

## Possible Mechanism of the Magnetic Field Generation in Crab Nebula

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### Abstract

Possible mechanism of the magnetic field generation in Crab Nebula is considered. It is based on the development of two-stream instability after the supernova explosion which resulted in the formation of Crab Nebula.

### 1. Introduction

Crab Nebula - the remnant of the 1054 supernova - is one of the most interesting object in the universe. This unique object is an intensive source of radiation in whole range of electromagnetic wave frequency spectrum - from radiowaves up to the high energy  $\gamma$ -rays. Shklovsky suggested the nonthermal synchrotron mechanism for the explanation of this radiation [1]. The prediction of this theory about the polarization properties of the Crab Nebula radiation was confirmed successfully by the observations of Vashakidze [2] in Abastumani Astrophysical Observatory and Dombrovsky [3] in Biurakan Observatory.

For the generation of synchrotron radiation the existence of relativistic charged particles and regular magnetic field is necessary in Crab Nebula. Besides, both these components must appear in the nebula permanently, otherwise the radiation will stop very soon - in several weeks. The problem of the relativistic charged particle source was solved after the discovery of pulsar with very interesting characteristics in the center of Crab Nebula [4]. These particles are brought in the nebula by the relativistic pulsar wind. As for the magnetic field (The magnitude of the Crab Nebula magnetic field, which has been estimated using the several different methods, is about  $10^{-3} G$ . Besides, this field has the regular toroidal structure.) generation - the solution of this problem turned out to be much more complicated.

For the solution of this problem several interesting ideas have been suggested [5-14], which have the several difficulties. Practically in all these mechanisms it is necessary the existence of the invisible outer shell in Crab Nebula which is totally opaque for relativistic charged particles and magnetic field. The existence of such shell is not proved by any observations yet.

Therefore, in order to overcome the difficulties of previous models the new plasma mechanism for the generation of the magnetic field in Crab Nebula is offered bellow. This mechanism is based on the development of two-stream instability after the supernova explosion causing the generation of the magnetic field in Crab Nebula.

## 2. Generation of the magnetic field in Crab Nebula

As we have mentioned above, Crab Nebula is the remnant of the supernova, which exploded in 1054. During this explosion plasma of the outer layers of the star was thrown radially outwards and moves against the interstellar plasma with the speed of about 10 000  $km/s$ . Let us discuss the dynamics of the electromagnetic perturbations in a small element of such plasma, which consists of two plasma streams. Below we will call the plasma of the outer layers of pre-supernova — the plasma stream 1, and the interstellar plasma - the plasma stream 2. We will discuss the problem in the local inertial frame, which moves radially outwards with the speed two times less than the speed of the plasma stream 1. In this frame the plasma stream 1 and plasma stream 2 move in opposite directions and the magnitudes of their velocities are equal.

Let us direct the axis  $z$  radially outwards, along the direction of the motion of plasma stream 1. So, the plasma stream 1 and plasma stream 2 have in this frame the velocities  $V_{0z}$  and  $-V_{0z}$  respectively ( $|V_{0z}^{(1)}| = |V_{0z}^{(2)}| = V_0$ ). We discuss the electromagnetic perturbations the wave vector of which is directed perpendicularly to the direction of the plasma stream motion, along the axis  $x$ :

$$\vec{k} = (k_x, 0, 0).$$

Besides, we assume that the electric field of the perturbations is directed radially outwards, along the axis  $z$ :

$$\vec{E}_1 = (0, 0, E_{1z}).$$

In such case the magnetic field of the perturbations is directed toroidally, opposite to the axis  $y$ :

$$\vec{B}_1 = (0, -B_{1y}, 0).$$

For the first time we will discuss the case, when the unperturbed static magnetic field is zero,  $\vec{B}_0 = 0$ . The cases with nonzero unperturbed static magnetic field will be discussed later.

