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Electron anisotropies in the inner heliosphere: a theoretical perspective

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Ulysses observations have indicated the presence of low-energy electron ‘jets’ with extraordinary anisotropies off the equatorial plane as far as 2.2 AU from Jupiter. Jovian electron ‘jets’ were also observed during Ulysses’ first encounter with Jupiter in 1992 and still needs a satisfactory explanation. These observations are a very interesting feature of the Jovian electron intensity-time profiles and are important in evaluating and testing propagation and modulation models. For this work, we revisit the basic modulation theory of what processes may cause anisotropies from a global modulation point of view and to what extent they contribute in understanding the mentioned observations. Emphasis is placed on the role that large polar perpendicular diffusion plays in establishing a large electron anisotropy in the inner heliosphere.

1. Introduction

It was discovered by the Pioneer 10 spacecraft (e.g., [16]) and firmly established by the Voyager spacecraft [18] and the recent Jupiter fly-bys of the Ulysses spacecraft [8,9,11] that the Jovian magnetosphere, located at ~5.2 AU in the ecliptic plane, is a relatively strong local source of electrons with energies up to ~30 MeV. Ulysses has sampled the inner heliosphere up to 80° off the ecliptic plane continuously since its launch in Oct. 1990. During this time the Jovian electron intensity has varied significantly with changing heliomagnetic distance to Jupiter and with changing solar activity.

In 1992 and 2004, Ulysses had encounters with Jupiter allowing the study of the propagation of electrons originating from this ‘point’ source in the inner heliosphere. The closest approach to Jupiter was 0.003AU (6RJ) in 1992 and 0.803AU (1682RJ) in 2004. These observations are important in evaluating and testing propagation and modulation models. Jovian electron ‘jets’ were observed during both encounters in the 3–10 MeV range as events with sharp increases and decreases, a strong field-aligned anisotropy, and durations of up to a few hours. They were observed as far out as 2.2 AU from the planet in 2004. After the 1992 flyby ‘jets’ had also been observed at distances of 0.6 AU from Jupiter, and at north-south displacements of almost 0.5 AU, implying direct magnetic connection to Jupiter over these distances. They were first described by Ferrando et al. [3], and Simpson et al. [16]. These ‘jets’, as McKibben [12], McKibben et al. [13] and Kunow et al. [11] noted, seem to be coming directly along flux tubes from Jupiter with an evident Jovian rotation modulation and with ~10 having a significant anisotropy, making their identification as Jovian electrons quite convincing - see also Heber et al. [this proceedings].

The physical process producing electrons within the Jovian magnetosphere and how jets are produced is not well understood, and requires a further in-depth study, in particular on the physics of the production and the distribution of electrons in the plasma-sphere and magnetosheet of Jupiter, and how the interplanetary magnetic field connects to the huge Jovian magnetosphere. During Ulysses' recent distant flyby its trajectory was such that direct magnetic connection to Jupiter was unlikely for a standard spiralling interplanetary magnetic field, implying that large deviations from a Parker-type spiral connecting to Jupiter, extending over many degrees of latitude, are not uncommon. Confinement of the particles (with a large anisotropy vector) to individual flux tubes implies that diffusion out of the tubes is weak. This is important information for how polar transport of low-energy particles may happen and how large it may be. For a theoretical review of perpendicular diffusion, see e.g. [1].

The main purpose of this work is to study theoretically the role that perpendicular diffusion in the polar direction plays in determining the electron anisotropies in the inner heliosphere for both galactic and Jovian electrons. It will be followed by comprehensive numerical computations.

2. Model and basic theory

The electron observations led to the development of new fully 3D steady-state models by solving Parker's [15] transport equation numerically [4,7]. This equation adequately describes the global transport and modulation of low-energy Jovian and galactic electrons in the heliosphere. The models provided insights into modulation parameters, particularly the radial and the latitudinal transport coefficients for low-energy electrons. It also produced solutions compatible with the 3-10 MeV electron observations during minimum to moderate solar activity conditions [4,5,6]. For the period after 1998, as solar activity increased to maximum conditions, the model solutions deviated significantly from observations [6,14]. This discrepancy suggested a consistent change in modulation parameters with increasing solar activity, in particular related to V and to perpendicular polar diffusion because at these low energies the electron modulation is insensitive to drifts [4]. Ferreira et al. [5,6] illustrated the importance of perpendicular diffusion and showed, for example, that the reduction in the enhancement of perpendicular diffusion with increasing solar activity seems required, correlated with changes in the latitudinal dependence of V with increasing solar activity.

