Assessment of mechanisms for Jovian synchrotrons variability associated with comet SL-9

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Abstract. The impact of comet S1,9 with Jupiter induced a number of variations in Jupiter's synchrotron radiation; including a 20-30% increase in emission intensity, spectral changes, and a possible broadening in the latitudinal distribution of the emission. Here we consider the consequences of three potential mechanisms for inducing such effects; namely electron acceleration, radial diffusion and pitch-angle scattering. While none of the processes can be ruled out as insignificant, we show that pitch-angle scattering is consistent with all of the available radio frequency data and demonstrate that this could be due to realistic enhanced amplitudes of cyclotron resonant whistler-mode waves associated with the comet impacts. We suggest that the waves could result from electrical storm activity or be excited by natural instabilities of the electron distribution in Jupiter's radiation belts.

1. Introduction

Jovian decimetric emission is caused by the combined effect of the synchrotrons radiation originating from relativistic electrons trapped in Jupiter's inner radiation belts and thermal emission from the planet's atmosphere. The nonthermal component has a spectrum that is nearly flat in the decimeter band, but it extends well in to the microwave region where it overlaps the thermal component. Extensive studies of the nonthermal synchrotrons emission component have provided information on the properties of Jovian relativistic electrons and suggests they are trapped in a pancake pitch angle distribution (e.g., Carr, Desch and Alexander 1983). The peak emission originates within 0.25 Jovian diameters of the magnetic equator; this is close to the resolution of the best interferometer maps. A

Paper number .

small fraction of the emission originates from high latitude lobes near $\lambda \approx 40°$ at $L \gtrsim 2$. The spectral properties of incoherent synchrotrons radiation are sensitive to the energy E (MeV) and pitch-angle α of relativistic electrons, and to the ambient magnetic field strength B (Gauss). Each electron emits radiation with a power $P = 6 \times 10^{-22} E^2 B^2 \sin^2 \alpha$ over a well defined frequency range with a peak at

$$f_{max} = 4.8\, E^2 B \sin \alpha \text{ MHz} . \tag{1}$$

Typically, electron energies between 10 MeV-30 MeV are required to produce radiation (for wavelengths 6–60 cm) near the core of the observed synchrotrons zone at $L \approx 1.5$ where $B \approx 1 G$.

Conservation of the first adiabatic invariant requires $\sin^2 \alpha(\lambda) \sim$ B(A); the power emitted by each electron $P(\lambda) \sim B^3(\lambda)$ consequently increases with geomagnetic latitude λ attaining a maximum value at the magnetic mirror latitude λ_m where $\alpha = \pi/2$. Since electrons spend more time near their mirror point, the intensity of radiation received at Earth originates mainly from particles near their magnetic mirror latitude λ_m.

The tilt of Jupiter's magnetic field with respect to the rotation axis and the pitch angle distribution of trapped electrons contribute to a flux density beaming curve as the planet rotates. The beaming curve during the impacts showed two significant changes. The curve flattened out indicating an increase of emission from latitudes $\lambda > 10°$ implying a broadening of the pitch-angle distribution (Klein et al. 1995). From these characteristic changes in the beaming curve we predict the interferometric images to show a broadening in the latitudinal distribution of the emission near the equator. The beaming curves also indicate pronounced longitudinal "hot spots". The hot spots require a localized change in the trapped electron distribution. These asymmetries should disperse over a few gradient drift periods which is approximately 3 days for a 20 MeV electron at $L = 1.8$. Figure 1 shows the location of impacts as a function of both L and system III longitude, λ_{III}. The location of the impacts are grouped primarily in two regions, $L > 2$ at $0 < \lambda_{III} < 90$ and $L < 2$ at $120 < \lambda_{III} < 280$.

2. Theoretical Mechanisms for Synchrotrons Variability

Both the spectral changes and the increase in total emitted power following the impact of S1,9 could be caused by either an increase in the number or energy of relativistic electrons or an increase in the strength of the mirror point magnetic field. Below we explore the implication of such changes for three distinct scenarios. In each case we follow Thorne (1965) and assume that the equatorial relativistic electron distribution can be expressed in terms of a model distribution of the form

$$f(\alpha_0) = \sum_q a_q sin^q \alpha_0 \qquad (2)$$

which yields a radiation intensity $I_\nu = \sum_q a_q I_{\nu q}$

Examples of the angular distribution $f(\alpha_0)$ are shown in Figure 2 as a function of equatorial pitch angle α_0 for representative value of q. Since the radiation is dominated by electrons near their mirror point, an estimate of the latitudinal variation in emitted power can be obtained from the profile of $B_m^2 f_q(\alpha_0(\lambda_m)) \sim \sin^{q-4} \alpha_0(\lambda_m)$ as plotted in Figure 3. The pronounced equatorial confinement of the most intense emission feature requires a dominant component with $q > 5$. Note, however, that emissions originating at high latitude ($\lambda \gtrsim 30°$) require the presence of a less anisotropic component with $q \lesssim 4$. By choosing the weighting functions a_q, one can adopt a composite distribution consistent with synchrotrons emission polarization, beaming characteristics and spatial variations.

