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The Pulsar Magnetosphere – A Stationary Self-Consistent Solution

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Abstract. Using fundamental equations of physics we determine with a simple model a globally self-consistent state of a pulsar magnetosphere.

1. Introduction

We investigate as a model for a parallel rotator a rapidly spinning, magnetized, electrically conducting sphere with a radius of 10 km. The magnetic field is aligned with the axis of rotation and has a field strength of 10^5 T up to 10^8 T at the poles. The period of rotation varies between 1.56 ms and 200 ms. The stellar surface is electrically ideally conducting.

As has been pointed out by Goldreich and Julian in 1969 already, this system has a strong electric field originating in unipolar induction. This electric field extracts particles from the surface of the sphere an accelerates them to ultrarelativistic speeds. On the surface the remaining charge is redistributed immediately due to the perfect conductivity of the sphere. The sphere may as a whole get electrically charged though.

The extracted particles change the charge distribution in the surroundings of the sphere and, through their motion, the distribution of electric currents. This means a change of the electric and magnetic field in the surroundings, the magnetosphere. In our model we take this change into account by solving equations derived from Maxwell's equations at short time intervals.

We simulate the particle motion during these time intervals by solving the Lorentz-Dirac equation in Landau's approximation. This iterative procedure is continued until we reach a stationary state which is then automatically self-consistent. We neglect gravitational effects, interaction between charged particles and a radiation field, and pair production.

2. Our Model

The emission of particles from the sphere's surface is simulated by a simple emission law: the emitted charge is proportional to the component of the electric field parallel to the magnetic field at the point of emission. The value of the emissivity constant is unimportant as long as it is sufficiently large, as it turns out that emission is space-charge limited.

It has been shown that radiation damping plays a dominant role in this system (cf. Finkbeiner et al.). This means that the inertia of a single particle is of small influence and the particle motion is determined by a velocity field. For the case of extremely strong radiation damping it is possible to derive an analytic equation for a velocity field from the Lorentz-Dirac equation in Landau's approximation. We have used this equation for the velocity field throughout our computations though it only holds true for extremely strong radiation damped particles such as ultrarelativistic electrons. Particles are treated via their density and their motion is computed by solving the continuity equation. For details cf. Herold et al.

Recent particle simulation calculations have not yet shown any major deviations from our earlier results so far, but have not been finished yet as the computation is very slow.

For the computation of electromagnetic fields we do not solve Maxwell's equations but equations for the electric potential, the magnetic flux, and the toroidal component of the magnetic field which are derived from Maxwell's equations. This leaves us with three fields to compute instead of six.

3. Results

The described computations have been carried out with different rotation periods and started with different states. The strength of the magnetic field is a mere scaling factor as long as we are not calculating a particle simulation but rather use the velocity field method. In all cases the resulting states which are about stationary show great similarities. This encourages us to believe that these states have real significance.

The results in detail:

- The poloidal magnetic field remains almost unchanged and is mainly dipolar.
- The polar axis very quickly turns into an equipotential line for the electric potential. This implies that there is no particle acceleration along the axis.
- A rough estimation of the radiation pattern obtained from the radiation damping has shown two hollow cones.
- There is a charge free region separating a polar and an equatorial region. The polar region carries an excess negative charge, the equatorial region an excess positive charge.
- Peak charge densities are of the order of magnitude of the Goldreich-Julian density.
- A wind is leaving the pulsar close to the equatorial plane and at the poles.

References

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