On the origin of the torus and jet-like structures in the centre of the Crab Nebula

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Accepted 2002 September 1. Received 2002 August 17; in original form 2002 January 31

ABSTRACT

The formation of the toroidal and jet-like structures in the central part of the Crab Nebula is explained in the framework of Kennel & Coroniti theory. The only new element introduced by us in this theory is the initial anisotropy of the energy flux in the wind. We estimate the X-ray surface brightness of the Crab Nebula from the region of interaction of this wind with the interstellar medium and compare it with observations.

Key words: MHD – shock waves – pulsars: general – ISM: individual: Crab Nebula – ISM: jets and outflows – supernova remnants.

1 INTRODUCTION

The Crab Nebula is powered by the wind of a relativistic e± plasma from pulsar PSR 0531 + 21. The wind is terminated by a shock front. The particles of the wind are redistributed in energy and their motion is randomized at the shock. Downstream of the shock (in the nebula) they emit synchrotron and inverse Compton radiation (Kennel & Coroniti 1984; De Jager & Harding 1992; Aharonian & Atoyan 1998). Detection of these emissions is still the only way to obtain information about the wind (see however Bogovalov & Atoyan 2000). Observations in the X-ray (Brinkmann, Aschenbach & Langmeier 1985; Weisskopf et al. 2000) and optical (Hester et al. 1995) have revealed a remarkable torus as well as jet-like structures in the central part of the Crab Nebula. The mechanism which produces these structures apparently gives rise to similar features observed around the Vela pulsar (Pavlov et al. 2000, 2001; Helfand, Gotthelf & Halpern 2001), PSR 1509 – 58 (Kaspi et al. 2001) and in the supernova remnants G0.9 + 1 (Gaensler, Pivovarof & Garmire 2001) and G54.1 + 0.3 (Lu et al. 2002). Understanding of this mechanism will certainly give us new information about pulsar winds.

The integral characteristics of the Crab Nebula are described by the theory of Kennel & Coroniti (1984). This theory explains well the spectra and luminosity of the Crab Nebula in photon energy range from eV up to TeV gamma-rays (Aharonian & Atoyan 1998). However, Kennel & Coroniti (1984) strongly simplified the physics of the nebula. They assumed that pulsar winds are isotropic. Therefor, this theory in its original form is not able in principle to explain non-uniform structures observed in the Crab Nebula.

Analysis shows that magnetic collimation of the pulsar winds into jets is impossible in conventional theories of the pulsar winds (Begelman & Li 1992; Beskin, Kuznetsova & Rafikov 1998; Bogovalov & Tsinganos 1999). Therefore, it is very difficult to interpret the observed jets as the result of collimation of the pulsar winds (Lyubarsky & Eichler 2001). The observation of the torus leads to the natural conclusion that the acceleration of the wind basically occurs near the equatorial plane (Aschenbach & Brinkmann 1975). It was shown recently (Bogovalov & Khangoulian 2002)(hereafter Paper I) that the formation of the torus and jets directly follows from conventional theories of the pulsar winds if the longitudinal distribution of the energy flux in the wind is taken into account. This work is the direct continuation of Paper I. Our main goal in this paper is to estimate the surface synchrotron brightness of the central part of the Crab Nebula and to compare the results of these estimates with observations.

2 CALCULATION OF THE SURFACE BRIGHTNESS

Pulsar winds have anisotropic distribution of energy flux (Bogovalov 1999). The particle flux can be considered to be more or less isotropic. The key point of our approach is that when this circumstance is taken into account, the Lorentz factor of the wind from the Crab pulsar should depend on polar angle θ as follows (Bogovalov & Atoyan 2000; Bogovalov & Khangoulian 2002):

\[ γ = γ_0 + γ_m \sin^2 θ, \]

(1)

here \( γ_0 \approx 200 \) is the initial Lorentz factor of the wind (Daugherty & Harding 1982), and

\[ γ_m = \left( \frac{Ω R^3}{c} \right)^3 \frac{B_0^2}{4π n_0 mc^2} \approx 10^{6}–10^{7}. \]

\( n_0, B_0 \) are the initial plasma density and the magnetic field on the surface of the pulsar with radius \( R \) (Bogovalov 1999). The interaction of this wind with the uniform interstellar medium results in the formation of a low density ‘hot’ region near the equatorial plane and high density but ‘cold’ jet-like features along the rotational axis (Paper I).
In this paper we use the same assumptions as in Paper I. The most important of them are the following. Calculations of the synchrotron volume emissivity in the conventional Kennel & Coroniti approach show that only the X-ray torus should be detected, while the jet-like features should be invisible in X-rays (Paper I). It is easy to understand why. In the calculations of the volume synchrotron emissivity \( I(r, \theta) \) it was assumed (as by Kennel & Coroniti) that the power law spectrum of electrons is formed at the shock. The evolution of the electron spectrum is defined by synchrotron cooling. The losses on the expansion of the nebula are neglected (for details see Paper I). All the energy of the electrons injected into the plerion is radiated as synchrotron radiation. In this case the total synchrotron luminosity \( \int I(r, \theta)r^2 \, dr \) integrated along a flow line at angle \( \theta \) is simply proportional to the energy density flux injected into the nebula at given angle \( \theta \). Thus, torus-like emission is formed, since the energy density flux is \( \sim \gamma_0 + \gamma_\infty \sin^2 \theta \). This implies that the brightness distribution in the torus depends basically on the energy flux distribution and is less dependent on the distribution of the particle flux in the pulsar wind.

