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Quantitative Analysis of the Role of Centrifugal Acceleration in a Rotating Magnetosphere Applied to Local time Variation of Jupiter's Equatorial Plasma Sheet

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Abstract

Dawn-dusk asymmetries of particle properties are far more extreme in Jupiter's magnetosphere than in Earth's. The asymmetric magnetic configuration of Jupiter's plasma sheet has been attributed to the action of centrifugal acceleration on particles whose bounce period is not short compared with the time for a flux tube to rotate from noon to dusk. The idea is that, as the flux tube rotates and stretches, bouncing particles responding non-adiabatically to the process gain energy efficiently from centrifugal acceleration. The process may lead to significant increase of the plasma β, which is expected to result in reconfiguration of the magnetic field. As a first step in understanding the effectiveness of this heating process, we have developed a model of a rotating magnetized plasma with a particle distribution representative of the bulk plasma of Jupiter's outer magnetosphere. We allow the flux tubes to expand as they rotate and use a Large Scale Kinetic (LSK) [3] approach to track the energy changes of the particles in the distribution. We demonstrate the response of the particle distribution and argue that our results support the proposed mechanism for plasma heating as a plausible explanation of the observed magnetospheric asymmetry at Jupiter.

1. Introduction

A striking aspect of the magnetic configuration of Jupiter's magnetosphere is the morning-afternoon asymmetry of the magnetic structure of the outer magnetosphere. The asymmetry is evident in plots (Figure 1) of magnetic field components and the total magnetic field measured by the Galileo magnetometer on near equatorial orbits at different local times. Evident from the plots is the systematic increase of the B_θ component of the field at fixed radial distance as local time increases in the dayside magnetosphere. The change of field configuration is similar to the rotation from stretched (tail-like) to dipole-like configurations observed during terrestrial substorms, a field rotation that would arise if the thermal energy of the bulk plasma increases significantly as a flux tube rotates through the afternoon sector. Kivelson and Southwood [2] have suggested that thermal energy can increase in a rotating plasma through the action of centrifugal acceleration on particles with bounce period comparable to or longer than the rotation time from noon to dusk. For these particles, the second

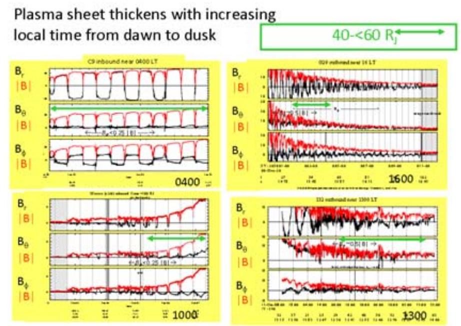

Figure 1: Three components (B_r, B_θ, B_ϕ) of the magnetic field at local times 0400, 1000, 1300, and 1600, increasing counterclockwise from the upper left. Green double arrows show distances from 40 to 60 R_J. The north-south (B_θ) component is seen to be a small fraction of the field magnitude (red traces in each panel) in the morning sector and become comparable with it in the afternoon sector,

adiabatic invariant is not conserved. The plasma sheet particles in Jupiter's dayside outer magnetosphere include many with energies and pitch angles for which bounce times are long compared with the time scale of flux tube expansion or contraction Thus one might expect that the plasma rotating from dawn to noon might cool somewhat and that in rotating from dusk to noon it would heat.

Conceptually, the argument regarding particle energization is plausible, but its relevance to the Jupiter plasma sheet requires quantitative confirmation. Here we report on a simulation [4] using a simplified model that confirms a significant increase of the thermal energy of a plasma rotating from noon to dusk on a flux tube that starts at 40 R_J and moves steadily outward to ~55 R_J in 5 hours. Although our simulation is not fully self-consistent, it confirms the expected net heating of the plasma.

2. The model

The field relevant to particles rotating from noon to dusk in Jupiter's magnetosphere is represented by an axially symmetric field based on Khurana's model [1] with B_ϕ =0 that slowly expands radially. We ignore azimuthal drifts negligible compared with rotational drift, which is set to half of corotation, thus 18˚/h.

The simulation starts with an isotropic Maxwellian at the equator. Using a LSK approach [3] we find the distribution vs. energy and pitch angle everywhere along a rotating flux tube (no expansion). Then we expand the rotating flux tube inferring the inductive electric field from Faraday's law. Particles, starting in many bins along the flux tube, are tracked for 5 hours. In order to establish what is special about the rapid expansion process, we establish how the distribution would respond adiabatically by running the same model with 100 times slower expansion.

3. Results

Whether adiabatic or not, stretching cools the bulk plasma and rotational forces produce significant anisotropy near the equator where a cigar-shaped pitch angle distribution develops. Figure 2 shows that rapid stretching increases the thermal energy of the plasma relative to the adiabatic case everywhere along the flux tube, although the distribution along the flux tube depends on the time step analyzed. Figure 3 shows the distribution of density along the flux tube. Because in the non-adiabatic case particles gain parallel energy more efficiently than in the adiabatic case, the density is more uniformly distributed along the flux tube in the former case.

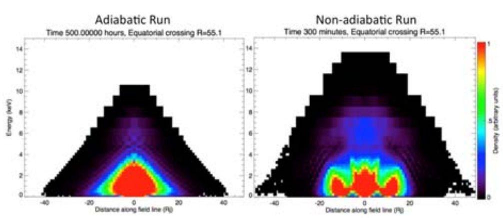

Figure 2: Final energy distributions for: slow, adiabatic (left) and fast (right) field stretching. Color represents density/equatorial density on a plot of energy vs. distance along flux tube (0 at equator).

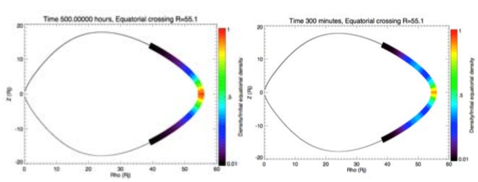

Figure 3: The ratio of density to equatorial density (color) along a flux tube stretched to 50.1 R_J for the adiabatic (left) and rapid (right) field-stretching cases.

4. Summary and Conclusions

We have demonstrated that a model mimicking the expansion of Jovian magnetospheric flux tubes between noon and dusk leads to non-adiabatic heating and modifies the distribution of density along the flux tube. The analysis is not self-consistent in its choice of the initial particle distribution and the field model, although this may not be a critical problem for analysis of a single flux tube. We ignore field bendback, effects of azimuthal particle drift on the field and pitch angle scattering of the anisotropic particle distribution. Nonetheless, by heating plasma sheet plasma, the mechanism can explain the thickening of the Jovian plasma sheet near dusk.

Acknowledgements

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