(a) Electron Acceleration

Local acceleration of synchrotron electrons to higher energy would both enhance the intensity of the emitted power and harden the spectrum since each electron would radiate at higher frequency (1). To explain the observed 27% increase in synchrotrons power at 13 cm (Klein et al. 1995) the average electron acceleration would have to be approximately 13%. Field aligned acceleration ($\Delta E_{\|}$) would require less overall energization since this would also tend to decrease the electron's pitch angle and thus increase the magnetic field strength at the mirror point. Field aligned acceleration would also tend to broaden the latitudinal width of the main emission region. The difficulty with this process is the identification of a viable mechanism which provides the energization over a few days and which affects the electrons trapped near the magnetic equator.

(b) Enhanced Radial Diffusion

Since the Jovian synchrotrons radiation belt is formed by a balance between inward radial diffusion and radiative loss, an increase in the rate of radial diffusion will cause the peak in the equilibrium flux to move to lower L. If such a change occurs on a timescale short compared to the radiative loss time, the first adiabatic invariant will be conserved and the average particle perpendicular energy $E_\perp \sim B$. Consequently the observed increase in radiation $(P \sim B^4)$ can be caused by a 6% increase in the average magnetic field. For a dipole field this would only require a modest 2% decrease (AL = -0.03) in the location of the peak electron flux, This could be accomplished by doubling the radial diffusion coefficient (Ip, 1995). The inward displacement of the synchrotrons electron belt during conservation of the first two adiabatic invariant would also increase the ratio $E_\perp / E_\parallel$. This would cause an increase in g and the synchrotrons flux received at Earth would therefore be more strongly confined to the equator in disagreement with observations.

(c) Pitch-Angle Scattering

Any enhancement in the rate of pitch-angle scattering will broaden the pitch-angle distribution (decreasing g) of trapped electrons. The observed increase in emitted power can be achieved by a modest 13% increase in the strength of the average mirror point magnetic field B_m. The observed broadening of the emitted radiation is also a natural consequence of changes in the electron pitch-angle distribution. This can be accomplished without any change in the energy content of trapped electrons. As an illustration of the effectiveness of enhanced pitch-angle scattering we utilize the detailed calculations of Thorne (1965) for the synchrotrons radiation intensity $I_{\nu q}$ from a distribution of the form (2). For simplicity we assume the pitch angle distribution to be represented by a single component. To conserve the total number of electrons we require that $\int_0^{\pi/2} a_q \sin^q \alpha d\alpha$ is conserved during pitch-angle scattering. Without loss of generality we equate each integral to unity to determine the change in the weighting coefficient $a_q = 2^{q+1} [\Gamma(q/2 + 1)]^2 / \pi\Gamma(q+1)$ when the index q is reduced. For any component in (2) the variation in the total intensity $\mathcal{I}_q = a_q I_{\nu q}$ associated with changes of q are listed in Table 1. The results have been normalized to the value for q = 20. A change in the pitch angle index q from 20 to between 6 and 10 accounts for the reported range of increase (20%–30%) in synchrotron power. This could be accomplished by a modest change in the average electron equatorial pitch angle $\Delta\alpha \approx 10°$ (Figure 2). Assuming that this reconfiguration occurs over a 6 day period, the required average rate of pitch-angle scattering $D_{\alpha\alpha} = \langle\Delta\alpha\rangle^2/2\Delta t \approx 2 \times 10^{-7} s^{-1}$. Since particle collisions are negligible, this scattering must be due to fluctuating plasma waves. In the following section we explore the consequence of cyclotron resonant interaction with whistler-mode waves that are known to be the dominant scattering mechanism for relativistic electrons in the terrestrial radiation belts (Lyons et al. 1972). We demonstrate that the observed changes in the synchrotrons spectrum could be caused by realistic wave amplitudes associated with the comet impact.

