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PULSARS AS COSMIC RAY PARTICLE ACCELERATORS: PROTON ORBITS

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ABSTRACT

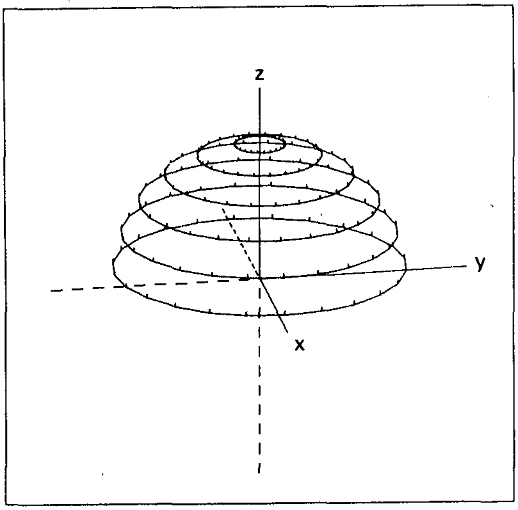
Proton orbits are calculated in the electromagnetic vacuum field of a magnetic point dipole rotating with its angular velocity $\vec{\omega}$ perpendicular to its dipole moment $\vec{\mu}$ by numerical integration of the Lorentz-Dirac equation. Trajectories are shown and discussed for various initial conditions. A critical surface is shown seperating initial positions of protons which finally hit the pulsar in the polar region from those which finally recede to infinity.

1. Introduction. In this paper proton orbits will be shown which I obtained with one of my students (Laue and Thielheim, 1985 a and b) by numerical integration of the Lorentz-Dirac-equation in the electromagnetic vacuum field of a magnetic point dipole rotating with its angular velocity $\vec{\omega}$ perpendicular to its dipole moment μ . Parameter values (model 1) are $\mu = 10^{30}$ G cm^3 and $\omega = 20\pi$ s^{-1}. The corresponding magnetic field strength in the polar region of a spere of radius R_p = 10 km is about 2 . 10^{12} G. The resulting light radius is R_L = 4.775 km. The procedures of numerical integration are described elsewhere (Marotzke and Thielheim, 1985).

The initial velocity of protons is zero, which is a reasonable specification since it turns out that particles very rapidly gain ultrarelativistic energies such that their orbit depends very little on their initial velocities as long as these are sufficiently small (i.e. nonrelativistic). The orbits under consideration, therefore, depend only on their initial positions. In a certain set of orbits these initial positions are defined by a given value of radius (R_o = 10, 2.2 and 1.8 in units of R_L), equidistant values of latitude (Θ_o = 10°, 25°, 40°, 55°, 70° and 85° against the vector of angular velocity $\vec{\omega}$) and equidistant values of longitude (ϕ_o = 0°, 15°, ..., 345° against the x-axis, which corresponds to the direction of the dipole moment $\vec{\mu}$ for zero phase $\omega t - r/R_L = 0$). These initial positions are shown in figure 1.

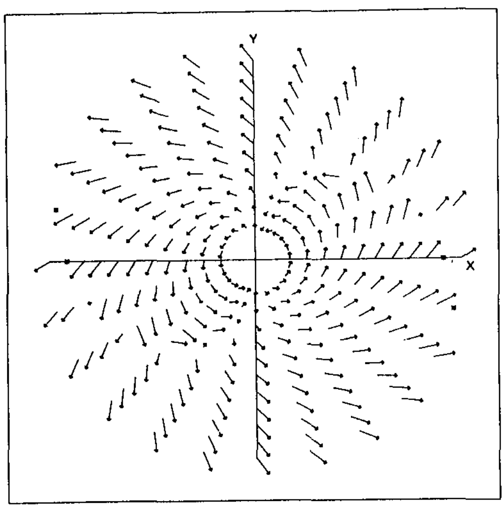
2. Symmetry Properties. In the given field configuration the magnetic vector is symmetric, while the electric vector is antisymmetric under point reflection. In view of the symmetry properties of the equation of motion, therefore, protons starting from point symmetric initial positions with opposite initial moments move on point symmetric orbits. For this reason one may restrict calculations to initial positions on one of the two hemispheres.

3. Particle Drift in the Equatorial Plane. In the field configuration considered here the electric vector is perpendicular to the equatorial plane z = o, while the magnetic vector in this plane is parallel to the z-axis, i.e. $(\mathfrak{E},\mathfrak{B}) = o$. Thus, in the equatorial plane, there is no acceleration along the magnetic field lines. Still there is an $[\mathfrak{E},\mathfrak{B}]$-drift within the plane. This is illustrated by figure 2, the arrows indicating the drift velocity. Asteriks mark regions, where $E^2 > B^2$ and thus protons are torn out of the equatorial plane by the dominating electric field. (In this diagram, the arrows at the outer edge correspond to initial positions with $R_o = 3$).



Definition of initial conditions

figure 1



E×B-Drift velocity of protons originating from the equatorial plane

figure 2

4. Protons starting in the Distant Zone. Orbits of protons starting from initial radius R_o = lo and latitude $\Theta_o = 25^o$ (with the radial coordinate r given in the logarithmic scale log (r/rmin)) are shown in figure 3 for Δt = 9o units of time. These protons move practically in the radial direction forming a narrow bundle slightly deflected towards the electric vector (broken line). An analogous diagram for $\Theta_o = 7o^o$ is shown in figure 4 exhibiting a wider bundle of orbits.