The work is based on the numerical solution of the steady-state transport equation [15]:

$$\left(\mathbf{V}+\langle \boldsymbol{v_D}\rangle\right)\cdot\nabla f-\nabla\cdot\left(\boldsymbol{K}_S\cdot\nabla f\right)-\frac{1}{3}\left(\nabla\cdot\mathbf{V}\right)\frac{\partial f}{\partial \ln P}+Q=0, \tag{1}$$

where $f(\boldsymbol{r},P,t)$ is the cosmic ray distribution function; P is rigidity, $\boldsymbol{r}$ is the vector position, t is time, and $\boldsymbol{V}$ is the time-average solar wind velocity. The tensor $\boldsymbol{K}_S$ consists of a diffusion coefficient parallel ($K_{||}$) and perpendicular ($K_{\perp}$) to the averaged background heliospheric magnetic field (HMF). Terms on the right hand side represent convection, gradient, and curvature drifts, diffusion, adiabatic energy changes, and the Jovian electron source function Q, respectively [3]. The averaged guiding centre drift velocity for a near isotropic cosmic ray distribution is given by $\langle v_D\rangle=\nabla\times(K_A\mathbf{e_B})$, with $\mathbf{e_B}=\boldsymbol{B}/B_m$, where B_m is the magnitude of the modified background HMF; K_A is the diffusion coefficient describing gradient and curvature drifts in the large scale HMF, specified by the anti-symmetric elements of the generalized diffusion tensor $\boldsymbol{K}$. For the diffusion coefficients we have the general expressions:

$$\begin{aligned}
&K_{rr}=K_{||}\cos^2\psi+K_{\perp r}\sin^2\psi, K_{\theta\phi}=K_A\cos\psi\\
&K_{r\phi}=(K_{\perp r}-K_{||})\cos\psi\sin\psi=K_{\phi r},\\
&K_{\theta\theta}=K_{\perp\theta}, K_{r\theta}=-K_A\sin\psi, K_{\theta r}=K_A\sin\psi,\\
&K_{\phi\phi}=K_{\perp r}\cos^2\psi+K_{||}\sin^2\psi, K_{\phi\theta}=-K_A\cos\psi.
\end{aligned}$$

The three-dimensional (3D) steady-state electron modulation approach [3,4,5,12] involves a reassessment of all the diffusion coefficients, especially in latitudinal and azimuthal directions, to fully understand the distribution of electrons as produced by the Jovian magnetosphere.

The anisotropy vector is defined as $\xi=3\boldsymbol{S}/(4\pi p^2 f)$, with $\boldsymbol{S}$ the streaming vector and $\psi=\tan^{-1}\left[\Omega\left(r-r_S\right)\sin\theta/V\right]$ the angle between the radial direction and the average HMF direction, Ω is the Sun's rotation speed, and r_s the Sun's radius, θ is the polar angle and V the solar wind speed. For a typical Park-type spiral, $\psi\sim 45°$ at Earth, but $\psi\rightarrow 90°$ beyond 10 AU, and $\psi\rightarrow 0°$ at the poles. In spherical coordinates (r, θ, φ), $\boldsymbol{S}$ has the three components:

$$S_r = -4\pi p^2[(K_{\parallel}\cos^2\psi + K_{\perp r}\sin^2\psi)\frac{\partial f}{\partial r} - \frac{K_A\sin\psi}{r}\frac{\partial f}{\partial\theta} + \frac{(K_{\perp r} - K_{\parallel})\sin\psi\cos\psi}{r\sin\theta}\frac{\partial f}{\partial\phi} + \frac{V}{3}\frac{\partial f}{\partial\ln p}],$$

$$S_\theta = -4\pi p^2[K_A\sin\psi\frac{\partial f}{\partial r} + \frac{K_{\perp\theta}}{r}\frac{\partial f}{\partial\theta} + \frac{K_A\cos\psi}{r\sin\theta}\frac{\partial f}{\partial\phi}],$$

$$S_\phi = -4\pi P^2[(K_{\perp r} - K_{\parallel})\sin\psi\cos\psi\frac{\partial f}{\partial r} - \frac{K_A\cos\psi}{r}\frac{\partial f}{\partial\theta} + \frac{(K_{\perp r}\cos^2\psi + K_{\parallel}\sin^2\psi)}{r\sin\theta}\frac{\partial f}{\partial\phi}].$$

With these streaming components, the anisotropy vector components can easily be calculated.

3. Results and discussions

The contribution of the diffusion coefficients $K_{\phi r} = K_{r\phi}$ can be considered "correction" terms which marginally reduces the radial and azimuthal gradients of cosmic rays. In order to calculate and interpret the three corresponding anisotropy components given above, we assume that for Jovian and low-energy galactic electrons drifts become negligible i.e. $K_A \rightarrow 0$. This gives:

$$\xi_r = -\frac{3}{v}[g_r(K_{\parallel}\cos^2\psi + K_{\perp r}\sin^2\psi) - g_\varphi(K_{\perp r} - K_{\parallel})\sin\psi\cos\psi - CV],$$

