first to suggest it). The phenomenon in question is very complicated, but there must be some tendency for expansion and dissipation in emission nebulae [10, 11]. Roughly speaking, the effect of the interstellar magnetic field is to restrain the motion of the nebular matter in the direction perpendicular to the magnetic lines of force and to let the matter move freely along these lines. The general expansion of nebulae must be accompanied by a decrease in brightness, approximately as $D^{-5}$, but if the expansion



https://doi.org/10.1017/S0074180900237777 Published online by Cambridge University Press

goes only in one direction (owing to the presence of a regular magnetic field), the brightness decreases much more slowly, roughly as $D^{-2}$, and the nebula must remain visible for a longer time. The filamentary structure, which is very often inherent to the elongated nebulae, is probably an additional factor of the longer visibility of the considered nebulae. Very elongated nebulae consist generally of a number of moderately elongated nebulae and filaments, giving an impression of a single very elongated nebulae. The great length of a number of emission nebulae as revealed by observations may be reached probably in the period of the order of $10^6$ years.

The matter of the dark nebulae seems also to be electrically conductive. Besides, the macroscopic motions of the order of 1–2 km/sec are present there, so that there are reasons to suggest that the magnetic field is also responsible for the shape of the numerous elongated nebulae.

One may prove that the observed elongated shape of dark and emission nebulae, at least in the majority of cases, could not be caused by the differential galactic rotation.

An attempt to interpret the elongated emission nebulae as single arcs, or bars—remnants of gigantic peripherical nebulae, leads to the conclusion that this hardly holds true, at least with respect to several most elongated ones. However, when taking into account both the frequent occurrence of the peripherical nebulae and the effect of magnetic fields, we get more opportunities to interpret the observed variety in the configurations of nebulae, particularly of the elongated ones [5].

## 2

There is a more direct argument in favour of the hypothesis of magnetic field as an important factor controlling, at least partly, the distribution and the motion of the diffuse matter [2, 3]. In fact, the hypothesis under consideration may be checked in some cases by comparing the orientation of the elongated nebulae with the results of observations of the polarization of the light of stars in the same region. Especially suitable for this purpose is the large region of $\xi$ and $\zeta$ Persei: high latitude, polarization caused by absorption (probably in one cloud), the presence there of a number of remarkable elongated dark nebulae and of the emission nebula NGC 1499. In the region under consideration of nearly $30 \times 30°$ (Fig. 1) the contours of large dark nebulae $> 2°$ are drawn according to Becvar's Atlas, as well as all the known polarization data were taken according to Hiltner [12] and Hall and Mikesell [13]. While in low latitudes the plane of vibration nearly coincides with the direction of the galactic equator, in the higher



https://doi.org/10.1017/S0074180900237777 Published online by Cambridge University Press

latitudes ($b > 12°$) is brought out a local magnetic field, diverging largely from the magnetic field along the galactic equator. It seems to be remarkable that the angle under consideration $\theta' - 90° = -41 \pm 3°$ is nearly the same, as the mean angle of inclination to the galactic equator ($-35 \pm 5°$) for the six very elongated dark nebulae in this region. By the way, some of these elongated dark nebulae consist of a number of mutually connected slightly elongated globules, and it seems that such a very strange structure is easier to understand in the light of the magnetic field hypothesis.

