Astronomy

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1958

SovietRxiv

Abstract

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Astronomy

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DIPOLE MAGNETIC FIELD IN PLANETARY NEBULAE

(Presented by Academician V. A. Ambartsumian, March 7, 1958)

As was shown ([1]), magnetic fields must be present in planetary nebulae. The further development of this idea has made it possible to draw certain conclusions about their nature. It turns out that the character of these fields is similar to that of the field of a magnetic dipole. However, they are not a continuation of the field of the central star-nucleus; the planetary nebula possesses its own dipole field, whose magnetic moment may vary depending on changes in the size and density of the nebula.

The concept of the existence of dipole-type magnetic fields in planetary nebulae satisfactorily explains the observed diversity of their forms and structures. In the present note a brief account is given of those results that were obtained by the author in a quantitative investigation of this question.

First of all, let us clarify for our problem the notions of a "point"and a "nonpoint" dipole. In the first case the size of the dipole l, i.e., the distance between two equal "charges" of opposite sign, is considerably smaller than the dimensions of the nebula R; in the second case l is comparable with R. In the case of a point dipole, the field strength $H(r, \varphi)$ along a given line of force and at the point (r, φ) is determined by the expression

$$H(r, \varphi) = \frac{a}{r^3}\,\eta(\varphi), \tag{1}$$

where a is the magnetic moment of the dipole, $\eta(\varphi) = \sqrt{1 + 3\sin^2\varphi}$.

It can be shown that in planetary nebulae there must exist dipole magnetic fields of the nonpoint type. In this case the field strength at the point (r, φ) is represented by the formula

$$H(r, \varphi) = a\eta_1(r, \varphi), \tag{2}$$

where $x^2 = l^2/4r^2$;

$$\eta_1(r,\varphi) = 2^{1/2}x^2 \frac{\left\{(1+x^2)^2 - 4x^2\sin^2\varphi + (1-x^2)\left[(1+x^2)^2 - 4x^2\sin^2\varphi\right]^{1/2}\right\}^{1/2}}{(1+x^2)^2 - 4x^2\sin^2\varphi}. \tag{3}$$

From the formulas given it is evident that, for example, in the central section of the nebula passing through the dipole axis, the magnetic field possesses a gradient of intensity both in the coordinate r and in φ. The gradient of the magnetic-field intensity creates a gradient of magnetic pressure, which leads to a disturbance of the initial equilibrium state of the distribution of gas density in the nebula; a macroscopic displacement arises of the ionized gas that is in a state of thermal motion. As a result, a nonuniformity is formed in the distribution of the density of matter, i.e., a gradient of gas pressure arises along both coordinates (the gas temperature T is taken to be constant everywhere). The gradient of the gas pressure is opposite to the gradient of the magnetic pressure, and at the moment when these two quantities become equal in absolute value

one another, the further motion of the gas will cease, and a stationary state will set in. Let us suppose that the time required to attain the stationary state after the application of a dipole field to the nebula is considerably shorter than the lifetime of the nebula. The condition of stationarity at a given point reduces to equality of the gradients of the magnetic and gas pressures and may be written as

$$\frac{H^2}{8\pi} + nkT = C, \tag{4}$$

where $n = n(r,\varphi)$ is the ion (electron) concentration; C is some constant. The latter is determined for two models of the nebula: "finite" and "infinite." In the case, for example, of an "infinite" nebula we have $n(r,\varphi) = n_0$ as $r \to \infty$, where n_0 is the concentration of the undisturbed nebula, constant at all points. Then from (4) we find for the relative ion concentration at the point (r,φ):

$$\frac{n(r,\varphi)}{n_0} = 1 - \frac{\sigma}{r^6}\eta^2(\varphi), \tag{5}$$

where $\sigma = a^2/8\pi kTn_0$ is denoted.

In the case of a "finite" nebula, the condition for determining C is the constancy of the masses of the "undisturbed" and "disturbed" nebulae.

It follows from formula (5) that, first, the distribution of concentration in the central section of the nebula is symmetric with respect to its magnetic axis and, second, the minimum value of the concentration at a given distance from the center of the nebula is obtained in the direction of the magnetic axis ($\varphi = 90^\circ$),

Fig. 1

Figure 1: Fig. 1

and the maximum in the direction of the equator of the nebula ($\varphi = 0$). Further, in regions close to the center of the nebula the concentration is small, while in distant regions it is larger.

The volume emission coefficient of the nebula is proportional to the square of the electron (ion) concentration. Therefore even a small difference in the values of the concentration between individual points of the nebula may lead to a noticeable difference in the surface brightnesses at these points. The difference will be greatest between the direction of the magnetic axis and the direction of the equator of the nebula. The contrast is preserved when we consider the projection of the real—spatial—picture, which is obtained by rotating the central section about the magnetic axis of the nebula. In this case we obtain a nebula with two regions of maximum brightness, situated symmetrically with respect to the center—that is, a bipolar nebula.

