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Pulsar magnetosphere and emission mechanisms

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The complex charm of the pulsar magnetosphere

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Abstract. I give a brief overview of recent results from self-consistent modeling of electron-positrons cascades in pulsar polar caps. These results strongly suggest that the pulsar magnetosphere is a more complex system than was assumed before.

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1. Introduction

Radio pulsars are rotationally powered highly magnetized isolated neutrons stars (NS) which emission is produced in their magnetospheres. There are strong observational evidences that pulsar magnetospheres are filled with dense plasma – pulsar wind nebulae (PWNe) are fed by dense flow of relativistic plasma produced by their parent pulsars. Most of theoretical models of pulsar magnetospheres, starting from the classical model of Goldreich & Julian (1969), also argue that pulsar magnetosphere is filled with plasma. The sharpness of peaks in pulsar light curves, especially in gamma, naturally leads to the conclusion that emitting regions, and, hence, the regions where particles are being accelerated, are small and everywhere in the magnetosphere, except those small accelerating regions, the electric field is screened by dense plasma.

The vast majority of NS energy losses goes into the pulsar wind, the outflow of relativistic plasma. Motion of the plasma in the magnetosphere results in electric currents which change the topology of the NS's magnetic field creating closed and open magnetic field lines zones. Plasma flow along open magnetic field lines starts at the NS surface and leaves the magnetosphere; that plasma must be constantly replenished. Even if charged particles can be extracted from NS surface, their number density would be several orders of magnitude lower than that inferred from observations of PWNe. Starting with the work of Sturrock (1971) the assumption about electron-positron plasma generation in pulsar polar caps has been an integral part of almost any pulsar model. It is also generally believed that pair creation is intimately connected to radio pulsar activity, as the death line – the place on the $P-\dot{P}$ diagram where radio emission ceases – roughly corresponds to such pulsar parameters when the potential drop generated by NS rotation becomes smaller than the threshold for pair formation. Hence, production of electron-positron plasma in polar caps is a cornerstone of current pulsar "standard model".

The problem of how plasma is generated in pulsar polar caps can not be considered separately from the problem of the global structure of the magnetosphere. Currents supporting the magnetosphere with its open and closed field lines zones flow along magnetic field lines all the way from the NS surface into the pulsar wind zone passing trough the plasma generating regions. Current density distribution is determined by the global magnetospheric structure and those small pair generation zones (which inductance is much smaller than that of the magnetosphere) must adjust to the current density imposed by the magnetosphere. Recently significant progress has been achieved in modeling of the global structure of pulsar magnetosphere (e.g. Contopoulos *et al.* 1999, Timokhin 2006, Spitkovsky 2006, Kalapotharakos & Contopoulos 2009), so the current density distribution in the magnetosphere is known. It has been explicitly shown (Timokhin 2006) that this current density distribution does not agree with assumptions about the current density used in than up to date quantitative "standard models" of polar cap plasma generation (e.g. Arons & Scharlemann 1979, Muslimov & Tsygan 1992, Daugherty & Harding 1982), which assumed stationary unidirectional plasma flow.

This discrepancy motivated me to start the study of pair plasma generation in pulsar polar caps which is free from assumptions about character of plasma flow and addresses the problem starting from first principles. The goal was to investigates how the pair plasma is generated when a given current density (set by the global magnetosphere structure) flows through the pair creating region. Here I give a brief overview of the first results of this study, described in more detail in Timokhin (2010) and Timokhin & Arons (2012), and discuss possible explanations for several phenomenas seen in pulsars.