Employing momentum, continuity and Maxwell equations to study the electromagnetic perturbation dynamics in plasma and taking into account all above mentioned, one obtains finally the dispersion relation in the following form:

$$\frac{k^2}{\omega^2} - 1 + \frac{\omega_p^2}{\omega^2} \left( 1 + \frac{k^2 V_0^2}{\omega^2} \right) = 0, \quad (1)$$

where  $\omega_p^2 = 4\pi n_0 e^2 / m$  is the plasma frequency. Let us consider the perturbations for which  $\omega \ll \omega_p$ . In such case

$$\omega^2 = -\omega_p^2 \frac{V_0^2}{1 + \omega_p^2 / k^2}. \quad (2)$$

As we know

$$B_1 \sim \exp(-i\omega t). \quad (3)$$

As it is evident from (2) and (3) the two-stream instability development and the generation of the exponentially growing toroidal magnetic field takes place in Crab Nebula.

Unperturbed static magnetic field such as pre-supernova magnetic field or the interstellar magnetic field are much weaker than the Crab Nebula magnetic field. But, nevertheless, let us consider the influence of nonzero unperturbed static magnetic field on the process of the regular toroidal magnetic field generation in Crab Nebula.

For the first time we consider that the static magnetic field  $\vec{B}_0$  is directed along the direction of plasma stream motion, i.e. along the axis  $z$ . In such case one can find that the dispersion relation has the following form for the low frequency ( $\omega \ll \omega_p$ ) perturbations:

$$\omega^2 = \omega_c^2 - \omega_p^2 \frac{V_0^2}{1 + \omega_p^2/k^2}, \quad (4)$$

where  $\omega_c$  is the gyrofrequency. One can easily conclude from (4) that the two-stream instability development and the generation of the exponentially growing toroidal magnetic field takes place in Crab Nebula if

$$\omega_p^2 V_0^2 > \omega_c^2, \quad (5)$$

or

$$\frac{B_0^2}{4\pi n_0 m V_0^2} < 1. \quad (6)$$

Now let us consider the case when the static magnetic field  $\vec{B}_0$  is directed across the direction of the plasma stream motion, for example along the perturbed magnetic field  $\vec{B}_1$ . The dispersion relation has the following form in such case:

$$\omega^2 - k^2 = \omega_p^2 \frac{\omega^2 + k^2 V_0^2}{\omega^2 - \omega_c^2}. \quad (7)$$

From (7) we obtain

$$\omega_{1,2}^2 = \frac{\omega_c^2 + k^2 + \omega_p^2 \pm \sqrt{(\omega_c^2 + k^2 + \omega_p^2)^2 + 4k^2(\omega_p^2 V_0^2 - \omega_c^2)}}{2}. \quad (8)$$

It is evident from (8) that the development of two-stream instability and the generation of the exponentially growing toroidal magnetic field takes place in Crab Nebula if we choose the corresponding sign - namely (-) - and if also the following condition is satisfied:

$$\omega_p^2 V_0^2 > \omega_c^2, \quad (9)$$

or

$$\frac{B_0^2}{4\pi n_0 m V_0^2} < 1. \quad (10)$$

The conditions (5) and (6) coincide with (9) and (10), which were obtained for the case, when the static magnetic field  $\vec{B}_0$  is directed along the direction of the plasma stream motion and not across it. All these conditions are very well satisfied in Crab Nebula, because the field  $\vec{B}_0$ , considered by us, is weaker than the Crab Nebula magnetic field by many orders of the magnitude.

So, we can conclude that the unperturbed static magnetic field has a very weak influence on the process of the regular toroidal magnetic field generation in Crab Nebula.

### 3. Conclusion

So, one of the possible mechanism of the toroidal magnetic field generation in Crab Nebula is the development of two-stream instability. Magnetic field extracts the energy from the plasma particle kinetic energy. The mass of the plasma, which was injected in the interstellar plasma during the supernova explosion is about one mass of Sun. According to the current observations, nowadays the radial velocity of this plasma is about 2000 km/s. So, the total kinetic energy of the plasma particles is about  $4 \cdot 10^{49}$  erg. According to the estimations, nowadays the total energy of the Crab Nebula magnetic field is about  $3 \cdot 10^{48}$  erg. Therefore, there is a sufficient amount of kinetic energy to provide the process of the magnetic field generation in Crab Nebula according to the mechanism suggested by us. Besides, as we have shown, the superimposed unperturbed static magnetic field has practically negligible influence on the process of the regular toroidal magnetic field generation in Crab Nebula.

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