UNDERSTANDING JUPITER'S RADIATION BELTS THROUGH OBSERVATION AND MODELING

S. J. Bolton* and R. M. Thorne†

Abstract

Jupiter's synchrotron radiation has been observed extensively over the last couple decades using primarily single dish operating at 2295 MHz to provide time variability and intensity information antennas [Klein et al., 1989] and occasionally using the VLA operating at 1400 MHz to obtain spatial distribution maps. The study of the synchrotron radiation characteristics and variations has provided substantial insight into the physical properties and processes of Jupiter's inner radiations belts. During 1994 a more intensive program was initiated to obtain data during the impacts of Comet SL-9 with Jupiter. The synchrotron radiation variation associated with the comet impacts include an emission intensity increase dependent on wavelength, longitudinal beaming curve distortions and a flattening of the latitudinal beaming curve. The observed changes have resulted in numerous theories on the responsible processes including pitch angle scattering by impacted stimulated plasma waves, increases in radial diffusion rates and/or the shock acceleration of electrons. The characteristics of the emissions will be reviewed along with a discussion on possible interpretations of the observed Comet SL-9 associated variations mentioned above.

1 Introduction

At frequencies above about 100 MHz, Jupiter's radiation belts generate an observable continuum of synchrotron radiation. The radiation belts have been the subject of numerous scientific investigations since their discovery in the late fifties using ground-based radio telescopes which observed the synchrotron emission. The trapped relativistic electrons assumed responsible for this emission were later confirmed with direct measurement by NASA spacecraft (Pioneer and Voyager). Early observations of Jupiter's synchrotron emission [Morris and Berge, 1962] revealed evidence of strong beaming and rocking of the plane of linear polarization as a function of Jovian longitude; these effects were interpreted

* *Jet Propulsion Laboratory, Pasadena, CA, USA*
† *University of California, Los Angeles, CA, USA*

as evidence for a tilt ($\sim 10°$) of Jupiter's dipole axis relative to the rotational axis. This was later confirmed by in-situ measurements of the magnetic field. Modeling by Thorne [1965] produced the first estimates of the distribution of relativistic electrons required to fit the beaming measurements and the observed polarization. Our understanding of the radiation belts has increased substantially since this early theoretical work primarily through the combination of observations from ground-based programs and data collected during spacecraft flybys. Previous studies have shown that synchrotron radiation can exhibit substantial spatial and temporal variability [Gerard, 1970b; Klein et al., 1989; Bolton, 1990]. However, knowledge of the physical mechanisms responsible for the long term spatial structure of the emitting electrons and their temporal variability is not possible without accompanying the data analysis with extensive modeling of the radiation belts and the synchrotron emission process.

A combination of observation and modeling analysis is necessary to relate characteristics of the synchrotron emission to the distribution of energetic electrons present in Jupiter's radiation belts. Fundamental to our understanding of the radiation belts is the detailed description of the electron distribution (both in energy and pitch angle) responsible for the synchrotron emission characteristics. The high order terms in Jupiter's internal magnetic field govern the observed changes in the synchrotron emission as Jupiter rotates. This is due to a combination of effects from beaming, loss cone geometry and the distribution of electrons. Determining the contribution from each of these components requires an elaborate model of the radiation belts and the emission mechanism and the solution is likely not singular. In the following sections we present how modeling in combination with observational results can be used to understand Jupiter's radiation belts and where the research stands today.

2 Background

The Jovian decimetric emission is caused by the combined emission of synchrotron radiation originating from relativistic electrons trapped in Jupiter's inner radiation belts and thermal emission from the planet's atmosphere. The synchrotron radiation component has been studied extensively and the existence of a long term variability has been established [Klein et al., 1989]. The combination of observations and theoretical analysis over the last few decades has led to an understanding of the physical details and characteristics of the synchrotron emission that are important for determining the physical description of Jupiter's inner radiation belts and magnetosphere. These characteristics are described

Figure 1: (plate, next page) VLA image of Jupiter's synchrotron radiation observed at 20 cm. Magnetic field lines corresponding to $L = 1.4$ and 2.5 are shown as well as an HST image of Jupiter centered and to scale. Note the presence of the emission originating at high latitude and near the equator. The high latitude emission is not originating from the same magnetic field lines as the equatorial emission. Emission originating from in front of the planet is not shown due to the overlay of the HST image.

