Modelling of Jupiter's Innermost Radiation Belt

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Abstract - In order to understand better source and loss processes for energetic trapped protons near Jupiter, a modification of de Pater and Goertz' [1990] finite difference diffusion calculations for Jovian equatorial energetic electrons is made to apply to the case of protons inside the orbit of Metis. Explicit account is taken of energy loss in the Jovian ring. Comparison of the results is made with Galileo Probe measurements.

Introduction

The Galileo Probe carried an energetic particle telescope for measurements in the innermost portion of Jupiter's radiation belt, down to the atmosphere, near the magnetic equator. Results from this experiment [Fischer et al., 1996] have clarified our understanding of the trapped energetic particle population in this innermost radiation belt, inside of the main planetary ring which is located inside of 1.81 R_j (Jupiter radii) [Ockert-Bell et al., 1999]. The ring region forms a barrier inside which energetic proton fluxes (62 - 131 MeV) were reduced by at least an order of magnitude [Fischer et al., 1996]. Here hypothetical characteristics for the innermost trapped radiation region of Jupiter are deduced and compared with Galileo Probe data in order to understand better source and loss processes for energetic protons there.

Model

Jupiter's innermost trapped radiation region is bounded below by Jupiter's atmosphere, and above by the main ring and its associated satellites Metis and Adrastea. An energetic trapped electron population, whose properties can be understood in terms of a standard radiation belt inward diffusion mechanism, conserving the first adiabatic invariant of the particles' motion [Birmingham et al., 1974; de Pater and Goertz, 1990], extends into this region from above. Galileo Probe results for this energetic electron population are discussed elsewhere [Fischer et al., 1996, 1997; Mihalov et al., 1998]. Inward diffusion should apply to protons also, and a decrease of their fluxes at the ring region can result from absorption by orbiting material, in particular the larger satellite Metis.

In the context of a model of proton inward diffusion, Metis [Thomas et al., 1998] (mean radius 21.5 km) introduces a filtering effect for equatorially trapped protons, as do the other Jovian satellites Simpson et al. [1974] have discussed this for the case of Io, Van Allen [1984] mentioned such a concept for the case of energetic electrons in Saturn's magnetosphere, with its system of satellites, and Paranicas et al. [1998] have employed such a model for part of Jupiter's trapped radiation region. 20 keV protons, which drift in longitude [Roederer, 1970] with about the same speed that Metis has relative to Jupiter's magnetic field, should be relatively unimpeded. Thomsen et al. [1977] and Hood [1981] have used the following estimate for absorption time

$$\tau_a = \left(\frac{t_s(E)}{\alpha_D \alpha_L}\right)\left(\frac{\Delta L}{2r_m(E)/R_J}\right)$$

where for the present purpose t_s is Metis' revolution period relative to the drift of protons of energy E, α_D and α_L are factors to account for protons' bounce motions and mirror latitudes, respectively, ΔL is the range of magnetic shells which Metis can sweep during one revolution with respect to Jupiter's magnetic field and r_m is the sum of Metis' radius and the proton gyroradius. For protons trapped near the magnetic equator, $\alpha_D \sim 1$ and the energy dependence of τ_a is given by

$$\frac{t_s}{r_m} \propto \frac{1}{\left(r_M + C\sqrt{E}\sqrt{2m_0 + E}\right)\left(\frac{c_d}{m_0 + E}\left(2E + \frac{E^2}{m_0}\right) - c_M\right)}$$

where c_d is a constant factor in the expression for the proton drift speed, c_M is Metis' orbital angular speed relative to Jupiter's magnetic field, C is a constant, r_M is Metis' radius and m_0 is the proton mass (energy units). The asymptotic behavior of this ratio for large E is E^{-2}. Paonessa and Cheng [1985] discussed corrections for τ_a for situations where the gyroradius greatly exceeds the diameter of a sweeping satellite (in the case of Metis, for E >> 115 MeV). In that higher energy range the absorption time should increase beyond that given by the above estimates.