It also follows from formula (5) that, for a given value of σ, there exist certain values r_0 and φ_0 for which the ion concentration becomes equal to zero. This is, evidently, an "avoidance" region, where charged particles cannot remain in equilibrium and must "be sucked out" of it. The equation of the curve determining the form of the "avoidance" region is determined from the condition $n/n_0 = 0$. It proves to be almost circular (spherical) in the case of a "point" dipole for all values of σ. In the case of a "non-point" dipole, the form of the "avoidance" region depends strongly on σ, i.e., on the magnitude of the magnetic-field strength. In Fig. 1 are shown some forms of the central section of the nebula for different values of the magnetic-field strength (it increases successively in passing from I to IV), the unshaded parts corresponding to the "avoidance" regions.

In order to find the distribution of brightness over the "magnetic"nebula, it is necessary to pass from the spatial three-dimensional isophotes to two-dimensional isophotes by integrating the radiation of each volume element along the line of sight. We have constructed theoretical isophotes for various values of the parameter σ, i.e., for various values of the magnetic-field strength, and also for various values of the ratio l/R, i.e., for

different values of the relative depth of "burial" of the magnetic poles. The constructed isophotes, in their variety, encompass almost all known forms of planetary nebulae. There are isophotes here that are quite similar to those of the nebulae NGC 6720, 7293, 3587, 3195; of the interesting bipolar nebula $\alpha = 16^h 13^m.3$, $\delta = -51°52$; $\alpha = 16^h 10^m.5$, $\delta = -54°50$; NGC 7662, etc. In Fig. 2 one example is given

Fig. 1

Fig. 2

Figure 2: Fig. 2

of a constructed system of isophotes (the numbers denote intensities in arbitrary units), corresponding to the value $\sigma = 1$ and $l/R = 2.25$. This system of isophotes agrees well with the structure of the nebula NGC 3587.

Proceeding from the identity of the theoretical and observed systems of isophotes, the magnitude of the intensity of the magnetic fields is determined for several nebulae. It proves to be of the order of 10^{-3}–10^{-4} gauss and varies not only in passing from one nebula to another, but also in passing from one point within a nebula to another.

Fig. 2

The influence of a dipole magnetic field on a real nebula expanding with some velocity requires special consideration. It turns out that in this case a force arises, directed opposite to the motion and retarding the motion (magnetic braking). The magnitude of this force, and consequently the effectiveness of magnetic braking, depends, in particular, on the angle α between the vector of the expansion velocity and the vector of the magnetic-field intensity. The magnitude of the angle α is different in different directions, and therefore the nebula must expand in different directions with different velocities: maximal in the direction of the magnetic axis and minimal in the direction of the equator.

Thus, the flattening and, in general, the elongation of the forms of most planetary nebulae are a consequence of the nonuniform expansion of the nebulae in different directions, caused by magnetic braking.

In Fig. 3a an example is given of a system of theoretical isophotes and of the form of a nebula with allowance for magnetic braking ($\sigma = 20$, $l/R \sim 0.1$).

This system of isophotes agrees well with the system of isophotes of the well-known "rectangular" nebula JC 4406, shown in Fig. 3b ([2], [3]).

It is further shown that the existence of dipole magnetic fields in planetary nebulae does not contradict the formation of a second shell ([4]). The ratio of the expansion velocities of both shells, it turns out, does not depend on the magnitude and character of the magnetic field, which apparently explains the similarity, in most cases, of the forms of the outer and inner shells. The brightness distribution over the second shell will be "distorted" by magnetic fields to a lesser degree than in the main shell. Therefore-

the bipolarity of the structure in the second shell will be expressed less distinctly than in the main one.

Along with this, one may outline a number of consequences that are due to the magnetic fields of planetary nebulae:

Fig. 3

Figure 3: Fig. 3

1. In some parts of the nebula, especially at the ends of its magnetic axis, the intensity of the dipole field may prove to be so small that it will be comparable with the intensity of the regular magnetic field of the Galaxy at that point. The combined action of both fields may lead to the formation of spiral arms, i.e., to the appearance of spiral-like nebulae [1].

Fig. 3

2. According to the concept advanced in [2], the nuclei of planetary nebulae are young, not yet fully formed stars, and therefore one may expect from them the ejection of ultrarelativistic electrons, whose interaction with the magnetic fields of the nebula should lead to the appearance of synchrotron radiation, continuous in spectrum, polarized, and with a maximum radiation density in the region of the "caps" (in bipolar nebulae). To distinguish this, in all probability quantitatively negligible, energy amid the ordinary continuous radiation of the nebula is a difficult task, but apparently a feasible one (by applying, for example, polarizational methods of investigation).

3. Since planetary nebulae, while expanding, must in the end disperse, together with their completely arbitrarily oriented magnetic fields, in interstellar space, the further fate of the nebulae and their magnetic fields should be studied as a possible path toward explaining the origin of the chaotic magnetic fields of the spherical and intermediate subsystems of the Galaxy.

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Received
3 February 1958

REFERENCES

Note: Figure translations are in progress. See original paper for figures.

[1] G. A. Gurzadyan, *Problems of the Dynamics of Planetary Nebulae*, Yerevan, 1954.
[2] G. A. Gurzadyan, *Problems of Cosmogony* **6**, 1958.