Divine-Garrett model and Jovian synchrotron emission

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Abstract. Simulations of synchrotron emission from relativistic electrons trapped in Jupiter's magnetic field are used to evaluate the energetic electron distribution of the Divine-Garrett Jupiter radiation belt model at radial distances less than 4 Jovian radii. The fundamental characteristic of synchrotron emission, narrow beaming from gyrating electrons, provides the basis for constraints on both the magnetic field and the distribution of particles in the inner magnetosphere. A comparison between model results and observations is presented. The results suggest the Divine Garrett model significantly underestimates the number of relativistic electrons (> 1 MeV) present in Jupiter's inner magnetosphere. The results also indicate that the pitch angle distribution of relativistic electrons in the Jovian radiation belts is different than assumed in the Divine-Garrett model. These results have important implications for the development of self-consistent models of Jupiter's magnetosphere and the planning of future missions requiring close flybys of Jupiter.

Introduction

In the mid-1970's the Jet Propulsion Laboratory (JPL) began developing models of the Jovian environment to provide the National Aeronautics and Space Administration (NASA) with estimates of the high-energy electron, proton, and heavy ion fluxes. For the electrons and protons, which produce the cumulative radiation damage, this effort culminated in the Divine-Garrett model (D-G, [*Divine & Garrett*, 1983]) and represents the sole tool to estimate the radiation dose for Jupiter flyby and orbiter missions.

The D-G model is a compact, quantitative model of the charged particles between 1 eV and several MeV based primarily on in-situ data returned from the Pioneer and Voyager flybys of Jupiter. The in-situ data were supplemented by Earth based radio telescope observations of the synchrotron emission and theoretical considerations. An important test of the reliability of the D-G model for energetic electrons in the inner Jovian magnetosphere is the ability to reproduce the observed pattern of synchrotron radiation. *Divine and Garrett* [1983] noted that their electron distributions at $L < 3$ did not match the synchrotron observation and that the in-situ data their model was based on were insufficient to constrain parameters at small L.

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High levels of radiation pose a challenge to spacecraft design, with factors of uncertainty of two to four in the design environment having major consequences on the selection of survivable technologies. The above considerations have led mission concepts to consider extremely close flybys of Jupiter in order to decrease propulsion mass requirements. While mission designers assume that the required shielding increases as Jupiter orbit insertion distances decrease, analyzing the cost and risk of missions with close flybys is complicated by the relatively sparse data available on Jupiter's inner radiation belts.

This paper compares the D-G model with synchrotron emission observations. A new emission model [*Levin et al.*, 2001] allows a more in depth investigation of the energetic electron distribution in phase space. The goal is to evaluate the energetic electron distribution in the D-G model and determine whether detailed improvements are necessary.

While this paper focuses on relativistic electrons, we note that earlier work demonstrated a mismatch between decametric observations and the D-G model for low energy electrons in the inner Jovian magnetosphere. The observed (lack of) Faraday rotation (from Jupiter's radiation belts) and the existence of 100% elliptical polarization on the decametric emissions places an upper limit on the electron density in Jupiter's inner magnetosphere (excepting the ionosphere and Io torus). This upper limit is about 5 cm^{-3} [*Warwick & Dulk*, 1964; *Dulk et al.*, 1992], which compares with 10-3000 cm^{-3} in the D-G model.

In this paper we use simulated observations to compare with single dish and interferometric maps of Jupiter's synchrotron emission at two frequencies (13 cm and 21 cm). Comparisons of beaming curves, spatial maps, and overall intensity are used to evaluate the D-G energetic electron distributions. Experience in comparing simulated observations with previously developed electron distributions is used to suggest modifications to the D-G model which may improve the model's fit to observation.