A diffusion calculation for equatorially mirroring protons based on that of de Pater and Goertz [1990] for energetic electrons is described in the Appendix. Hypothetical energetic proton populations in Jupiter's innermost radiation belt after inward diffusion past Metis have been obtained from such calculations and are discussed subsequently and compared with Galileo Probe results. Various fairly flat differential energy spectral forms have been assumed just inside Metis' orbit. The equations above suggest a 1/E energy spectrum just inside Metis' orbit, assuming a flat spectrum outside Metis' orbit.

Results

On Figure 1 the effect of varying ring densities by factors of 1/10 and 3 × on proton energy distributions calculated for a location just inside Jupiter's main ring are shown. A path length in matter of 0.010, 0.10 or 0.30 μ each time a proton traverses the densest portion of the ring plane, and a 1/E differential energy spectrum at the outer boundary of the calculations at L = 1.85 are assumed. For this Figure the computation is modified to illustrate the absorption effects better, by exaggerating the proton energy losses below 0.3 MeV as compared with correct values, which deepens signatures of the absorption. The absorption due to a uniform main ring appears at energies below 0.1 MeV, where the energy loss rate for protons in SiO_2 is greatest. The modeled energy spectra at higher energies at all locations inside the ring are similar. This agrees with Galileo Probe results, where a power law exponent of about -1.6 was measured at several locations inside the ring, although at those locations some contamination due to sensitivity to protons with energies above the planned experimental energy range penetrating the body of the Probe and entering the experiment from its rear is suspected. The trend of the densities as Jupiter is approached is given on Figure 3 below. The increases of the plotted curves on Figure 1 at the lowest energies are artifacts of the computations that represent populations of protons with degraded energy. In fact, for energies for which the path length through the ring exceeds the thickness within which the protons will lose all their energy, the proton density will be zero. These artifacts may be eliminated by extending the calculations to lower energies.

On Figure 2 are shown proton energy distributions calculated again for a location just inside the main ring, and for different values of the diffusion coefficient, D_{LL} (0.3, 7, 100 and 1000 $\times$ that for Figure 1). The intermediate value of the three ring densities from Figure 1 was used.

On Figure 3, peak directional proton fluxes (62 - 131 MeV) from the Galileo Probe inside Jupiter's main ring are compared with flux profiles for 100 MeV protons (arbitrary normalization) calculated as described above, for six different values of D_{LL}, and ~~three~~ four different radial dependences of D_{LL}. There is little effect of the ring at such high energies. The measured proton flux at the lowest altitude is reduced due to energy loss in Jupiter's atmosphere. The proton flux measurement at the highest altitude is within the absorption region associated with Metis, Adrastea and the main ring, and is increased because it does not lie outside the region affected by all the principal absorption effects.. The four intermediate measurements show an increasing trend with decreasing altitude which is the result of an estimated correction for stray coincidences that has not been applied previously. While the magnitude of this correction is not well known it must be applied to some degree. The flux uncertainty due to counting statistics is ~ 2% and so is negligible. Corrections for responses due to protons penetrating the telescope from behind have not been made. The D_{LL} values used should span the range of plausible values but the rise of the proton fluxes with decreasing altitude is more rapid than the calculated curves and is not matched, which would suggest that a loss mechanism just inside Jupiter"s main ring and/or a source adjacent to the atmosphere have not been accounted for. However one may also be witnessing an effect due to changes of the energy spectrum at lower altitudes, such that at lower altitudes relatively more protons penetrate the telescope from behind and are counted. A steeper radial dependence of D_{LL} results in a steeper radial flux profile.

Summary

De Pater and Goertz' [1990] finite difference diffusion calculation for equatorial electron fluxes has been modified for the case of energetic protons inside Jupiter's main ring. Explicit account of energy loss in ring material is made. Results have been shown that should encompass plausible ranges of ring matter densities and diffusion coefficients and show the effect of energy loss in ring matter only at relatively low proton energies, below 1 MeV. Energetic proton data (62 - 131 MeV) from the Galileo Probe are also compared with results from the model. The comparison suggests that the proton flux may be rising more rapidly than the model shows, as altitude decreases, just outside the location where atmospheric absorption of the protons becomes dominant.