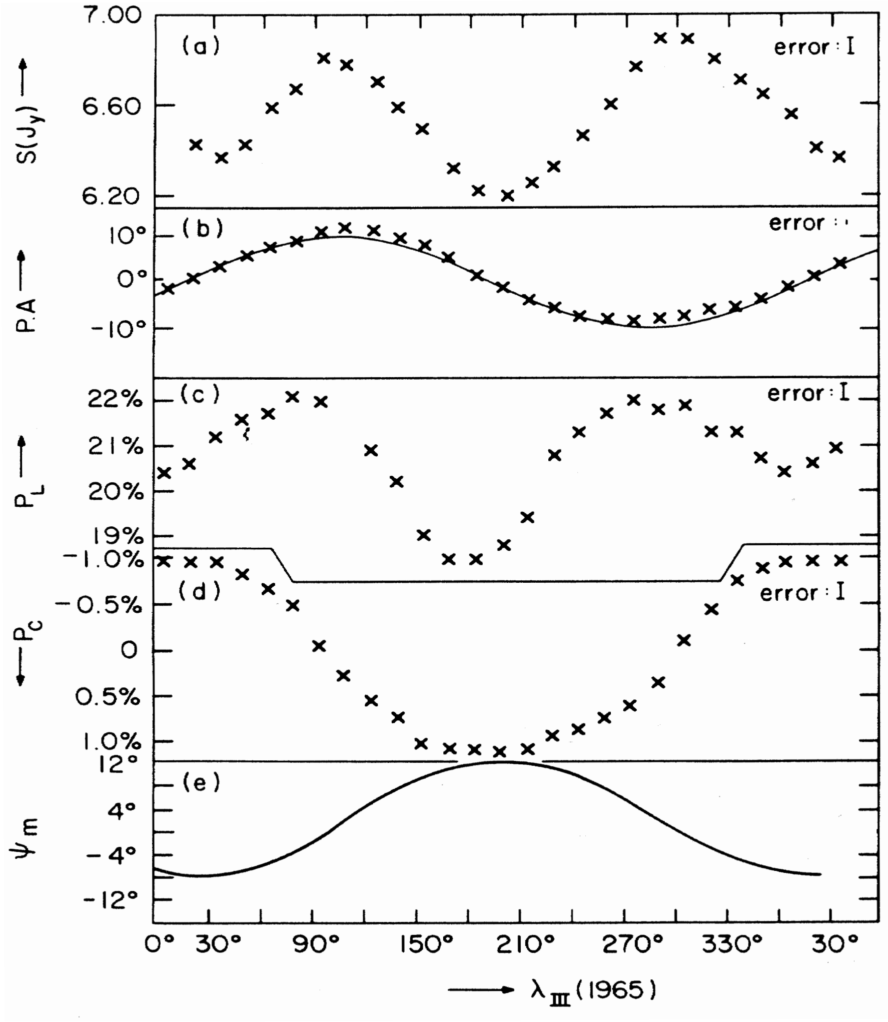

Figure 2: Examples of modulation of the synchrotron radiation due to Jupiter's rotation. The panels show total flux density S, polarization angle of the electric vector PA, degree of linear polarization PL, degree of circular polarization PC, and magnetic latitude of Earth.

in a number of reviews on the subject (e.g. Carr and Gulkis, [1969]; Berge and Gulkis, [1976]; Carr et al., [1983]) and are briefly summarized below:

- The synchrotron emitting electrons have a pancake like pitch angle distribution, with the peak of the emission at the magnetic equator distributed roughly 3 Jovian diameters wide east-west (See Figure 1).
- A small fraction of the emission originates from high latitude lobes (30–40 degrees latitude) between $2 \leq L \leq 2.5$.
- The tilt of Jupiter's magnetic field with respect to the rotation axis and the pitch angle distribution of the electrons contribute to the production of a "beaming curve". The emission is observed to vary as a sinusoid peaking twice during each rotation (see Figure 2).

- Jupiter's synchrotron emission is known to have a long term variation (months to years), possibly related to variations in the solar wind. There may also be short term variations (days to weeks).
- The emission contains a linear polarized component, amounting to 20–25% of the total intensity, with the remainder being largely unpolarized.
- The emission includes a weak circularly polarized component that alternates between right and left hand polarization as the planet rotates.
- The non thermal spectrum is nearly flat in the decimeter-wavelength band, but extends well into the microwave region where it overlaps the thermal component.