2. Self-consistent numerical model of pair cascades

We assumed that pulsar magnetosphere is already filled with plasma and studied how this state is sustained †. In the reference frame corotating with the NS, the star's rotation results in the effective background charge density, the Goldreich-Julian (GJ) charge density η_{GJ}. Existence of the open magnetic field lines requires these lines to be twisted; this twist must be supported by a certain current density j_{m} which flows along the lines and through the cascade zone as well. Both these effects must be included in modeling of electrodynamics of the cascade zone, but almost all previous quantitative models of pair cascades did not include the inductive effects, i.e. they ignored j_{m}. We modeled how the cascade zone behaves under different current loads – in each simulation we required that a given current density j_{m} flows through the cascade zone; in contrast to almost all previous works we studies the pair production when the current is fixed rather that the voltage.

We used a specially developed hybrid Particle-In-Cell/Monte Carlo (PIC/MC) numerical code which models electromagnetically driven pair cascades in truly self-consistent way, whereby particle acceleration, photon emission, propagation, pair creation, and screening of the electric field are calculated simultaneously (Timokhin 2009, 2010). As such truly self-consistent simulations had never been done before we started with the simplest possible model which, however, includes all types of physical processes relevant for pair formation in the polar caps of pulsars. Our model is one-dimensional, it includes curvature radiation as a gamma-ray emission mechanism and single photon absorption in strong magnetic field as a pair production mechanism. The electrodynamics takes into account the effects due to the GJ charge density η_{GJ} as well as the current density j_{m} imposed by the magnetosphere. The electrodynamics and plasma dynamics – particle acceleration and electric field screening by charged particles – are modeled by the PIC part of the code. Emission of gamma-rays, their propagation in magnetic field, and pair creation are modeled by the MC part of the code.

Boundary conditions implemented in the code included the case when particles cannot leave the NS surface as well as the case of free particle outflow from the surface, the so-called Space Charge Limited Flow (SCLF) regime. The latter, less trivial case was

† In other words, we did not study the (more difficult) problem of how the magnetosphere is formed.

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modeled by creation of a pool of numerical particles just outside of computational domain at its NS's end. The system was allowed to extract as many particles as it needed, in other words we allowed the cascade zone to set the electric field at the NS to zero self-consistently, without imposing it in the code manually. Particles were allowed to leave domain freely (if not prevented to do so by the electric field) and no particles were injected at the outer end of the domain.

3. Main results

We performed self-consistent simulations of pair cascades in pulsar polar cap in 1D for two most important classes of pulsar polar cap cascade models (i) when particles cannot be extracted from the NS surface (Timokhin 2010), the so-called Ruderman-Sutherland (1975; hereafter RS) model; and (ii) for currently the most popular model when particles can freely leave the surface (Timokhin & Arons 2012), the space charge limited flow regime, so-called Arons-Scharlemann (1979) model.

In both cases the cascade zone easily adjusts to *any* given current density $j_{\rm m}$ imposed by the magnetosphere provided the physical parameters allow for pair creation. This adjustments proceeds locally due trapping of some fraction of plasma particles by small fluctuating electric field. $j_{\rm m}$ turned out to be the most important parameter determining the efficiency of particle acceleration. In some cases sustaining if the imposed current density results in a flow with no particles acceleration and pair creation. If the imposed current density leads to pair formation, it always occurs non-stationary, a burst of pair formation is followed by a quiet phase when accelerating electric field is screened and no pairs are produced.

For the Ruderman-Sutherland model the cascade easily adjusts to the current density required by the magnetosphere and always produces dense electron-positron plasma in accordance with qualitative expectations of the original model, provided $j_{\rm m} \neq 0$. Particle acceleration and pair production occur in form of discharges. At the beginning of each discharge cycle a gap (a charge starved spatial region) with accelerating electric field appears and grows in size until the potential drop across it becomes larger than the pair formation threshold. Particles accelerated in this gap emit pair production capable gamma-rays which inject electrons and positron into the gap, these secondary particles screen the electric field and destroy the gap. When the newly generated plasma leaves the domain the discharge starts anew. Surprisingly, the pair formation turned out to be very regular showing a limit cycle behavior, and gaps do not stay at the same place but move along magnetic field lines. The pair plasma has a thermalized low-energy component.