We have assumed an additional acceleration of the electrons in the volume of the plerion with the amount of the accelerated electrons proportional to the local density of plasma to brighten the jet-like features in the post-shock region (Paper I). Some evidence that the population of the electrons in the ‘jets’ really differs from the population of the electrons responsible for the emission in the torus follows from XMM–Newton observations (Willingale et al. 2001). The surface brightness is calculated for the inclination angle of the equatorial plane to an observer of \( 33^\circ \) (Hester et al. 1995).

It has been proposed by Pelling, Paciesas & Peterson (1987) that the high brightness of the northwestern part of the torus relative to the low brightness of its opposite part is due to the relativistic boosting of photons. We took into account this effect. The photon flux from different parts of the nebula has been transformed according to the equation (Lind & Blandford 1985)

\[
F(\varepsilon) = s^{2/\gamma} F'(\varepsilon),
\]

where \( \varepsilon \) is the photon energy, \( s = [\gamma(1 - \beta \cos \phi)]^{-1}, \) \( n \) is the unit vector directed to the observer, and \( \beta \) is the local bulk motion velocity of the plasma. In the range \( \varepsilon = 400-1000 \) eV \( \beta \) is close to 2 (Aharonian & Atiyon 1998; Willingale et al. 2001).

\section{3 COMPARISON WITH OBSERVATIONS}

The results of our calculations of the surface brightness of the nebula are shown in Fig. 1. It is seen that indeed we obtain the torus of synchrotron radiation and two jet-like structures. The letter are visible due to the additional component of the accelerated particles.

The calculated radial distribution in surface brightness of the torus in the equatorial plane corresponds well to that observed. The maximum in brightness is reached at a distance of \( \sim 40 \) arcsec, which is close to the radius of the outer torus of 38 arcsec (Weisskopf et al. 2000). The calculated torus is evidently wider than the observed one in the direction perpendicular to the equatorial plane. This is the first essential difference between the calculations and observations.

The second difference is that the brightness difference of the torus edges directed from us and toward us is evidently smaller than in the observed torus (Weisskopf et al. 2000). The calculated picture is rather symmetric. Careful inspection of Fig. 1 shows that the relativistic boosting only slightly changes the relative brightness of the opposite edges of the nebula. This happens because the regions of maximum brightness are located at a distance of \( \sim 3\alpha \) where the plasma velocity falls down below \( c/27 \). Relativistic corrections (2) are rather small here.

We guess that these two disagreements between the calculated picture and the observed one are of general origin. We assumed that the flow downstream the shock remains radial. This is rather crude approximation. Our analysis of the flow downstream of the shock (Paper I) and direct numerical time-dependent simulations of the interaction of the anisotropic wind with the interstellar medium (Koldoba & Ustyugova, private communication) show that the wind is strongly deflected to the equatorial plane after the shock. This happens first at the shock. It is easy to make sure that the flow lines diverge to the equator at the shock front. Downstream of the shock the flow is further compressed to the equator by the pressure gradient. It is clear that if this effect is taken into account, the synchrotron torus will have a smaller width across the equatorial plane. In addition, the compression of the post-shock flow to the equator will result in a slower decrease of the velocity with \( r \). The effect of the relativistic boosting will be more stronger. Therefore, we believe that the disagreements between the calculations and the observations found at the present stage of our analysis are caused by the approximations used. These disagreements can be reduced or may be removed altogether through a more accurate treatment of the flow in the post-shock region.

The shape of the calculated jet-like structures differs from the observed ‘jets’ as well. The observed ‘jets’ are more laterally extended and expand with distance from the centre. This disagreement is due to the assumption that the additional acceleration of the particles is simply proportional to the plasma density in the post-shock region. At least two effects will result in better agreement with the observations. The first one is the deflection of the flow lines away from the rotational axis as it follows from real dynamics of the plasma in the post-shock region. The second one is an averaging of the density and magnetic field near the rotational axis at the development of the kink instability, which must take place for the configuration of the
magnetic field formed in the post-shock region (Paper I). More accurate treatment of all these processes will result in better agreement of the theoretically predicted brightness distribution of the X-ray Crab Nebula with observations.

4 CONCLUSION

The fact that the morphology of the central part of the Crab Nebula can be explained in frameworks of the theory developed by Rees & Gunn (1974); Kennel & Coroniti (1984); Emmering & Chevalier (1987) is the basic result of our work. The elucidation of the nature of the torus and jets opens for us new horizons. In particular, comparison of the observed brightness distribution of the torus with calculations based on an accurate modelling of the plasma flow in the post-shock region will open the way to obtain observational information about the energy flux distribution in the pulsar wind.

ACKNOWLEDGMENTS

The work is performed under support of collaborative INTAS-ESA grant N 120–99. We are grateful to Felix Aharonian, for important comments. S. V. acknowledges R. Sunyaev, H. Spruit, J. Trümper and B. Aschenbach for useful discussion of the problem. The authors thank Richard Tuffs for help in preparation of the manuscript.

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