Jupiter's synchrotron emission has been monitored since 1971 as part of the Jupiter Patrol program using the NASA/JPL DSN antennas. These measurements have provided the primary evidence of a long term yearly variation [Klein et al., 1989]. Analysis of the data has indicated that the variations in the synchrotron emission are correlated with variations in the near-Earth solar wind [Bolton et al., 1989]. Close inspection of the Jupiter Patrol data and earlier observations by Gerard [1970b] suggest the possibility that short term variations (days to weeks) are also present in the synchrotron emission. The existence of variation on time scales short relative to the radial diffusion rates is an important clue to the types of processes present deep within the radiation belts.

During the impacts from comet SL9 in 1994 the Jovian synchrotron emission was observed to undergo a rapid dramatic change. This was considered absolute evidence that physical processes within the radiation belts can alter the synchrotron emission on very short time scales and a number of physical mechanisms were offered to explain the observations [Bolton and Thorne, 1995]. The comet's strong effects were the result of the impacts occuring in a region of the atmosphere coincident with the footprints of the magnetic field lines leading to the heart of the synchrotron emission zone (see Figure 3). This coincidence enabled the disturbances associated with the impacts to trigger a multitude of processes directly effecting the synchrotron emission [Bolton, 1997]. Implications of similar processes active during non-impact times are not evident, however, the presence of high latitude lobes in the emission implies that at least a process capable of changing the pitch angle distribution of electrons must be present deep within the belts. VLA images at decimetric wavelengths (Figure 1) indicate the presence of radiating electrons at high magnetic latitudes and the polarization and beaming characteristics (Figure 2) are

Figure 3: (plate, next page) VLA image of Jupiter's synchrotron radiation observed at 20 cm during the comet SL9 impacts. Magnetic field lines corresponding to $L = 1.4$ and 2.5 are shown as well as an HST image of Jupiter centered and to scale. The dark regions visible in the southern hemisphere of Jupiter's atmosphere indicate the locations of cometary fragment impacts from SL9. Note the magnetic field lines connect the comet impact locations to the synchrotron radiation zone. Emission originating from in front of the planet is not shown due to the overlay of the HST image.

also consistent with an electron pitch angle distribution that includes a substantial number of electrons that mirror at high latitude. Previous theoretical studies of synchrotron radiation variability [de Pater and Goertz, 1990, 1994] have not included non-equatorial particles, and traditional diffusion theory cannot explain the maintenance of pitch angle distributions as suggested by the observations. Such characteristics and short term variability could be associated with changes in the pitch angle distribution of the trapped radiating electrons due to resonant scattering with whistler mode waves [Bolton, 1990]. Waves could be stimulated either by electrical storms in the atmosphere [Lewis, 1980] or triggered by natural instabilities induced by the anisotropic pancake distribution of trapped electrons [Sentman and Goertz, 1978].

3 Physical processes effecting synchrotron emitting electrons

Inward radial diffusion from the outer Jovian magnetosphere is considered to be the dominant source for high energy electrons in the inner radiation belts [Coroniti, 1974; de Pater and Goertz, 1990]. However, the spatial distribution of the synchrotron radiation indicates that a substantial fraction of the emission originates at high magnetic latitudes, implying a significant population of electrons with pitch angles near the loss cone. The distribution of relativistic electrons in the Jovian synchrotron belts is controlled by a balance between radial diffusion, energy degradation and various loss processes. The electron phase space density $f(\mu, J, L, t)$, expressed in terms of the first ($\mu = p_\perp^2/2mB$) and second ($J = \oint p ds$) adiabatic invariants and magnetic L shell, is governed by the equation (e.g. Birmingham et al., [1974])

$$L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial t}\right) - \frac{\partial}{\partial \mu}\left(\left\langle\frac{d\mu}{dt}\right\rangle f\right) - \frac{\partial}{\partial J}\left(\left\langle\frac{dJ}{dt}\right\rangle f\right) - \sum_i \frac{f}{\tau_i} = \frac{\partial f}{\partial t} \qquad (1)$$