In the case of the space charge limited flow, however, the cascade behavior turned out to be *qualitatively* different from what was expected in "standard" cascade models. The character of the flow strongly depends on the ratio of the average current density flowing through the cascade zone to the GJ current density $j_{\rm GJ} \equiv \eta_{\rm GJ} c$, see Fig. 1. For field lines where the imposed current density is smaller that the GJ current density $0 < j_{\rm m}/j_{\rm GJ} < 1$ (sub-GJ) no pair plasma is produced † because the accelerating zone is very small due to an instability of the plasma flow and a moderately relativistic electron low-density plasma (with the number density $n = \eta_{\rm GJ}/e$) streams along those field lines. Pair formation is possible only along field lines where the current density is either larger than the GJ current density $j_{\rm m}/j_{\rm GJ} > 1$ (super-GJ), or has the opposite sign to it $j_{\rm m}/j_{\rm GJ} < 0$, in regions with the return current. Pair creation is highly non-stationary,

† in this regard our results support conjectures about the sub-GJ flow of Shibata (1997) and Beloborodov (2008)

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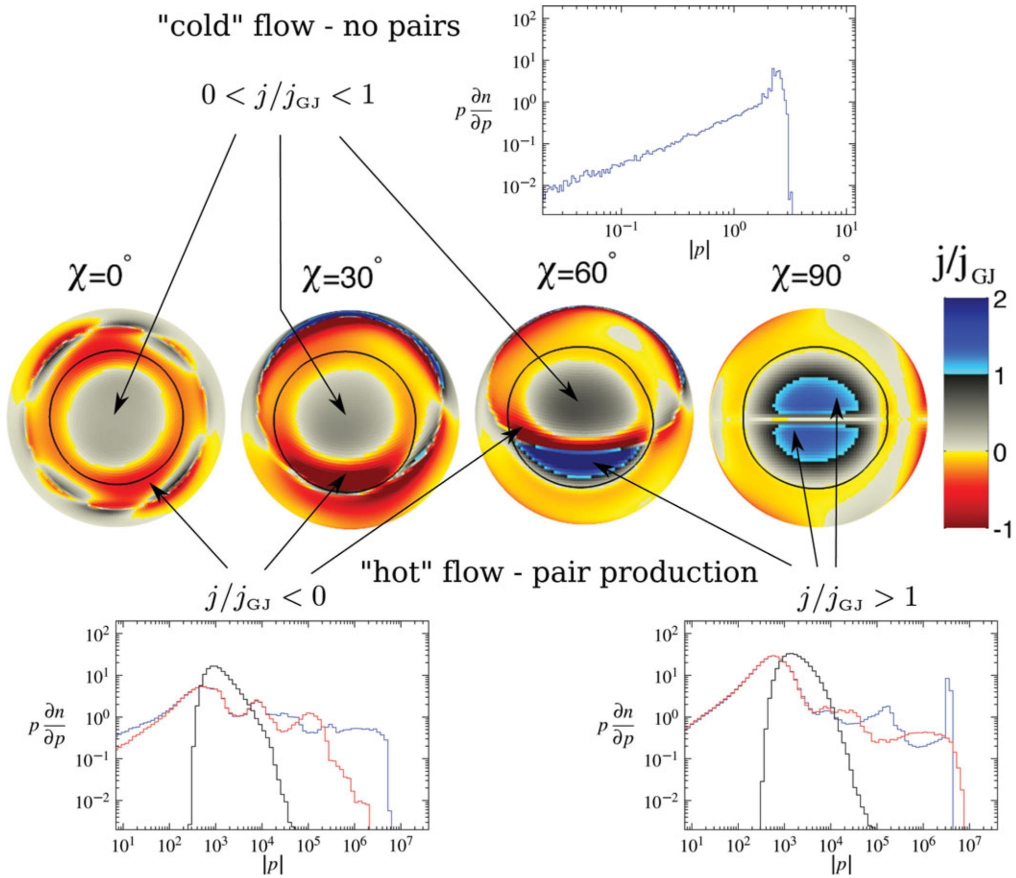