Appendix

De Pater and Goertz [1990] analyzed Jupiter's energetic trapped electrons using observed synchrotron emission fluxes and steady state finite difference solutions of the following convection-diffusion equation, derived from a continuity equation for phase space densities f of an equatorially mirroring (drift and bounce averaged) population [Schulz and Lanzerotti, 1974]:

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L} \left(\frac{D_{LL}}{L^2} \frac{\partial f}{\partial L} \right) - \frac{d\mu}{dt} \frac{\partial f}{\partial \mu} - \frac{f}{\tau} \quad (1)$$

The second term on the right hand side of equation 1 represents the flux due to energy loss of μ, the first adiabatic invariant (μ/γ is the particle magnetic moment); this term was introduced by Birmingham et al. [1974] who gave an explicit expression applicable for synchrotron radiation. In equation 1, L is a label for trapped particles' drift shells [Roederer, 1970], D_{LL} is a radial diffusion coefficient and τ is a lifetime for additional "local" loss; γ is the usual relativistic dilation factor. De Pater and Goertz [1990] calculated values of τ to account for pitch angle scattering of the electrons and for interactions of the trapped electrons with dust orbiting Jupiter. Also they deduced that electron losses due to collisions with the inner Jovian satellites, and to Coulomb scattering by neutral hydrogen in the magnetosphere were negligible.

In this paper finite difference solutions of equation 1 have been compared with proton fluxes measured by the Galileo Probe [Fischer et al., 1996]. Values of D_{LL} appropriate for ions in Jupiter's magnetosphere, and an energy loss term to represent the decrease in energy E experienced by protons passing through ring matter (SiO_2) localized in Jupiter's equatorial plane were used:

$$\frac{d\mu}{dt} = \frac{d\mu}{ds}\frac{\Delta s}{\Delta t} = \frac{E}{m_0 B_0 / L^3} \frac{dE}{ds} \frac{s}{t_b/2} \quad (2)$$

In equation 2, m_0 is the proton mass and s is the path length traversed in ring matter each time a proton crosses the ring plane. B_0 is a surface magnetic field strength introduced in order to facilitate computation of values for μ; a value of 4.26 G was adopted. Values of dE/ds, the rates of energy loss for protons in SiO_2 were obtained from the TRIM program (version 95.09; see Ziegler et al. [1985]). t_b is the proton bounce time [Roederer, 1970], given by

$$t_b = \frac{4r_0}{v} f(\alpha_0) \quad (3)$$

with r_0 the planet-centered distance at which the magnetic equator is crossed, v the proton speed, and $f(\alpha_0) \cong 0.74$ near the magnetic equator, where α_0 is the proton equatorial pitch angle. Pitch angle scattering that is associated with the energy loss is ignored.

Roederer [1970] noted that under some simplifying assumptions, and with appropriate scaling of the variable f, the quantity τ in equation 1 represents the loss time due to pitch angle scattering if the L^2 terms are changed to $L^{5/2}$. Also, there has been a persistent anticipation [Burns et al. 1984] that energetic particle measurements could provide significant new insights into the nature of the Jovian ring. Sufficient time resolution to directly reveal details of microsignatures [Van Allen, 1982] is not available in the Galileo Probe data. Future work may provide the result of assuming a distribution of values for the path length s in equation 2.

Equation 1 was solved as described by de Pater and Goertz [1990], except that the tridiagonal matrix solver from Press et al. [1992] was used. A logarithmic grid was used for μ. In setting up to numerically account for the flux of μ due to energy loss (the second term on the right hand side of equation 1), it is convenient to write that term in the form $K(L)\,H(\mu)\,f$. Using equation 2

$$K(L) = L^2 \qquad (4)$$

and

$$H(\mu) = \frac{E}{m_0 B_0}\,\frac{\sqrt{2m_0E + E^2}}{m_0 + E}\,\frac{dE}{ds}\,\frac{1}{f}\,\frac{\partial f}{\partial \mu} \qquad (5)$$

where

$$E = E(\mu) = m_0\left(\sqrt{1 + \frac{2B_0\mu}{m_0 L^3}} - 1\right) \qquad (6)$$

Here $H(\mu)$ has an implicit dependence on L but that is irrelevant.

