# PULSARS AS COSMIC RAY ACCELERATORS: ENERGY DEVELOPMENT OF PROTONS

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ABSTRACT

Results of numerical integrations of the Lorentz-Dirac-equation with Landau-approximation for protons in the electromagnetic vacuum field of a magnetic dipole rotating with its angular velocity $\vec{\omega}$ perpendicular to its magnetic moment $\vec{\mu}$ will be discussed with special attention to the energy development of protons.

## 1. Introduction.

Numerical data on the orbital motion of protons discussed in the proceeding paper also give information on the development of proton energy and may therefore be helpful in discussions about pulsars as possibly accelerators of high energy cosmic ray particles. Present results were obtained under the specifications of our model 1 and are intended to illustrate some of the general features observed in particle acceleration by rotating magnetic dipoles.

## 2. Maximum Energy of Protons originating from the Distant Zone.

As I have shown before, protons starting from $R_o$ = 1o (in units of light radius) move outwardly more or less in radial direction. Still the maximum value of energy they achieve during the first 9o units of time (corresponding to 14.3 revolutions of the magnetic dipole) depends strongly on both, the initial latitude $\Theta_o$ as well as the initial longitude $\phi_o$. This can be seen from figure 1 showing the maximum value of energy (precisely: the maximum value of the Lorentz factor $\gamma$ in a logarithmic scale) within the time interval under consideration for various values of initial latitude ($\Theta_o$=1o$^o$, 25$^o$, 4o$^o$, 55$^o$, 7o$^o$ and 85$^o$) as a function of initial longitude $\phi_o$. It should be noted that not always the final energy equals the maximum energy. Protons starting near the axis of ration (e.g. from $\Theta_o$ = 1o$^o$) practically all have the same maximum energy (which under the assumptions of model 1 is about 1o$^{5.2}$ times their rest energy). In contrast to this behaviour, protons starting near the equator of rotation (e.g. from $\Theta_o$ = 85$^o$) obtain maximum values of energy, which may differ by a factor up to about 1oo depending on their initial value of longitude

$\phi_o$. Largest values of maximum energy correspond to initial positions of maximum (electric as well as magnetic) field strength for t = o. This is already an indication to the fact that particles in general experience a very strong acceleration in their earliest stages of orbital motion which thereby become decisive also for what the final energy of the particles will be.

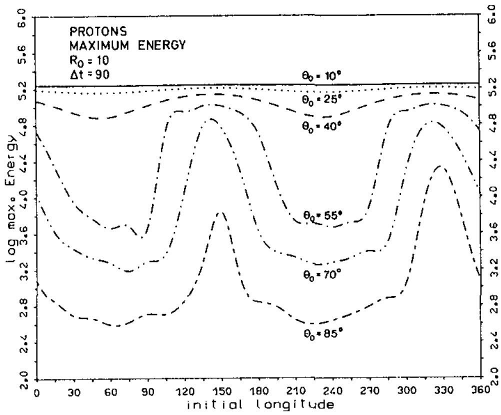


figure 1

## 3. Development of Energy of Protons originating from the Distant Zone.

This is further illustrated by figure 2 showing the energy development of protons starting from $R_o$ = lo as a function of time (On a log (1 + t) scale) for four orbits starting near the equator of rotation ( $\Theta_o = 85^o$) at various values of initial longitude ( $\phi_o = o^o, 165^o, 135^o$ and $33o^o$). On any of these orbits a Lorentz-factor of about loo is reached already within the first very small fraction of a unit of time ( $\omega^{-1}$). But otherwise there are different features visible in these orbits: Two of them ( $\phi_o = o^o$ and $165^o$) exhibit a considerable oscillation of energy before the latter ap - proaches what appears to be a limiting value. Particle motion in these cases obviously is drift dominated and the energy

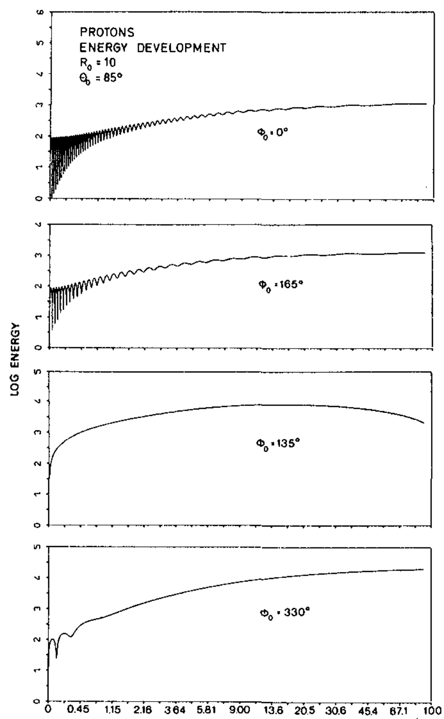


figure 2

oscillations reflect particle gyrations in a region of field where the electric and magnetic field vectors to a very good degree are perpendicular to eachother. The characteristics of the other two orbits are different. For $\phi_o = 135^o$ e.g. energy increases monotonically during the first stages of orbital motion. This can be explained by the presence of a considerable component of the electric vector parallel to the magnetic field vector on this part of the orbit under consideration.