The first term describes the source of particles due to inward radial diffusion. Various models for the radial diffusion coefficient D_{LL} have been developed. In most previous studies an empirical form $D_{LL} \sim D_0 L^n$ has been adopted; values of $n \approx 3$ (indicative of diffusion driven by atmospheric winds) and $D_0 \sim (1 \div 4) \times 10^{-9}\text{s}^{-1}$ provide the most realistic fit to the observed synchrotron emission profiles [de Pater and Goertz, 1990; Ip, 1995]. The second and third terms in (1) describe the violation of the first two invariants due to the synchrotron emission process. Since a large fraction of the observed synchrotron emission originates near the equatorial region, corresponding to electrons with a pitch-angle distribution $f(\alpha)$ peaked near $\alpha = \pi/2$, it is usually assumed acceptable to ignore the third term (involving changes in J) and simply retain the term due to first invariant violation. For highly relativistic electrons, $\langle d\mu/dt\rangle \sim \mu^{3/2} L^{-15/2}$ [Coroniti, 1974]. This term is most important for higher energy electrons in the inner portion of the synchrotron zone. The last term on the right hand side of Equ. (1) is used to include the effect of local electron removal due to processes such as satellite sweeping [Mead and Ness, 1973; Mogro-Campero, 1976], collisions with dust in the Jovian ring [de Pater and Goertz, 1990], and pitch-angle scattering [Sentman and Goertz, 1978; Thorne, 1983] leading to loss to the atmosphere.

Realistic models have been used to describe both the radial diffusion of electrons and the change in μ and J caused by synchrotron radiation. Under steady state conditions, the spatial structure of synchrotron emission places severe constraints on the rate of radial diffusion (e.g. de Pater and Goertz, [1990]). Long term ($\sim$ years) variability of the emission [Klein et al., 1989] has been associated with changes in the solar wind [Bolton et al., 1989]. Such changes have been adequately modeled by allowing the electron phase space density to vary by some unspecified process in the outer Jovian magnetosphere [Coroniti, 1974; de Pater and Goertz, 1994].

There are, however, several important features of the synchrotron emission that remain poorly understood. Inward radial diffusion under the influence of satellite sweeping loss and enhanced radiative emission for electrons which mirror well away from the equator will naturally produce a "pancake" pitch-angle distribution that is strongly peaked near $\alpha = \pi/2$. As a consequence, the observed synchrotron emission should be strongly confined to a narrow region ($\lambda \leq 20°$) near the magnetic equatorial plane. In contrast to this expectation, the high latitude lobes in the reported VLA maps (see Figure 1) require the presence of a significant and persistent electron component that mirrors at high latitudes $\lambda > 30°$. This requires a persistent mechanism for pitch-angle scattering which will naturally drive the electron distribution towards isotropy and thus maintain a significant population that mirrors well away from the equator. The pitch-angle scattering mechanism should be dominated by plasma waves, since Coulomb scattering is negligible at synchrotron energies for realistic plasma densities in the inner Jovian radiation belts.

4 Pitch angle scattering of Jovian synchrotron electrons

Pitch-angle scattering of relativistic electrons in the Earth's inner magnetosphere is dominated by resonant interactions with naturally produced whistler-mode waves [Lyons et al., 1972]. These waves are thought to be generated by cyclotron resonant instability with ambient anisotropic electrons (e.g. Church and Thorne, [1983]; Huang and Goertz, [1983]). It has also been suggested that lightning generated whistlers could contribute to the scattering process [Burgess and Inan, 1993]. The plasma environment in the inner Jovian magnetosphere naturally provides the anisotropic pitch-angle distribution which is required for whistler-mode instability [Kennel and Petschek, 1966]. There is also ample evidence for Jovian lightning activity (e.g. Lewis, [1980]) on field lines that map into the synchrotron zone, and dispersed whistlers have been directly observed in the Jovian magnetosphere [Gurnett et al., 1979b]. A thorough understanding of the distribution of electrons requires a quantitative assessment of the rate of pitch angle scattering by both classes of whistler mode waves.

Energy transfer between waves and particles leading to pitch-angle scattering is most effective under cyclotron resonant conditions, which occurs when the wave frequency is Doppler shifted to a multiple (n) of the electron gyrofrequency Ω in the particle's reference frame.

$$\omega - k_{\parallel} v_{\parallel} = \frac{n\Omega}{\gamma} \tag{2}$$

First order ($n = 1$) cyclotron resonance between whistler-mode waves and relativistic electrons occurs when

$$1 - n_* \beta = Y/\gamma \tag{3}$$

where $n_* = \eta_\parallel \cos\alpha$, $\eta_\parallel = \frac{k_\parallel c}{\omega}$ is the parallel component of the wave refractive index, $\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$, and $Y = \Omega_-/\omega$ is the ratio between the gyrofrequency and the wave frequency. This yields a quadratic equation which can be solved for the relativistic resonant energy $\gamma = 1 + E/mc^2$,

