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The Termination Shock in a Striped Pulsar Wind

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Abstract. Toroidal stripes of opposite magnetic polarity are formed in the equatorial belt of the wind emanating from an obliquely rotating pulsar magnetosphere. Such a striped wind transfers most of its spindown energy because the angular distribution of the energy flux in the pulsar wind is maximum at the equator. The alternating field annihilates either in the pulsar wind or at the termination shock so that the flow in the equatorial belt downstream of the termination shock is weakly magnetized. At high latitudes, the magnetization of the flow is higher than in the equatorial belt whereas the total energy flux is smaller. At such a distribution of the energy flux and magnetization, the downstream flow separates into an equatorial disk and a magnetically collimated polar jet. Particle acceleration at the termination shock in a striped wind is discussed. It is argued that the radio emitting electrons are accelerated by driven reconnection of the alternating field at the shock whereas the Fermi acceleration of electrons preaccelerated in the reconnection process results in a high energy tail responsible for the X- and γ-ray emission.

1. Introduction

According to the available models, the pulsar wind is launched as a Poynting dominated outflow. In the equatorial belt of the wind from an obliquely rotating pulsar magnetosphere, the sign of the magnetic field alternates with the pulsar period forming stripes of opposite magnetic polarity (e.g., Bogovalov 1999). Observations of X-ray tori around pulsars suggest that it is in the equatorial belt where most of the wind energy is transported. Therefore the fate of the striped wind is of special interest. In the striped wind, the Poynting flux converts into the particle energy flux when the oppositely directed magnetic fields annihilate. The flow acceleration in the course of the energy release dilates the dissipation timescale so that the wind may enter the termination shock before the alternating field annihilates completely (Lyubarsky & Kirk 2001; Kirk & Skjæraasen 2003). Then the alternating field dissipates by driven reconnection at the shock (Lyubarsky 2003b) therefore in any case only the mean magnetic field remains downstream of the termination shock, the energy of oscillating field being already converted into the plasma energy. Exactly at the equator, where the energy flux is maximum, the mean field is zero.

If the alternating field completely annihilates at the shock, the downstream parameters of the flow are the same as if the field has already annihilated upstream of the shock. Therefore the available limits on the ratio of the Poynting to the kinetic energy flux just upstream of the termination shock (Kennel & Coroniti 1984) should be attributed not to the total Poynting flux but to the Poynting flux associated with the mean magnetic field. The upstream flow may be Poynting dominated provided most of the Poynting flux is transferred by alternating magnetic fields.

At higher altitudes, where the magnetic field does not change sign, the energy is partly transferred by electro-magnetic waves and partly by the mean field. The waves may decay relatively easily (e.g., Lyubarsky 2003a); however, the residual mean magnetic field remains at these altitudes in any case. As a self-consistent solution for the obliquely rotating dipole magnetosphere is not available, the fraction of the Poynting flux transferred by the mean large-scale electro-magnetic field is not known. However the mean magnetic field is anyway zero at the equator, and it should also be zero at the axis because there is no singular current at the axis of real flows.

The polar jets seem to indicate that they are formed within the pulsar wind and the collimation by the magnetic hoop stress suggests itself. However, such a collimation is found to be extremely ineffective in ultra-relativistic flows (e.g., Chiueh, Li & Begelman 1998; Lyubarsky & Eichler 2001). Moreover, jets of such an origin would have to be ultra-relativistic whereas the observed jets are certainly not. Lyubarsky (2002) pointed out that downstream of the termination shock the flow is no longer ultra-relativistic and therefore the observed jet may be formed by magnetic collimation in the shocked plasma. Annihilation of the alternating field ensures that in the equatorial belt, where most of the energy is transferred, the residual magnetic field is low. However, magnetization of the high latitude flow may be significant. This naturally results in separation of the postshock flow into the equatorial disk and polar jet. If most of the energy flows in the pulsar wind along the equator, the termination shock is non-spherical, being significantly closer to the pulsar at the axis than at the equator (Lyubarsky 2002; Bogovalov & Khangoulian 2002). Therefore the jet looks as if it originates from the pulsar.

Komissarov & Lyubarsky (2003, 2004) simulated numerically the flow produced by the pulsar wind within a plerionic nebula assuming that in the equatorial direction magnetization of the wind drops to zero but its energy flux reaches maximum. They found that the termination shock has a shape of a distorted torus and most of the downstream flow is initially confined to the equatorial plane. The magnetic hoop stress stops the outflow in the surface layers of the equatorial disk and redirects it into magnetically confined polar jets. Velocities both in the disk and in the jet were found to be about $0.5c$, close to those inferred from the observations (Hester et al. 2002; Pavlov et al. 2003). The synchrotron images of the nebula were simulated taking into account the relativistic beaming effect and the particle energy losses. These images are strikingly similar to the images of the Crab and other pulsar wind nebulae obtained by *Chandra* and *HST*. They exhibit both a system of rings, which makes an impression of an equatorial disk-like or even a toroidal structure, and well-collimated polar jets, which appear to originate from the pulsar. The result of these simulations show that one can account for the jet-torus structure with standard assumptions about the pulsar wind.