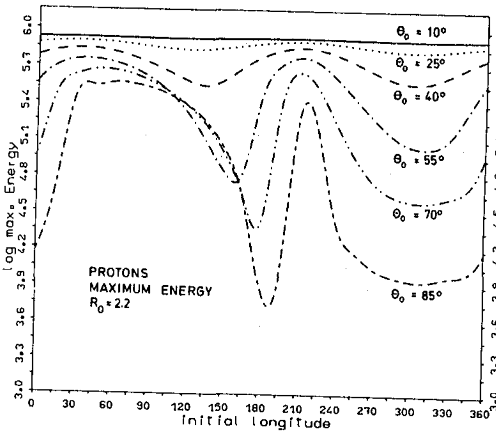


figure 3

## 4. Maximum Energy of Protons originating from the Transition Zone.

The maximum value of energy reached during the first 3o units of time (corresponding to 4.8 revolutions of the dipole) by protons originating from $R_o = 2.2$ at various values of initial latitude ( $\Theta_o$ = 1o°, 25°, 4o°, 55°, 7o° and 85°) is shown as a function of initial longitude $\phi_o$ in figure 3. Again the maximum value of energy is practically the same for all protons starting near the axis of rotation (e.g. $\Theta_o$ = 1o°) amounting to about $10^{5.9}$ times proton rest energy. But otherwise maximum energy of protons starting nearer to the equator of rotation (e.g. $\Theta_o$ = 85°) strongly depends on the initial value of longitude $\phi_o$.

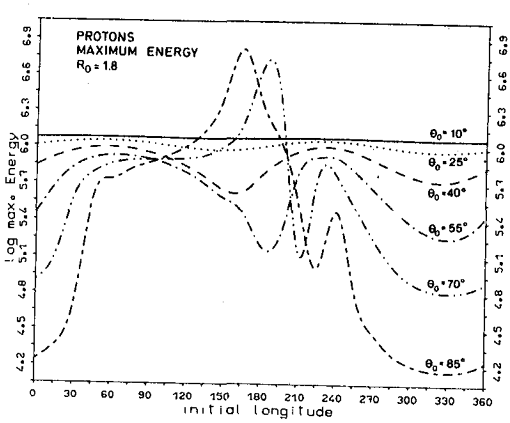


figure 4

The asymmetry in the maximum - minimum structure of the dependence of these curves from initial longitude $\phi_o$ certainly indicates an increasing influence of the near-field contributions as one approaches the dipole.

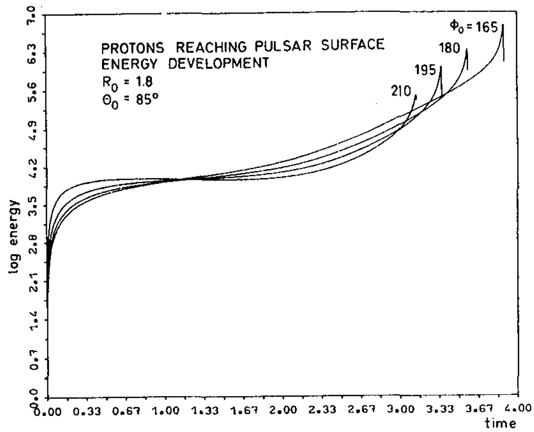


figure 5

5. Energy of Protons originating from the Near-Zone. Maximum energy of protons starting from $R_o$ = 1.8 within the first 3o units of time (or else before their radial distance from the dipole becomes smaller than lo km) is shown in figure 4 for different values of initial latitude $\Theta_o$ as a function of initial longitude $\phi_o$. Protons starting near the axis of rotation (e.g. at $\Theta_o$ = lo$^o$), which as has been shown receed from the dipole region more or less in radial direction, attain energy values of about lo$^{6.1}$ times their rest energy. Protons starting near the equator of rotation (e.g. at $\Theta_o$ = 85$^o$) within a certain region of initial longitude (around $\phi_o$ = 16o$^o$) which ultimately reach the lo km limit attain much higher energies about lo$^{6.8}$ times their rest energies. As I have demonstrated earlier, these protons are focussed to one of the polar regions.
The development of energy with time on these orbits some of which are shown in figure 5, is obviously quite different from the one discussed before. A very strong acceleration during the very first stages of orbital motion and the slow increase of energy in the succeeding stages are followed by a second regime of strong acceleration during which the energy again increases by a factor up to loo or even l.ooo. Ultimately, before the protons reach the lo km limit, their energy decreases sharply as they invade the polar region of extremely strong magnetic field strength (about lo$^{12}$G).