Figure 1. Current density distribution in the polar cap of pulsar for different pulsar inclination angles α (central panel) and examples of particle distribution functions (as functions of particle momenta normalized to $m_e c$) for different cascade regimes in the space-charge limited flow model (top and bottom panels). Colors show the ratio of $j/j_{\rm GJ}$ and the polar cap boundary is shown by a thin black circle on each subplot. Distribution function of electrons is shown by blue lines, positrons by red dashed lines, and gamma-rays by dotted black lines. Note that on the upper plot particles are only mildly relativistic and no pairs are produced (adapted from Timokhin & Arons (2012) with contribution of Xue-Ning Bai (Bai & Spitkovsky 2010))

similar to discharges in the RS model. SCLF regime can sustain any imposed current density $j_{\rm m}$ as well.

Contrary to expectations of previous models, the place where discharges occur is different for different flow regimes. For RS cascades with $j_{\rm m}/j_{\rm GJ} > 0$ discharges start close to the NS surface. For flows with $j_{\rm m}/j_{\rm GJ} < 0$ discharges start at the largest possible distance from the NS in both RS and SCLF regimes. For SCLF with $j_{\rm m}/j_{\rm GJ} > 1$ the position where discharges start depend on how the GJ charge density changes with the distance: discharges can start close to NS if the ratio $|\eta_{\rm GJ}/B|$ (B – magnetic field strength) increases with the distance from the NS, otherwise discharges start at large distances from the NS.

Discharges results in strongly fluctuating electric field, electrostatic waves. Fig. 2 shows an example of how the screening of the electric field in a discharge proceeds, there are 3 snapshots of a discharge in SCLF with $j_{\rm m} = -0.5 j_{\rm GJ}$. Fluctuating electric field during discharge event has a power low spectrum, with long-wavelength (small k) cut-off moving

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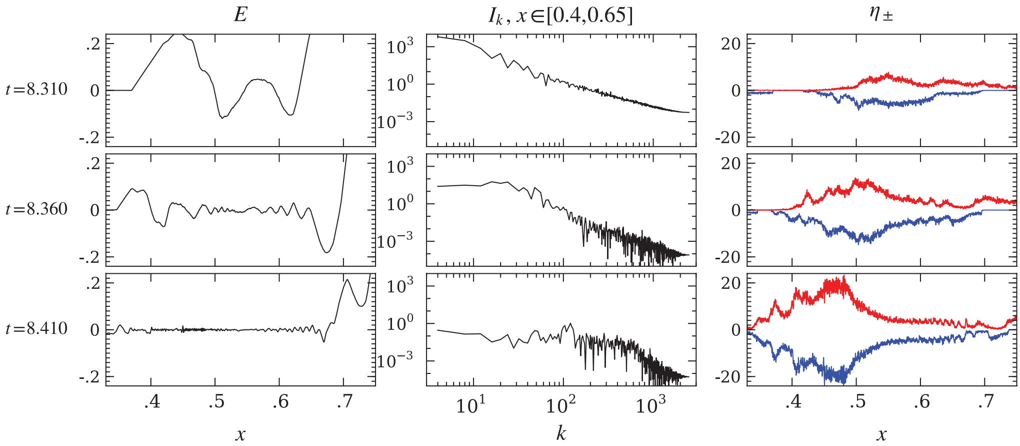