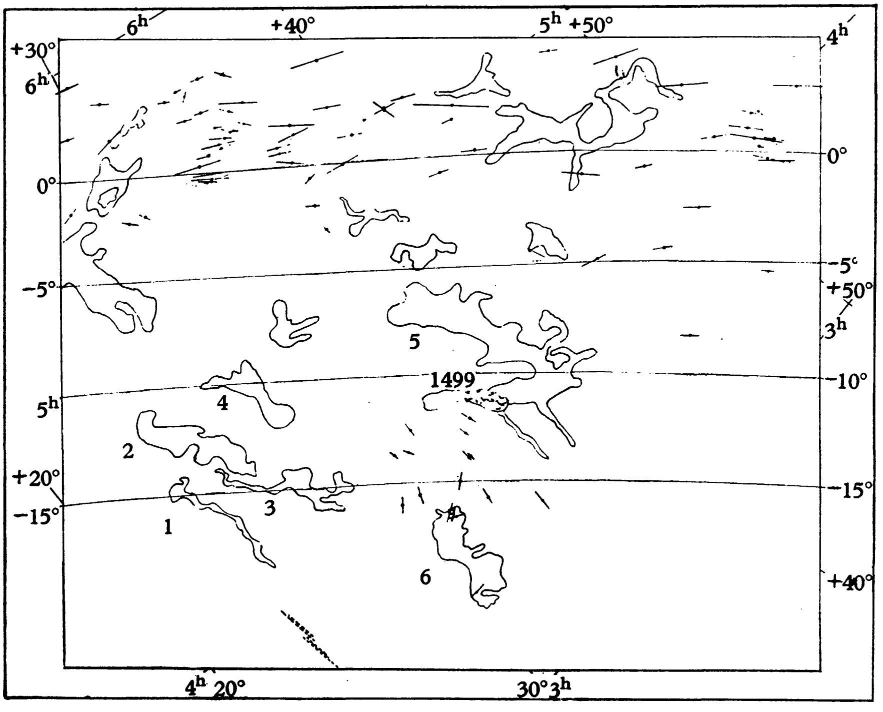


Fig. 1

One may add that the filaments of the emission nebula NGC 1499 in this region are slightly diverging from the galactic parallel also in the same direction. At last, attention has to be attracted to the fact that the very thin and long single bright filaments in the Pleiades, located on the SO border of Fig. 1, also oriented nearly in the same direction as the local magnetic field mentioned above. In connexion with this one may remember that Hall found recently that the final direction of short curved filaments (as though emanating from Merope) nearly coincide with the direction of magnetic field in this region [13].



https://doi.org/10.1017/S0074180900237777 Published online by Cambridge University Press

Not entering here into details one may say that in higher latitudes ($b > 12°$) of this large region we have a complicated local magnetic field, which is responsible, on one hand, for the peculiar direction of the plane of vibration and, on the other hand, for the elongated shape of the nebulae.

The region in Sagittarius with its centre about $18^h 30^m - 13°$ is another illustration of the above idea (Plate I). In connexion with that the line of sight is oriented in Sagittarius approximately along the inner spiral arm, we have here as it is to be expected, a nearly occasional distribution of the plane of vibration. However, besides the enormous mass of dark matter along the galactic equator, there are outstanding dark nebulae, stretching from $18^h 30^m - 10°$ towards SO and O at an angle of inclination $\geqslant 60°$ to the galactic equator. The general picture of good agreement between the great inclination of these elongated nebulae and the direction of the plane of vibration here (vectors $P$, $\theta'$ being parallel and the polarization $P$ very considerable) shows that in the region under consideration to the east from the galactic equator there is a local magnetic field oriented at an angle $\geqslant 60°$ to the regular galactic magnetic field, in harmony with the outstanding feature of the structure of the Galaxy in the region of Sagittarius [5].

The correspondence between the apparent orientations of the local magnetic fields, as derived from polarization observations, is also found in Oph, Mon, in two large regions of Cyg and others. For instance, we have a satisfactory agreement between the orientation of the well-known very elongated dark nebulae to the east from $\rho$ Oph and the plane of vibration of the measured stars in this region. At last, we shall mention here one of the large regions in Cygni. As it is known there is in Cygni a lot of elongated filamentary emission nebulae with moderate and small inclination to the galactic equator. But further to the south-west, in the region around $20^h 5^m + 35°$ a considerable group of filamentary emission nebulae of similar structure, oriented nearly perpendicular to the galactic equator, were brought out. One may therefore suggest here a local field oriented in the same peculiar direction, which is observed in reality [3].

Additional examples of the correspondence under consideration might be given. When in many cases the direction of magnetic fields (as derived from the polarization observations) and the direction of the elongated nebulae differ but little from one another, and, on the other hand, both show a large inclination to the galactic equator, the conclusion seems to be almost inevitable that, namely, the interstellar magnetic field is responsible for the elongated shape of these nebulae. At the same time it is easy to understand that the correspondence under consideration may hold only under certain conditions.



https://doi.org/10.1017/S0074180900237777 Published online by Cambridge University Press