3. Cyclotron Resonance with Whistler-Mode Waves

First order cyclotron resonance between relativistic electrons and whistler mode waves occurs when 1 -- $n_*\beta =$ Y/7 where $n_* = \eta_{||}$ cos α, $\eta_{||}$ is the parallel component of the wave refractive index, $\beta = v/c$, $\gamma = (1 - \beta^2)^{-1/2}$, and Y = Ω_-/ω is the ratio between the gyrofrequency and the wave frequency. This yields a quadratic equation which can be solved for the relativistic resonant energy 7 = 1 + E/mc^2,

$$7 = \frac{\mathrm{Y} + n_*[Y^2 - (1 - n_*^2)]^{1/2}}{1 - n_*^2} \qquad (3)$$

For electrons mirroring near the equator $(\alpha = \pi/2)$, $n_* \approx 0$ and $\gamma \rightarrow Y$. Whistler mode waves with frequency between 130 kHz and 46 kHz would resonate with 10–30 McV electrons near the peak of the synchrotron zone at L = 1.5. The corresponding resonant frequencies would be a factor of 4 lower in the outer portion of the synchrotrons zone at L = 2.5. For any specified wave frequency the resonant energy can be significantly lower for electrons that mirror well away from the equator. The resonant energy is also controlled by the field aligned component of the wave refractive index $\eta_{||}$; this in turn is influenced by both the wave normal angle and the plasma density of the medium. The variation in resonant energy with equatorial pitch-angle is illustrated in Figure 4 for a realistic range of whistler mode refractive indices. Low values of $\eta_{||} \approx$ 1 are representative of low frequency waves in a tenuous plasma while higher values $\eta_{||}$ >> 1 would correspond to wave propagation in a dense plasma. Density changes can also influence access of waves to the synchrotrons zone. The plasma frequency $w_p = \sqrt{4\pi N e^2/m}$ establishes an upper limit for the frequency of whistler-rnode wave that can propagate in the inner Jovian magnetosphere. An increase in plasma density should enhance the access of higher frequency waves into the synchrotrons zone.

To estimate the average wide band wave amplitude B_w required to produce the broadening of the 20 MeV electron distribution near L = 1.5, wc equate our earlier estimate of $D_{\alpha\alpha}$ to the rate of pitch-angle scattering by whistlers (Thorne, 1983) $D_{\alpha\alpha} \approx$ (Q_ /7) $(B_w/B_0)^2$ to obtain $B_w \approx 80pT$. This is only slightly larger than the amplitude of naturally generated whistler mode waves in the inner terrestrial magnetosphere (Thorne et al., 1973); it is **also comparable to the** more intense whistlers produced by lightning discharges (Burgess and Inan, 1993). This give some assurance that similar waves could be present at Jupiter.

4. Discussion

A persistent mechanism is required to maintain the population of electrons with small equatorial pitch angles that produce the high latitude emissions prior to the comet impact. Such electrons radiate more efficiently near their mirror latitude and their lifetime in the synchrotrons zone is consequently much shorter than those near the equator. Pitch angle scattering by whistler-mode waves provides a natural mechanism to maintain this persistent high latitude population. Fluctuations in the whistler mode wave intensity or changes in the cyclotron resonant energy *(3)* due to changing plasma conditions could therefore be responsible (Bolton 1990) for the previously reported short term variations in synchrotrons radiation.

We have demonstrated that increased emissivity and broadening of the distribution of Jupiter's synchrotrons radiation following the impacts could result from an enhancement in the intensity of whistler mode waves. One potential source for this enhancement is lightning discharges associated with thunderstorm activity initiated by the comet impacts. Results from Voyager previously indicated the existence of Jovian lightning (Lewis 1980, Gurnett et al. 1979) and estimates of the power input by Jovian lightning suggest much stronger whistler amplitudes than at the Earth (Zarka 1994). Our preliminary results using a ray tracing code demonstrate that lightning generated waves originating at impact sites can readily gain access to the synchrotrons zone.

Alternatively, waves could be excited by natural instability (Kennel and Petschek 1966) of the highly anisotropic electron distribution in the inner Jovian magnetosphere. A marginally stable electron distribution could be driven unstable by a number of processes associated with the comet impacts. One possibility is the reduction in cyclotron resonant energy caused by an influx of thermal plasma from the Jovian ionosphere.

Since the power spectral density in whistler-mode waves should decrease at higher frequencies, the higher energy synchrotrons electrons should be subject to more effective scattering; the efficiency for scattering of any specific particle energy should also be higher for particles which mirror further from the equator (see Figure

4). The hardening of the spectrum is a natural consequence of the preferential scattering of electrons with higher energy and lower pitch angles. This should also be accompanied by an increase in circular polarization. The intensification of synchrotrons emissions at high latitudes also requires a larger flux of electrons with pitch angles near the edge of the loss cone ($\alpha_{LC} \simeq 45°$ at L=2). Enhanced wave intensity associated with the comet impact would therefore also cause scattering loss into the atmosphere. Rapid electron scattering might therefore be related to the intense X-ray bursts and ultraviolet emissions that were observed following the K impact, The particles responsible for observable precipitation effects probably have much lower energy ($\simeq$100 keV) and there should be ample trapped particle flux in the inner Jovian magnetosphere to accomodate the energy requirements of either process. The maximum precipitation rate occurs if the scattering wave amplitudes approach the level for strong diffusion: this requires $B_w \approx 10^3 pT$ for 100 keV electrons at L=3 (Thorne 1983).