Figure 2. Screening of the electric field and formation of superluminal electrostatic waves during a discharge for SCLF with $j_{\rm m} = -0.5 j_{\rm GJ}$ (cf Fig. 19 in Timokhin & Arons 2012). There are three snapshots for the electric field E, power spectra of the electric field $I_k = |E_k|^2$ (for the spatial interval $x \in [.4, .65]$), and the charge density of electrons (negative values, blue line) and positrons (positive values, red line) $\eta_\pm$. E and $\eta_\pm$ are plotted as functions of distance x for the part of the calculation domain with intense pair formation. x is normalized to the domain size L, E normalized to the "vacuum" electric field $E_0 \equiv |\eta_{\rm GJ}| \pi L$, $\eta_\pm$ is normalized to the absolute value of the Goldreich-Julian charge density $|\eta_{\rm GJ}|$. Time t is measured in flyby time L/c.

to larger k as the wavelength of fluctuations decreases. The phase velocity of such waves is larger than the light speed and they can not be effectively dumped via Landau damping.

4. Discussion

Results of these simulations imply that the pulsar magnetosphere is a much more complex physical system than it was assumed before. For the same pulsar period and magnetic field strength properties of plasma flowing along a given magnetic field line strongly depend on the value of the imposed current density $j_{\rm m}$ along that line. Plasma properties (density, particle energy distribution) along different magnetic field lines can differs substantially due to non-uniform distribution of $j_{\rm m}$ across the polar cap, and plasma content of magnetospheres in pulsars with different inclination angles will also differ as the current density distribution $j_{\rm m}$ strongly depends on the inclination angle (see the middle panel of Fig. 1).

The locations of particle acceleration and emission zones depend in a non-trivial way on the pulsar inclination angle. For example, in the SCLF regime there is no pair plasma generation over the most areas of the polar cap in an aligned pulsar, but in an orthogonal rotator pair plasma is efficiently generated over the whole polar cap. Our results also indicate that magnetic field lines with the return current ($j_{\rm m}/j_{\rm GJ} < 0$) can have particle acceleration zones in the outer magnetosphere, as discharges tend to start at the furthest possible distance from the NS. This agrees with observations of pulsars with *Fermi* which indicate that gamma-rays are produced in the outer magnetosphere, in regions close to those where the field lines carrying the return current are expected to be.

Non-stationary discharges in flow regimes with pair creation incorporate time dependent, quasi-coherent currents on microsecond and shorter time scales. Such fluctuations might be a direct source of radio emission from the low altitude polar flux tube, a region strongly suggested as the site of the radio emission by the radio astronomical phenomenology. The energy in such fluctuations is enough to power the radio emission

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and the spectrum of the fluctuations is a power law, consistent with radio phenomenology. Fluctuating electric field is also present in the domain the low energy flow with sub-GJ current density $0 < j_{\rm m}/j_{\rm GJ} < 1$ in SCLF regime, however, the amplitude of this field is so low that it is unlikely that those fluctuations could directly result in observable radio emission.

It is natural to assume that all these different flow regimes have different observational signatures, i.e. are responsible for different components in pulse profiles. If so, from the current density distribution (the central panel on Fig. 1) one can see that pulsar profiles should be roughly symmetric and the maximum number of separate emission regions should not exceeds 5, what seems to agree with results of phenomenological analysis of pulsar profiles (Rankin 1983).

Changes in $j_{\rm m}$ could result in significant changes of pulsar emission. For example, in SCLF regime changing $j_{\rm m}$ from super-GJ to sub-GJ will result in highly relativistic plasma flow becoming a low energetic one. If pulsar magnetosphere has a few metastable states with different current density distributions, then the character of radio emission could be qualitatively different in these two states; it could be that there will be no radio emission in one of the states state at all. This might be a low-level mechanism for nulling and/or mode changing in (at least some of) pulsars.

It must be said, however, that the resulting 1D model of the cascades is very simplified. Within the frame of 1D model many important issues cannot be addressed, such as influence of physical conditions at adjacent field lines on the accelerating electric field and excitation and propagation of electromagnetic waves. In SCLF regime the spatial scales involved are larger that the polar cap size, the characteristic transverse size of the system, what makes 1D model not suitable for accurate quantitative predictions. However, we expect that most of qualitative results obtained with the current model holds a multi-D treatment which will be reported in later papers.

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