In the low latitudes the general trend of the plane of vibration to be parallel to the galactic plane is expressed well enough (excluding the directions where the line of sight is oriented approximately along the spiral arms as Cygnus and Sagittarius, where naturally nearly occasional distribution of the position angles $\theta'$ is observed). However, this seems to be but the first approximation. In fact, appreciable systematic deviations from the trend in question are revealed for a number of regions in low latitudes. The observed data by Hiltner [12], Hall and Mikesell [13] and Smith [14] for all measured stars with $P > 0{\cdot}3$ within $\pm 8°$ in latitude are plotted in Figs. 2 and 3. The deviations seem to be mostly real, since some of these regions are large and the number of measured stars in them is considerable. Such regions we have, for instance, in Monocer and Cygnus. There are also smaller areas, for which the plane of vibration differs appreciably from the direction of the galactic parallel. It is remarkable that, at least in a number of cases, such as in Cyg, Mon, Sgr and others, a correspondence between this peculiar direction of the plane of vibration and of the elongated nebulae in these regions was noticed. Therefore, there are very serious reasons to adopt that in the low latitudes, besides the general regular galactic magnetic field, there exist also local magnetic fields. This conclusion seems to be an essential feature of the interstellar magnetic field. One may suggest that a magnetic field of such character is conditioned by the complicated spiral structure of the Galaxy [6].

As it is known, the position angles $\theta'$ for the light of stars in latitudes $> 8°$ are distributed nearly at random. This may be interpreted as a serious indication of the local character of the interstellar magnetic field in the higher latitudes. Such fields, embracing sometimes tens or hundreds of square degrees, seem to be more or less uniform in direction as well as in strength. For instance, in the region $\xi$ Persei, the plane of vibration makes an angle about 41° with the galactic parallel. If our representation of the cause of the elongated shape of nebulae is correct, one must expect the absence of the tendency of these nebulae to have small or moderate inclinations to the galactic equator, the tendency which does hold in the low galactic latitudes. In fact, the discussion of all available data shows that while below 10° (by latitude) the elongated dark nebulae have predominantly small and moderate inclinations to the galactic equator, no such tendency is observed for small angles in the elongated nebulae within latitudes from 10⁹ to 21°. When comparing this with small and very great dispersion of angles $\theta'$ for the plane of vibration below and above 8° of



https://doi.org/10.1017/S0074180900237777 Published online by Cambridge University Press

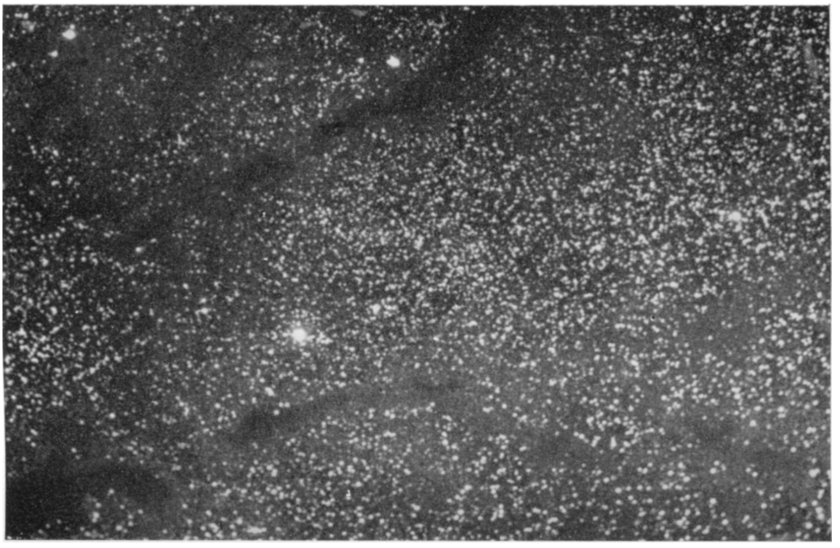

Plate I

(*facing p.* 188)

https://doi.org/10.1017/S0074180900237777 Published online by Cambridge University Press

galactic latitude respectively (as revealed from polarization observations) a conclusion is drawn that the elongated shape of dark nebulae below 10° is conditioned by the known regular galactic magnetic field and also partly by the local fields mentioned above, while in the higher latitudes ($b > 8°$) almost exclusively by the local fields [6].