Background

At frequencies above about 100 MHz, electrons trapped in Jupiter's radiation belts generate a continuum of syn-

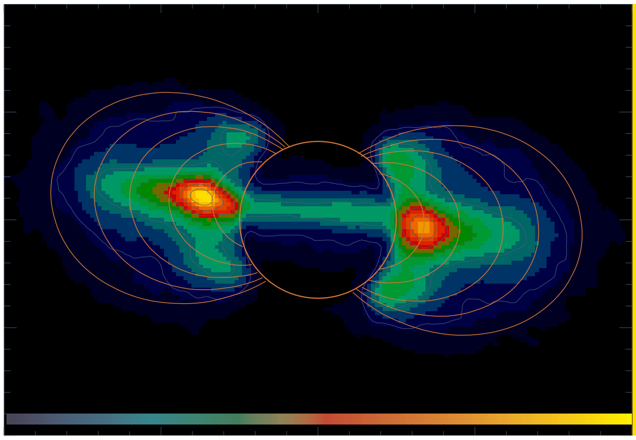

Figure 1. VLA map at 21 cm (1400 MHz) at 340° CML and $D_E = 0°$. Thermal emission has been subtracted and outline of Jupiter disk and O6 magnetic field lines are shown for reference.

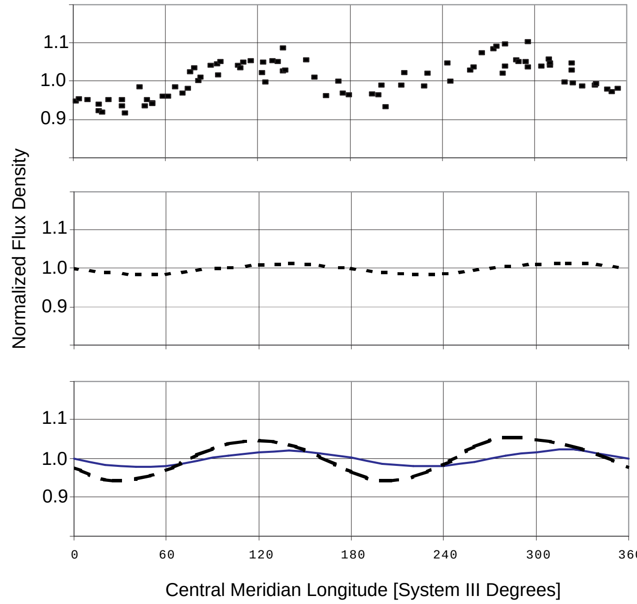

Figure 3. Comparison of beaming curves. Top: DSN observations. Middle: Beaming curve calculated from the D-G model distribution (note the flatter curve). Bottom: Two simulated beaming curves calculated with $q \sim 10$ (dotted line, $sin^{10}(\alpha)$, more anisotropic distribution) and with q∼1 (solid line, $sin^{1}(\alpha)$ more isotropic distribution). All curves are for 13 cm wavelength observations at $D_E = 0°$.

chrotron emission. The Jovian decimetric emission is a combination 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 has indicated a long term variability [*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 in a number of reviews on the subject [*e.g., Carr & Gulkis, 1969; Carr et al. 1983; Bolton & Thorne, 1997*].

Modeling and Observations

This study utilizes two types of radio telescope observations of synchrotron radiation. Single dish antennas measure the total flux density originating from the synchrotron emission region and arrayed antennas produce interferometric maps of the spatial distribution of the emission. Observation results are used to constrain input parameters in the synchrotron emission model. An iterative process is used to develop a static model of the radiation belts describing the energy spectrum, radial profile and pitch angle distributions of the high energy electrons. The sensitivity to errors in the magnetic field model are tested by producing simulated maps and beaming curves using both the O6 and VIP4 magnetic field models [*Connerney*, 1993].

Combined with modeling results the observations demonstrate the importance of the magnetic field orientation to the relative intensity of the observed emission. VLA images at decimetric wavelengths (Figure 1) indicate the pres-

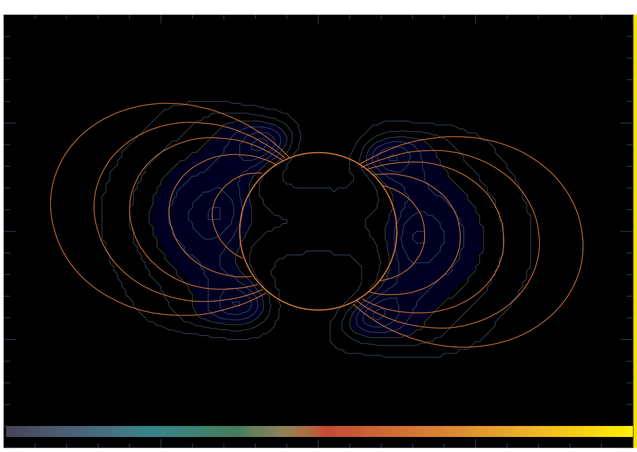

Figure 2. Map based on D-G model. The frequency, viewing geometry, and color scale are identical to Figure 1.