The preferred functional form $D_{LL} \sim 10^{-10}\,L^4\,s^{-1}$, agrees with analyses of Voyager LECP data [Barbosa, 1994] as well as of the signature of Europa's absorption of magnetospheric ions [Paranicas et al., 1998], but is smaller by perhaps an order of magnitude and has a steeper radial dependence than values deduced previously for protons and sulfur and oxygen ions in the Io torus region [Schardt and Goertz, 1983; Cheng, 1986].

De Pater and Goertz' [1990] study of Jupiter's energetic electron fluxes found that the "local" loss term, not varying with radial distance and required to properly fit the synchrotron radiation data was characterized by a lifetime of $\tau \sim 1.5 \times 10^7$ s. For these calculations, the value for this lifetime was increased by a factor of 10^2.

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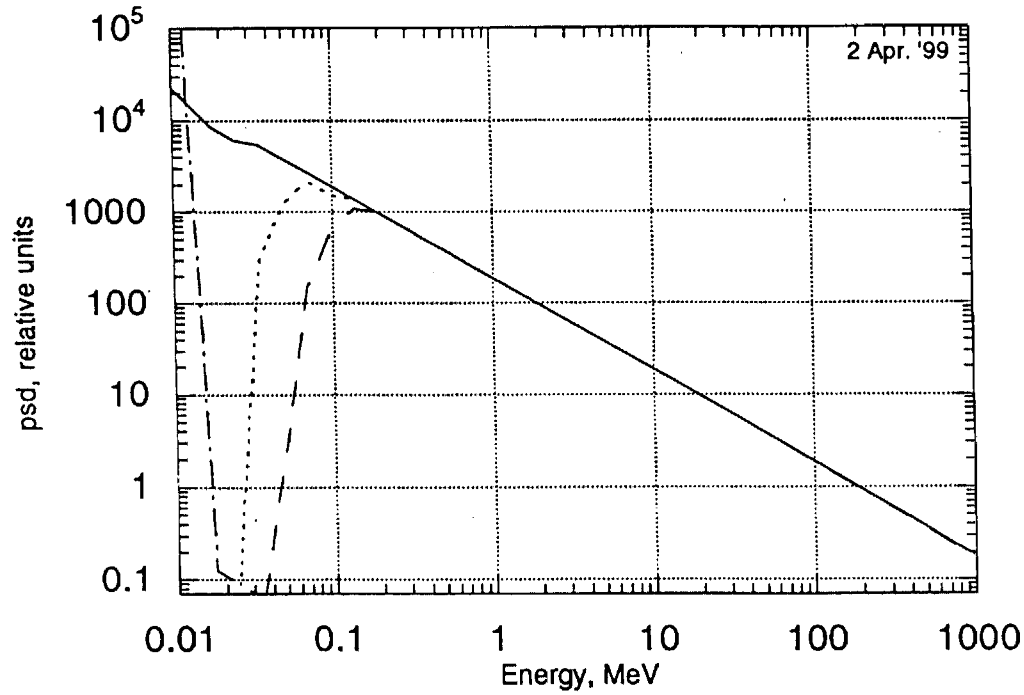
Figure Captions

Figure 1 - Proton energy distributions calculated at $L = 1.7$ for three different ring densities *(smallest, solid line; largest, largest dashes)* described in the text, and for $D_{LL} = 10^{-10} L^4 s^{-1}$. A 1/E differential energy spectrum at $L = 1.85$ was assumed.

Figure 2 - Proton energy distributions calculated at $L = 1.7$. Values of D_{LL} 0.3 (solid line), 7 (shortest dashes), 100 and 1000 × (longest dashes) that for Figure 1 were used.