$$\gamma = \frac{Y + n_*[Y^2 - (1 - n_*^2)]^{1/2}}{1 - n_*^2} \tag{4}$$

For electrons mirroring near the equator ($\alpha = \pi/2$), $n_* \approx 0$ and $\gamma \to Y$. Whistler mode waves with frequency between 130 kHz and 46 kHz would therefore be required to resonate with 10–30 MeV electrons ($\gamma = 21 \div 61$) 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 synchrotron 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 (namely those with an equatorial pitch-angle closer to the loss cone, i.e. as $\cos\alpha \Rightarrow 1$). The precise resonant energy is then also controlled by the field aligned component of the wave refractive index $\eta_\parallel$; this in turn is influenced by both the wave normal angle and the total plasma density of the medium.

Variations in plasma density N can modify the dispersive properties of whistlers and significantly change the conditions for resonant interactions with electrons that mirror well away from the equator. This could influence the natural instability of whistler mode waves that can be locally excited in the inner magnetosphere and also modify the ability of lightning generated waves to gain access to the synchrotron zone. The plasma frequency $w_p = \sqrt{4\pi N e^2/m}$ establishes an upper limit for the frequency of whistler-mode wave that can propagate in the inner Jovian magnetosphere. An increase in plasma density should enhance the access of higher frequency waves into the synchrotron zone. This will lower the threshold energy for resonance and thus allow more equatorially trapped electrons to come into resonance. Natural variations in plasma density could therefore lead to short term variability of synchrotron emissivity.

As an illustration of the average wide band whistler wave amplitude B_w that is required to produce significant scattering of the 10 MeV electron distribution near the equatorial region of the high latitude lobes at $L \approx 2.5$, we employ an earlier estimate for the rate of pitch angle scattering by whistlers [Thorne, 1983]

$$D_{\alpha\alpha} \approx \epsilon\,(\Omega_-/\gamma)\,(B_w/B_0)^2 \approx 1/\tau_{loss} \tag{5}$$

where ϵ is a parameter representing the fraction of the bounce orbit in cyclotron resonance and B_0 is the ambient equatorial magnetic field strength ≈ 0.15 G. Loss rates of $\tau_{loss} = 10^7$ s for $E_e = 10$ MeV have been inferred by de Pater and Goertz [1990] to account for the radial distribution of equatorial trapped electrons in the inner Jovian magnetosphere. For $\gamma = 21$ we estimate a whistler mode wave amplitude of $B_w \approx 45$ pT is required to obtain $\tau_{loss} = 10^7$ s. This wave amplitude is comparable to the amplitude of broadband hiss in the Earth's plasmasphere [Thorne et al., 1973]; it is also comparable to the more intense terrestrial whistlers produced by lightning discharges [Burgess and Inan, 1993]. The power input by lightning at Jupiter is thought to be much higher than at Earth. Realistic whistler-mode amplitudes could therefore account for the lifetime necessary to match radial diffusion solutions of de Pater and Goertz [1990]. Note, however, that the lifetimes would strongly depend on electron energy (due to the resonance condition) and therefore an accurate estimate requires detailed modeling.

5 Model simulations of Jovian synchrotron radiation

Although a large fraction of the observed synchrotron emission originates near the equatorial region corresponding to electrons with a "pancake" distribution, a portion originates from high latitudes requiring a more isotropic component of electrons. Early analysis of single dish observations described the distribution as $\sin^q \alpha$ [Thorne, 1965]. Later studies by Roberts [1976] suggest a two component bi-modal distribution described by

$$\frac{f(\alpha)}{f(\pi/2)} = Ak_a \sin^a \alpha + Bk_b \sin^b \alpha \tag{6}$$

The terms A and B are the fractional component of each distribution, k_a and k_b are normalization factors and a and b represent the degree of isotropy in the electron distribution. Roberts reported that the polarization and intensity characteristics of the emission were best fit using values of $A/B = 2.47$, $a = 1.14$ and $b = 45$ suggesting both a very isotropic and a very anisotropic component with the isotropic component being more numerous. Roberts assumed the bi-modal distribution described above was constant throughout the radiation belts. Maps from interferometers show the bi-modal distribution evolves from having a significant isotropic distribution near $2.5R_J$ to being dominated by a pancake anisotropic distribution near $1.5R_J$. This change to the distribution was in part confirmed by the Galileo Probe results [Fischer et al., 1996]. Figures 4 and 5 show simulations of the synchrotron radiation using a Roberts pitch angle distribution and bi-modal pitch angle distribution evolving to a more pancake like distribution at $R \leq 2.5R_J$. The simulations are calculated using the O6 magnetic field model [Connerney, 1993] and an electron energy

Figure 4: (plate, next page) Early model results showing simulated synchrotron emission from a bi-modal pitch angle distribution. This simulation uses the O6 magnetic field model and a bi-modal pitch angle distribution as described in Roberts [1976]. This simulation is for 0 degrees system III CML.