The MHD structure of the postshock flow is independent of whether the waves decay in the upstream flow or at the termination shock. However if the waves decay at the shock, both the structure of the shock and the physics of the particle acceleration is significantly modified. This new physics may help to resolve difficulties with particle acceleration in plerions. The generic observational feature of plerions is a flat radio spectrum. The overall spectrum of the Crab may be described as a broken power law with the spectral breaks around 10^{13} Hz, a few times 10^{15} Hz, and around 100 keV. The synchrotron lifetime of the radio emitting electrons (and positrons, below by electrons I mean both electrons and positrons) significantly exceeds the plerion age therefore one can not exclude a priori that they were injected at the very early stage of the plerion evolution. In this case the overall spectrum depends on history of the nebula. However the spectral break at 10^{13} Hz may be simply accounted for the synchrotron burn-off effect assuming that the radio to optical electrons are injected more or less homogeneously in time with the single power law energy distribution (Rees & Gunn 1974). This view is strongly supported by Gallant & Tuffs (2002) who found that the infra-red spectral index in the central parts of the Crab is close to that in the radio, and gradually steepens outward. Recent observations of wisps in the radio band (Bietenholtz, Frail & Hester 2001) suggest unambiguously that the radio emitting electrons are accelerated now in the same region as the ones responsible for the optical to X-ray emission.

If the radio emitting electrons are injected into the Crab Nebula now, the injection rate of electrons should be about $10^{40} - 10^{41}$ s^{-1}. It is interesting that the observed pulsed optical emission from the Crab pulsar suggests that about the same amount of electrons is ejected from the pulsar magnetosphere (Shklovsky 1970) so the pulsar does supply the necessary amount of particles. The observed spectral slope in the radio band implies the energy distribution of the injected electrons of the form $N(E) \propto E^{-1.5}$. In this case, most of the particles find themselves at the low energy end of the distribution whereas particles at the upper end of the distribution dominate the energy density of the plasma. Taking into account that no sign of a low frequency cut-off is observed in the Crab spectrum down to about 10 MHz whereas the high frequency break lies in the ultra-violet band, one concludes that the above distribution extends from $E_{min} \lesssim 100$ MeV to $E_{br} \sim 10^6$ MeV. At $E > E_{br}$ the distribution becomes steeper; the spectral slope in the X-ray band corresponds to $N(E) \propto E^{-2.2}$. Thus, most of electrons have the energy $\lesssim 100$ MeV whereas the plasma energy density is dominated by TeV electrons.

The above considerations place severe limits on the pulsar wind parameters and possible mechanisms of the particle acceleration at the termination shock. The energy distribution with such a low cut-off is incompatible with the popular assumption (Kennel & Coroniti 1984) that the Lorentz factor of the pulsar wind in the Crab is about 10^6; the kinetic energy of the upstream flow should be much lower. On the other hand, the flat energy distribution implies that the total energy per electron in the upstream flow is much larger than 100 MeV so there should be an energy reservoir in the flow. Thus, the conventional two-step model (Poynting flux $\rightarrow$ kinetic energy of the upstream flow $\rightarrow$ accelerated particles) faces severe difficulties in both steps: the Poynting flux can scarcely be totally transformed into the kinetic energy flux in the wind and the kinetic energy dominated upstream flow cannot produce the observed energy distribution of the particles in the nebula. For this reason, the one-step process (Poynting flux $\rightarrow$ accelerated particles) looks preferable (Lyubarsky 2003b). If most of the spin-down energy is still stored in the magnetic stripes when the flow enters the termination shock, the Lorentz factor of the flow is relatively small. At the shock, the flow is squashed so that the alternating magnetic fields easily annihilate transferring the energy to accelerated particles. In this case, a flat energy distribution with a low energy cut-off may be formed easily. A rough estimate of E_{min} and E_{br} for the Crab parameters yields values compatible with those inferred from the observed spectrum (Lyubarsky 2003b). In this model, the high-energy spectrum may be attributed to the Fermi acceleration of particles preaccelerated in the reconnection process. Note that the Fermi acceleration at the ultra-relativistic shock yields the particle energy distribution $N(E) \propto E^{-2.2}$ (e.g., Gallant 2002), just what is necessary to explain the X-ray spectrum of the Crab.

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