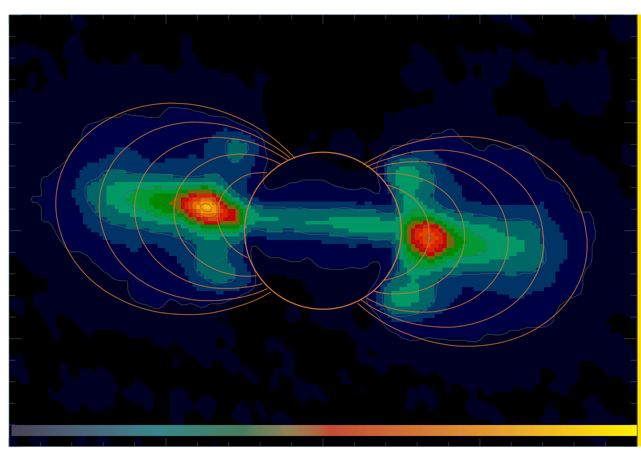

Figure 4. Difference map of VLA data minus the DG model, with the same frequency, viewing geometry, and color scale as Figures 1 and 2. This map looks very similar to Figure 1, indicating the lack of synchrotron emission produced by the D-G model.

ence of radiating electrons at high magnetic latitudes as well as significant emission originating near the magnetic equator. For this reason, models of the Jovian synchrotron emission usually involve two distinct high energy electron distributions. A quasi-isotropic distribution responsible for the high latitude emission and a strongly pancake distribution representing electrons confined close to the magnetic equator. Observations of the polarization and beaming of the emission are also consistent with a bi-modal electron pitch angle distribution [*Roberts*, 1976]. Previous theoretical studies of synchrotron radiation variability [*de Pater & Goertz*, 1990, 1994] have not included non-equatorial particles. These previous studies of diffusion theory cannot explain the maintenance of the quasi-isotropic population as suggested by the observations.

Comparison with Divine Garrett

Using input derived from the Divine-Garrett radiation model the predicted synchrotron emission is calculated and compared with observation. Differences between the calculated emission and the observations can be due to errors in the magnetic field model and/or errors present in the electron distribution. The results of [*Levin et al.*, 2001] indicate the importance of the magnetic field, however, the results also suggest that both the VIP4 and O6 magnetic field models qualitatively capture the gross features of the field geometry in the radiation belts. Comparing simulated maps of the synchrotron emission from the D-G model and the model of *Levin et al.* [2001] with identical magnetic field models limits the source of errors to the electron distributions. The differences in overall emission intensity are directly proportional to errors in the assumed density of high energy electrons and the associated energy and pitch angle distribution of the electrons.

Figure 2 is the calculated synchrotron emission map using the Divine-Garrett model at 340° CML (Central Meridian Longitude). Comparison of the VLA (Figure 1) and the D-G map illustrates two important errors in the D-G model. The D-G model significantly underestimates the number of high energy electrons present in the inner Jovian magnetosphere, and the pitch angle and radial distribution of the electrons is different than represented in the D-G model. A more detailed discussion of these two points is offered below.