Figure 5: (plate, following page) Early model results showing simulated synchrotron emission from a bi-modal pitch angle distribution. This simulation uses the O6 magnetic field model and varies the pitch angle distribution from a larger isotropic component to a more equatorial confined component at $2.5R_J$. This simulation is for 0 degrees system III CML.

distribution described by Divine and Garrett [1983] ranging from 1 MeV to 100 MeV. Figure 4 indicates that although Roberts distribution fits the polarization characteristics well the radiation belts are not well described by a homogeneous distribution at $R \leq 4.0R_J$ (as Roberts used). In Figure 5 the simulated emission begins to appear similar to the high latitude lobes visible in the VLA observations shown in Figure 1. The high latitude lobes appear in approximately the correct place and the radiation sharply evolves to provide equatorial peaks near $R = 1.5R_J$. Because the appearance of the emission is also dependent on the loss cone geometry and the beaming is governed by Jupiter's non-dipolar magnetic field a comparison of model and observation is required to identify the true electron distribution present in the belts. The preliminary results shown in Figures 4 and 5 need to be further studied and the modeling comparison will have to include beaming curve and polarization analysis as well as total intensity estimation. The evolution of the distribution as a function of radial distance will provide important clues to the processing present in the belts.

The origin of the electron pitch angle distribution is dependent on a number of processes. The inward radial diffusion required to obtain the relativistic energies will enhance the equatorial mirroring component while conserving μ and J. This can produce a modest "pancake" distribution. The satellite sweeping will selectively remove electrons with $\lambda \geq 10°$. This can produce a strongly peaked distribution inside $L \approx 2.5$ which corresponds roughly to the orbit of Amalthea. Resonant scattering by whistler-mode waves can lead to a "stop hat" distribution if the waves are band limited in frequency. Sentman and Goertz [1978] applied this concept to explain the Pioneer observations of energetic electron distributions in the inner Jovian magnetosphere. Finally, synchrotron radiation will selectively degrade the electron energy which mirrors at high latitude due to the stronger magnetic field strength at the mirror point.

The simple bi-modal distribution used to generate Figure 5 produces the high latitude lobes and the equatorial peaks reasonably well. In Figure 5 the high latitude emission appears only near $L = 2.5$ even though the exact same distribution of electrons is present over the range $2.5 \leq L \leq 4.0$. The model indicates observable emission along the $L \approx 2.7$ magnetic field line which is not present in the real data indicating this simple distribution is not completely correct. We expect that the true distribution includes energy and density dependence on radial distance which is substantially more complicated than we presently model. This is consistent with the physical processes such as wave-particle interactions being both energy and density dependent.

6 Discussion

An accurate description of the high energy electron distribution present in the Jovian radiation belts can be determined from the comparison of the synchrotron radiation and models of the radiation belts. Previous studies reported modeling results which included the effects of satellite sweeping and synchrotron losses from equatorial electrons, and the pitch angle distribution required to fit the polarization and total intensity observations. Our early results indicate that a fit to the observational data requires a two component distribution dependent on radial distance. Our results also suggest that a change in pitch angle distribution between $2.5 \leq L \leq 4.0$ is not required to produce high latitude peaks solely at $L \approx 2.5$, however, more modeling is necessary to provide a definitive answer. The modeling results shown in the earlier sections present strong evidence that future modeling efforts must treat the full pitch angle distribution of the electrons as well as the energy and radial distribution to effectively simulate the emission. The dependence of the synchrotron emission characteristics on the magnetic field and loss cone geometry suggests detailed modeling will lead to an improved understanding of the internal magnetic field structure of Jupiter. This may have important implications to a wide variety of study including the interaction between the atmosphere and magnetosphere of Jupiter.

Acknowledgements: The authors thank S. Levin, and B. Bhattacharya for assistance with the early modeling results presented in this paper. A portion of the work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract to the National Aeronautics and Space Administration. The research was also supported in part by the NSF grant ATM 93 13158.