$$\xi_\theta = -\frac{3}{v}[g_\theta K_{\perp\theta}],$$

$$\xi_\phi = -\frac{3}{v}[g_r(K_{\perp r} - K_{\parallel})\sin\psi\cos\psi - g_\varphi(K_{\perp r}\cos^2\psi + K_{\parallel}\sin^2\psi)],$$

with g_r, g_θ, and g_φ the radial, latitudinal and azimuthal gradients respectively; C is the Compton-Getting factor, and v the particle speed. It is evident that the low-energy latitudinal electron anisotropy is determined by the latitudinal gradient and $K_{\perp\theta}$. If we further assume that $K_{\perp r} \propto K_P$ [1] and that $K_{\perp\theta}$ increases significantly off the equatorial plane [10], together with the given that at lower electron rigidities $K_{\parallel}$ is an order of magnitude larger than for protons [2], we can argue that ξ_θ may totally dominate the anisotropy vector off the equatorial plane because $K_{\perp\theta}$ becomes very large. Since $K_P >> K_{\perp r}$ in the inner heliosphere, these anisotropy components for low-energy electrons become:

In general:

$$\xi_r = 3[CV - K_{\parallel}(g_r\cos^2\psi + g_\varphi\sin\psi\cos\psi)]/v,$$
$$\xi_\theta = 3[-g_\theta K_{\perp\theta}]/v,$$
$$\xi_\phi = 3K_{\parallel}[g_r\sin\psi\cos\psi + g_\varphi\sin^2\psi]/v.$$

Near Earth:

$$\xi_r = 3[CV - 0.5K_{\parallel}(g_r + g_\varphi)]/v,$$
$$\xi_\theta = 3[-g_\theta K_{\perp\theta}]/v,$$
$$\xi_\phi = 3K_{\parallel}[0.5(g_r + g_\varphi)]/v.$$

Near Jupiter:

$$\xi_r = 3[CV - K_{\parallel}(0.04g_r + 0.2g_\varphi]/v,$$
$$\xi_\theta = 3[-g_\theta K_{\perp\theta}]/v,$$
$$\xi_\phi = 3K_{\parallel}[0.2g_r + 0.96g_\varphi]/v.$$

Near the heliospheric poles:

$$\xi_r = 3[CV - g_r K_{\parallel}]/v,$$
$$\xi_\theta = 3[-g_\theta K_{\perp\theta}]/v,$$
$$\xi_\phi = 3[g_\varphi K_{\perp r}]/v.$$

In the outer heliosphere:

$$\xi_r = 3[CV - g_r K_{\perp r}]/v,$$
$$\xi_\theta = 3[-g_\theta K_{\perp\theta}]/v,$$
$$\xi_\phi = 3[g_\varphi K_{\parallel}]/v.$$

The Compton-Getting factor is:

$$C = -\frac{1}{3}(\frac{\partial\ln f}{\partial\ln P}),$$

in essence the spectral slope at different energies.

It follows that for electrons, ξ_θ is determined byeverywhere in the heliosphere; near Jupiter ξ_r is determined by $V, K_{\parallel}$ and mainly g_ϕ. In the outer heliosphere it is determined by V and $g_r K_{\perp r}$. Near Jupiter ξ_ϕ, with a significant enhancement towards the poles, indicates that the latitudinal anisotropy increases by a factor of ~10 over the first 20° off the equatorial plane from Jupiter.

Since all three gradients (e.g. at 10 MeV) for Jovian electrons must be relatively large close to Jupiter as a strong source, the anisotropy components will also be relatively large. This means that from a modulation point of view, a large anisotropy close to Jupiter should be expected. The question remains whether the very large observed values [12] can be fully explained by the known modulation mechanisms. This will be studied in future, using the 3D code mentioned above.

4. Conclusions

It follows that the latitudinal anisotropy for Jovian electrons is everywhere in the heliosphere determined by $g_\theta K_{\perp\theta}$, and it dominates the anisotropy vector off the equatorial plane because $K_{\perp\theta}$ becomes very large towards the poles. A simple calculation using typical values for the diffusion coefficient $K_{\perp\theta}$ [5, 6] with a significant enhancement towards the poles, indicates that the latitudinal anisotropy increases by a factor of ~10 over the first 20° off the equatorial plane from Jupiter.

Measuring the electron anisotropies can contribute significantly to improve the computation of the various diffusion coefficients, especially at lower energies (< 50 MeV).

Further study will be focused on understanding how much perpendicular diffusion contributes to the large Jovian electron anisotropy observed by Ulysses, and/or if it indicated modified diffusion owing to different interplanetary magnetic field geometry near the ecliptic at solar maximum, and/or it indicated scatter-free connections at these low energies between the HMF and the enormous Jovian magnetosphere. In the latter context, the observed large electron anisotropy near Jupiter may indicate that the basic diffusion coefficients are indeed large at low energies in step with theoretical predictions [1, 2, 4]. However, the question remains whether the large observed values [11, 12] can be fully explained by known modulation mechanisms.

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