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Figure 1. Locations of the comet fragment impact as a function of L shell (06 model, Connerney 1993) and λ_{III} longitude.

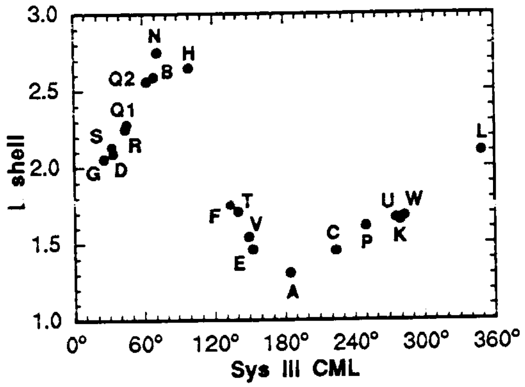
Figure 2. An illustration of changes in the electron distribution caused by pitch-angle scattering.

Figure 3. Relative emission intensity near λ_{m} for various values of q. Synchrotrons changes following the S1,9 impacts are consistent with a change in q from 20 to between 6 and 10.

Figure 4. Pitch-angle variation in the normalized cyclotron resonance energy for a representative range of whistler-mode refractive indices.

Table 1. Variations in Synchrotrons Intensity due to Pitch-Angle Scattering

9	a_q	$I_{\nu q}$	$\mathcal{I}_q = a_q I_{\nu q}$	$\mathcal{I}_q/\mathcal{I}_{20}$
2	1.27	27.4	34.8	1.90
3	1.50	19.6	29.4	1.61
4	1.70	15.7	26.7	1.46
5	1.88	13.3	25.0	1.37
6	2.04	11.7	23.9	1.30
8	2.33	9.60	22.4	1.22
10	2.61	8.25	21.5	1,18
16	3.24	5.97	19.4	1.06
20	3.60	5.09	18.3	1.00
25	3.98	4.30	17.1	0.93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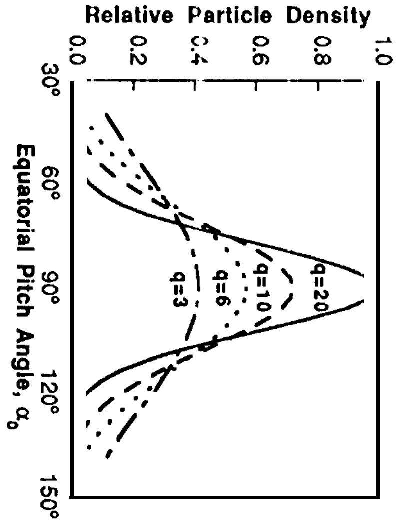
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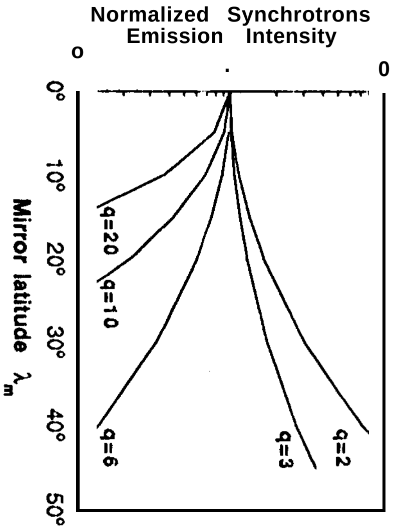
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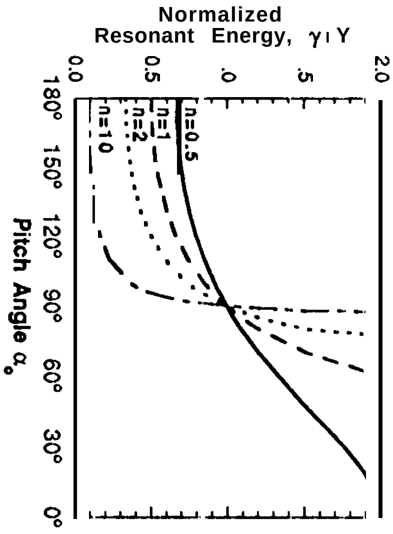
Normalized
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Pitch Angle α₀