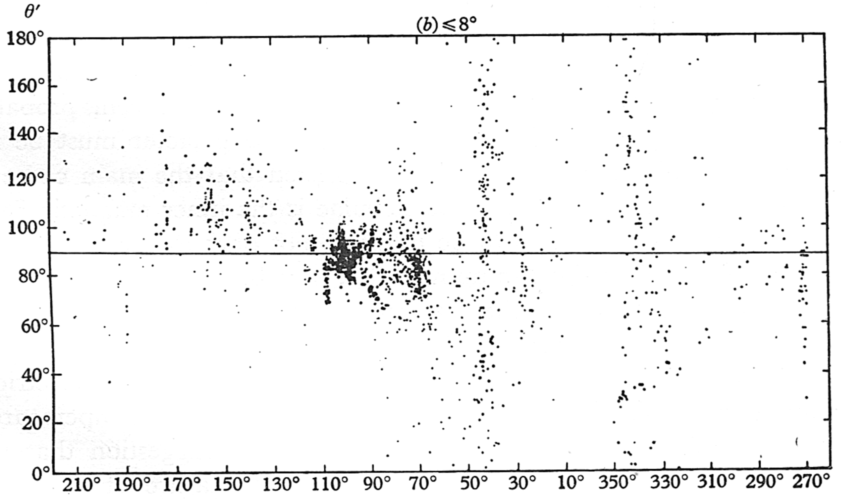


Fig. 2

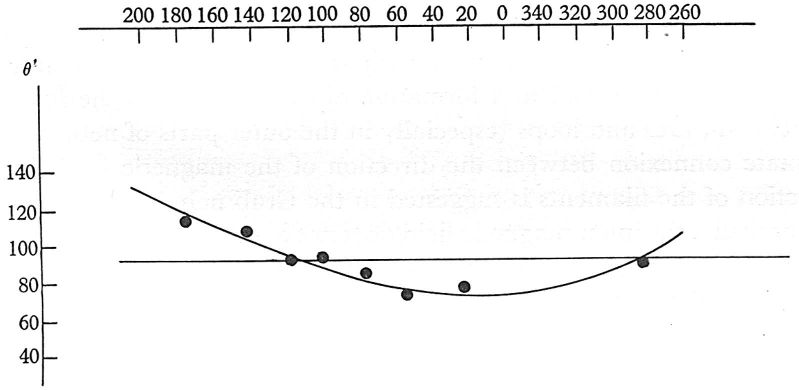


Fig. 3

## 4

There is no doubt that there must exist in the nebulae an inner magnetic field. Particularly, this follows from the fact that the turbulence is the observed phenomenon in some nebulae, for instance, in the Orion nebula. When applying to the Orion nebula the relation $\frac{1}{2}\rho v^2 = H^2/8\pi$ one derives



https://doi.org/10.1017/S0074180900237777 Published online by Cambridge University Press

for the densest central part the strength $H$ of the order of $10^{-4}$ gauss. It is probably smaller or much smaller in other nebulae. Generally it seems that the variations are large within the observed nebulae, as well as within a single nebula. Some correspondence between the structural feature of the nebulae IC 1396 and the Coal Sack and the orientation of the plane of vibration of the light of stars in these regions seems to be another observed fact in favour of the presence of an inner magnetic field [3, 14].

Attention must be paid to the fact that practically all brighter nebulae, larger than 5′, are of more or less filamentary character. It seems probable that some widespread and nearly always operating factor must be responsible for this phenomenon. It is suggested that the main cause of universal occurrence of filaments in nebulae is the inner magnetic field. Filamentary structure seems to be inherent not only to the majority of emission nebulae, but also to a number of dust nebulae, both the reflexion and the dark ones (where the filamentary structure may be discerned evidently only in rare cases). Occurrence of the filamentary structure in the emission and dust nebulae, consisting both of matter of high electrical conductivity and having at the same time such different temperatures, $\sim 10{,}000°$ and $\sim 100°$ K respectively, leads to the suggestion that the structure in question is questioned by the very nature of magneto-hydrodynamics.

A combination of such factors as the inner and outer magnetic fields, preferential outward motion, the turbulent motion and some hydrodynamical phenomena, connected with the encounters of single masses of gas and dust, may lead to a formation of such details, as the filaments, striae, rims, arcs and loops (especially in the outer parts of nebulae). An intimate connexion between the direction of the magnetic field and the direction of the filaments is suggested in the Crab nebulae [15].

Generally, the inner magnetic field does not ensure probably the stability of nebulae, although in some cases it may be very efficient (for instance, in the central dense part of the Orion nebula).

## 5

One may suggest apparent manifestation of the magnetic field in the emission nebulae, which is probably connected with the ancient novae or super-novae. Though there are large differences in the structure of these nebulae, it is quite evident that in addition to the ejection of matter and the turbulence, some other factor played there an important role. Such characteristics, as the systematic distribution and orientation of many



https://doi.org/10.1017/S0074180900237777 Published online by Cambridge University Press

details, sometimes the great curvature of the filaments and even the presence of closed loops, lead to the suggestion that this factor is the magnetic field. In the light of this idea we have discussed the filamentary nebula IC 443 (a radio source) [16], as well as two other filamentary nebulae S 147 and NGC 6960—NGC 6992 probably connected with ancient super-novae, or novae [3]. It seems to be probable that the magnetic field in question was carried out together with the matter ejected from supernovae and novae. One may suggest that the magnetic field of novae and super-novae influenced the primary conditions of the ejection of matter, and, on the other hand, caused to some extent the observed distribution of matter and of the magnetic line of force in the far environs of the stars (see also the paper by E. Mustel [17]). Though we deal here mainly with the inner magnetic field, it seems at the same time that the distribution of matter, as observed now in these nebulae, was influenced also to some degree by the controlling action of the interstellar magnetic field.