Figure 3 - Peak directional proton fluxes (62 - 131 MeV) plotted as crosses within circles against magnetic shell parameter values (L) from the VIP4 magnetic field model [Connerney et al., 1998]. Profiles of 100 MeV proton flux (equatorial, arbitrary normalization) calculated for six different values for D_{LL} (top), and for four different radial dependencies for D_{LL} (bottom) are also shown. The factors by which D_{LL} is changed from the value used for Figure 1 (smallest dashes) are given on the top panel. On the bottom panel, the exponent n for $D_{LL} = 10^{-9} L^n s^{-1}$ for the calculated profiles, is 7, 5, 4 and 3,. from top to bottom.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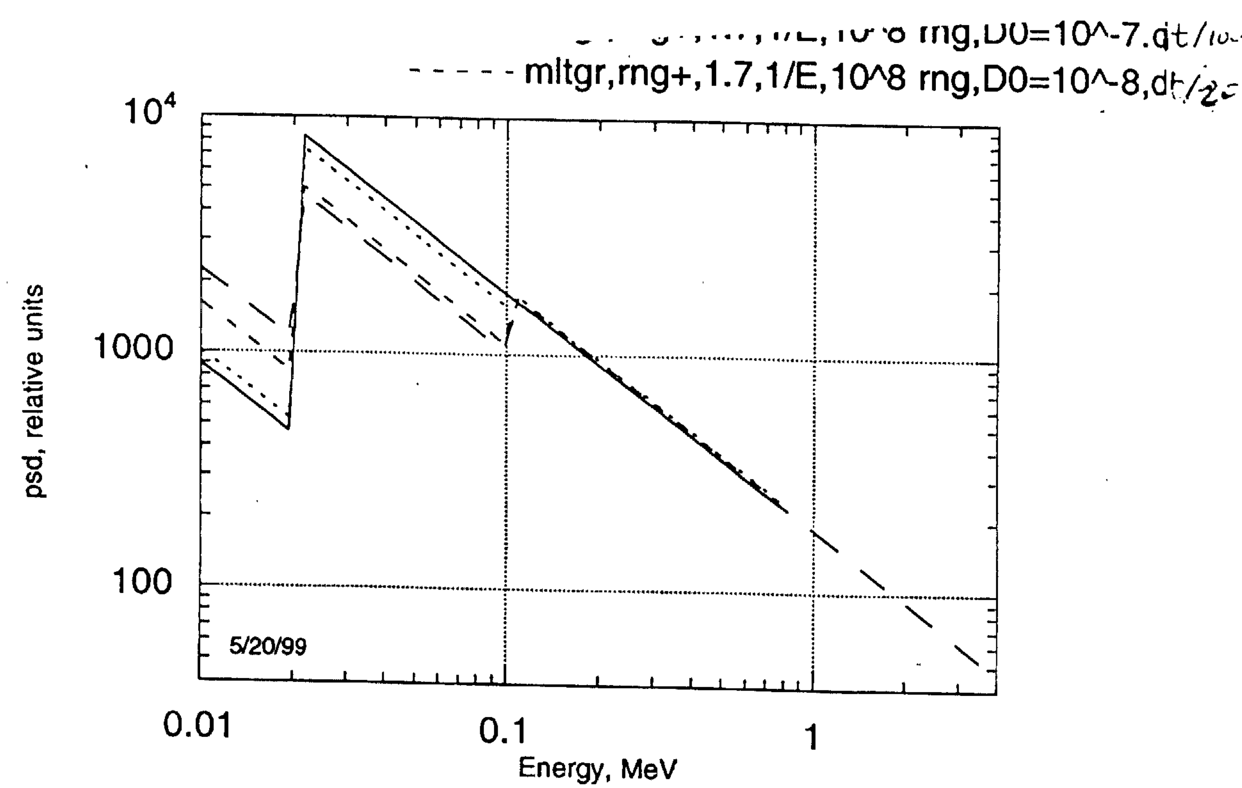