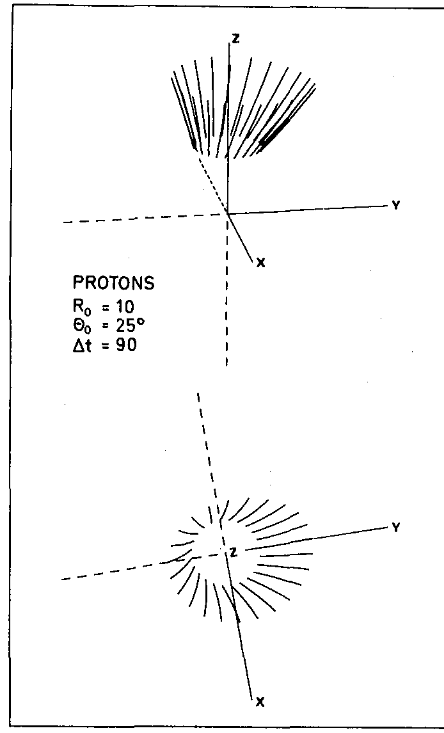


figure 3

5. Protons starting in the Near-Zone. The topography of orbits is quite different for small values of initial radius R_o, as is shown for R_o = 1, $\Theta_o = 7o^o$ and Δt = 2 (with linear scale) in figure 5. Here, trajectories originating from a certain range of ϕ_o do not eventually recede but finally hit the pulsar surface in one of the two polar regions (protons originating from corresponding initial positions of the other hemisphere would eventually reach the opposite polar region).

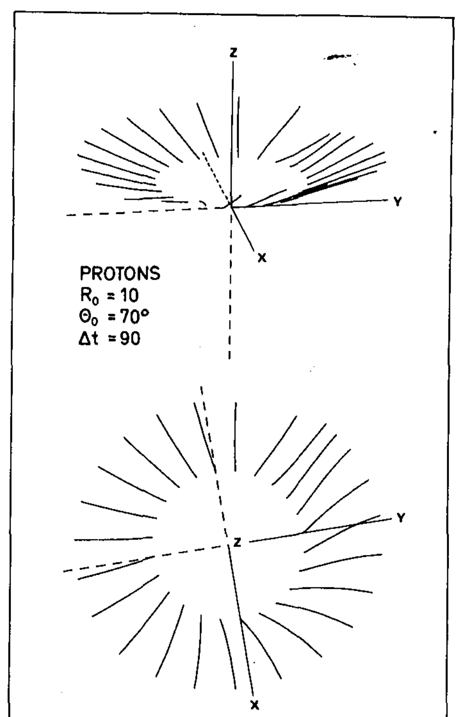


figure 4

6. Critical Surface. Obviously, for each pair of given initial latitude Θ_o and longitude ϕ_o there is a critical initial radius $R_c = R_c(\Theta_o, \phi_o)$, which is the minimum of all initial radii $R_o \geqslant R_c$ such that tra-

jectories starting from (R_o, Θ_o, ϕ_o) run to infinity. Thereby a critical surface is defined (for parameter values as specified in model 1) which is illustrated by figure 6 in a perspective view (The largest radius is about $R_c = 2$).

References. H.Laue, K.O.Thielheim: Kleinheubacher Berichte No. 28(1985).Astrophys.Space Sci.(1985),submitted for publication.

J.Marotzke,K.O.Thielheim:unpublished(1985).

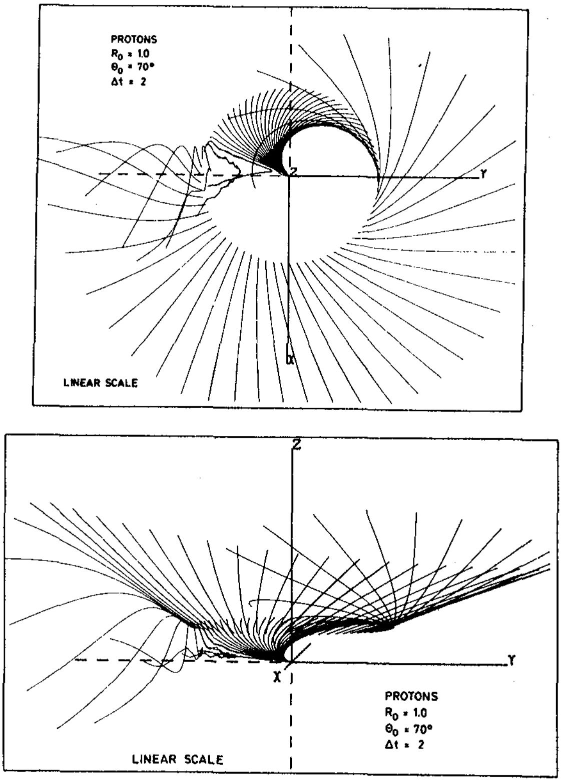


figure 5

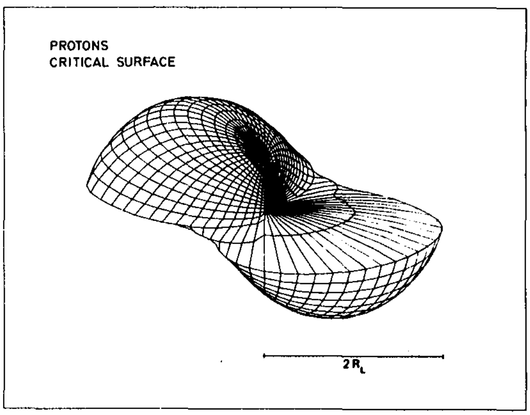


figure 6