6

The well-known strange peculiarity of many planetary nebulae, namely, the weakening of the brightness along the major axis or at its ends, was not interpreted reasonably. A good example of a nebula belonging to such class is NGC 6818 (according to Curtis). There is some analogy in such structure with the uneven and systematic distribution of matter in some large peripherical emission nebulae, namely of some shells particularly, probably the mentioned above remnants of the ancient super-novae and novae. One may suggest that the peculiarity under consideration in the planetary nebulae may be explained in terms of the magnetic field hypothesis: in both cases the magnetic field of the central star influencing somewhat the primary conditions of the shell motions, caused to some extent the observed peculiar distribution of matter and probably the magnetic field in the observed shells of nebulae, connected with super-novae and novae in question, as well as in planetary nebulae [5]. The filamentary structure as revealed in the shells, of the former and sometimes in planetary nebulae, is probably connected with the magnetic field (section 4 above).

7

The high occurrence of elongated dark nebulae (oriented predominantly at small and moderate angles with respect to the galactic equator) is interpreted as a result of high efficiency of the controlling action of the interstellar magnetic field on the motion of matter in nebulae. At the



https://doi.org/10.1017/S0074180900237777 Published online by Cambridge University Press

same time we have to see in it also an argument in favour of the presence in the dark nebulae of appreciable macroscopic motions. The action of the magnetic field seems to be very efficient also in respect to emission nebulae, notwithstanding that the number of the observed elongated nebulae is, relatively, not great. The conclusion arrived at above must relate also to the extra-galactic spiral nebulae, where the greater and smaller bulks of dark matter often look, indeed, like elongated nebulae, predominantly oriented along the spiral arms. An efficient control of the motion of diffuse matter by the magnetic field means that the latter hinders to some extent the dissipation of matter and contributes in maintaining the spiral structures of galaxies with respect to the gas-dust population, as well as probably to some classes of stars.

## REFERENCES


[1] Shajn, G. A. *A.J. U.S.S.R.* **32**, no. 2. 110, 1955.
[2] Shajn, G. A. *A.J. U.S.S.R.* **32**, no. 5, 838, 1955.
[3] Shajn, G. A. *A.J. U.S.S.R.* **32**, no. 6, 489, 1955.
[4] Shajn, G. A. *A.J. U.S.S.R.* **33**, no. 2, 210, 1956.
[5] Shajn, G. A. *A.J. U.S.S.R.* **33**, no. 3, 1956.
[6] Shajn, G. A. *A.J. U.S.S.R.* **33**, no. 4, 1956.
[7] Shajn, G. A. and Hase, V. *C.R. Acad. Sci. U.R.S.S.* **82**, 857, 1952.
[8] Shajn, G. A. and Hase, V. *Publ. Crim. Astroph. Obs.* **8**, 80, 1952.
[9] Spitzer, L. *Harv. Obs. Monogr.* **7**, 87, 1948.
[10] Kahn, F. *B.A.N.* **12**, no. 456, 1954.
[11] Oort, J. H. *B.A.N.* **12**, no. 455, 1954.
[12] Hiltner, W. A. *Astrophys. J.* **109**, 478, 1949; **114**, 241, 1951; **120**, 454, 1954.
[13] Hall, J. S. and Mikesell, A. H. *Publ. U.S. Nav. Obs.* **17**, pt. 1, 1950; *Les particules solides dans les astres* (1955), p. 543.
[14] Smith, E. V. P. *Sky and Telescope*, **14**, 8, 324, 1955.
[15] Shajn, G. A., Pikelner, S. and Ikhsanov, R. *A.J. U.S.S.R.* **32**, no. 5, 395, 1955.
[16] Shajn, G. A. and Hase, V. *C.R. Acad. Sci. U.R.S.S.*, **96**, 713, 1954.
[17] Mustel, E. *A.J. U.S.S.R.* **33**, no. 2, 182, 1956.




https://doi.org/10.1017/S0074180900237777 Published online by Cambridge University Press