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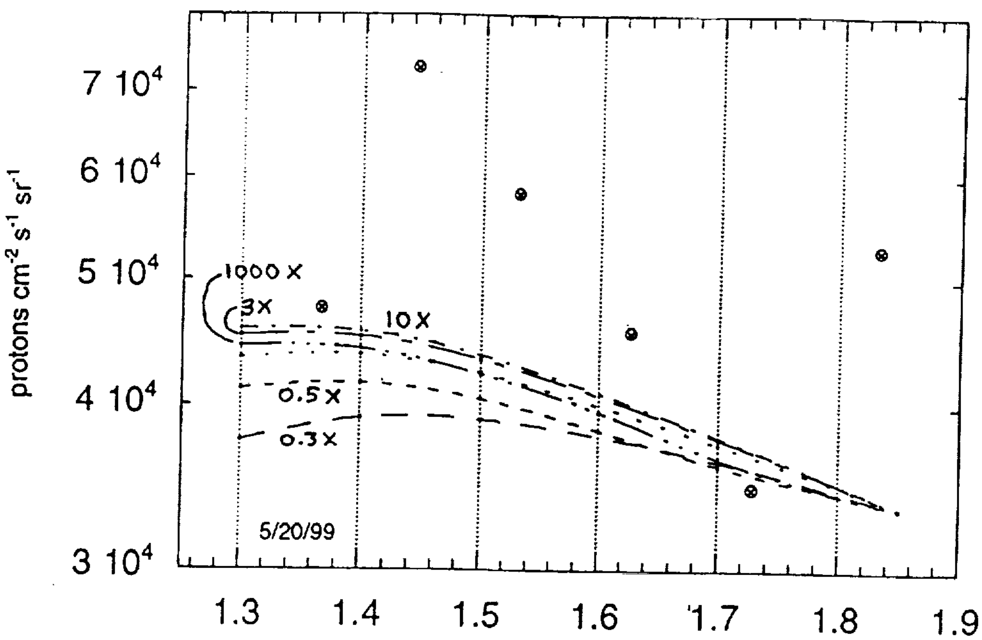
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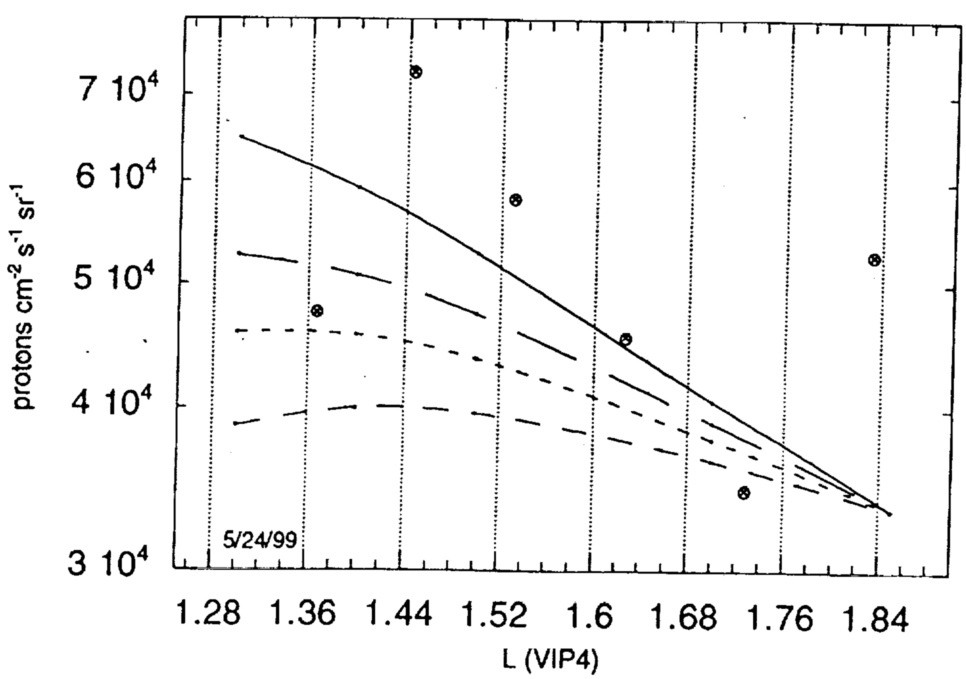
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