Discussion

Beaming Curve Comparison

The misalignment of Jupiter's magnetic field and spin axis causes Jupiter's magnetosphere to wobble as Jupiter rotates. The combination of non-dipolar terms in the Jovian magnetic field, the narrow beaming of the synchrotron emission [*Jackson*, 1975] and the distribution of synchrotron emitting electrons produce the observed variability in the intensity during a Jovian rotation. Beaming curves of Jupiter's synchrotron emission show the total intensity variations observed from Earth based telescopes during a single Jovian rotation (~10 hours). The relativistic beaming of the emission is sufficiently narrow to produce observable effects in the beaming curve as a function of D_E, the declination of Earth as seen from Jupiter, which varies ± 3.3° during the Jovian year [*Klein et al.*, 1989]. An example of the beaming curve at $D_E = 0°$ is shown in Figure 3 (top panel) as observed using the NASA/DSN antennas operating at 13 cm wavelength. The emission intensity is seen to vary ~10% during a single Jovian rotation. In contrast to the observed data, the center panel of Figure 3 shows the D-G beaming curve with ~2% variation. We discuss below how an error in the degree of anisotropy of the equatorial component of electrons can produce beaming curves similar to the D-G model.

The shape of the beaming curve is controlled by the pitch-angle distribution in Jupiter's inner radiation belts. The bottom panel of Figure 3 shows beaming curves simulated by modeling the equatorial electron pitch-angle distribution with two distinct functional forms; $sin^1\alpha$ (solid) and $sin^{10}\alpha$ (dashed), respectively (the electron and magnetic field models used are identical otherwise). A decrease in the pitch-angle anisotropy leads to a dramatic flattening of the beaming curve. A highly anisotropic distribution ($sin^q\alpha$ with $q > 10$) is required to reproduce the observed beaming curve and the equatorial component in the VLA maps (Figure 1). A less anisotropic distribution such as in the D-G model yields a smaller beaming effect and relatively more emissivity in the high latitude lobes.

Map and Intensity Comparisons

The simulated synchrotron emission map (at 1400 MHz) calculated using the D-G model and the VIP4 magnetic field model [*Connerney*, 1993] is shown in Figure 2. This can be compared directly with the VLA map (from an identical geometry and observing frequency) shown in Figure 1. To compare the maps, we developed a simple "goodness of fit" statistic. The simulated map is smoothed to reflect the finite resolution of the VLA, and then subtracted from the VLA map to produce a residual map. We then calculate the variance of the residual map, summing the squares of all the (0.05 R_J by 0.05 R_J) pixels. The results indicate the D-G model is a factor of 3 worse than the model described in [*Levin et al.*, 2001].

The emission distribution of the D-G model maps differ dramatically from the observations indicating significant errors in both the electron distributions and densities. In addition to being significantly weaker in intensity, the high latitude lobes of the D-G model occur at higher L-shells (L~3.5 instead of L~2.4) and closer to the planet. The equatorial emission of the D-G model is more widely distributed in latitude and extends less in radial distance. The overall equatorial emission intensity is under represented in the D-G model by more than a factor of 5-10. The total map intensity of the D-G map is approximately 1.3 Jy as compared to 6.0 Jy in the observations. This suggests that the D-G model contains substantially fewer relativistic electrons (~1-50 MeV) than are actually present in Jupiter's inner radiation belts. In comparison, the simulated model map by *Levin et al.* [2001] is qualitatively similar to the VLA observations shown in Figure 1. The maps shown in Figures 1 and 2 indicate the synchrotron at 340° CML. VLA maps differ as a function of CML due to the same effects that cause the beaming curve (discussed above). We compared VLA maps with D-G model simulated maps for all CMLs and note that the D-G model consistently failed to match the emission distribution observed in the VLA maps.

Synchrotron radiation characteristics are dependent on both the magnetic field and electron distributions. To identify errors in the electron distributions of the D-G model we compare models using identical magnetic field and electron energy spectral index. Errors associated with the electron energy spectrum will be common to all simulations. We further investigated the sensitivity to errors in the energy spectrum by reproducing maps and beaming curves for a variety of energy distributions (including distributions similar to *Divine & Garrett* [1983] and *Mihalov et al.* [1998]). All results indicate that the D-G model underestimates the synchrotron radiation environment at $< 4R_J$.

Figure 4 is a difference map between the D-G model of Figure 2 and the VLA data of Figure 1. The difference map is calculated by subtracting the D-G model from the VLA data. The results indicate that the D-G model underestimates the total overall emission intensity (factor of ~6) and underestimates emission in specific regions by factors as high as 50. At the equator near $R = 1.4R_J$, the error is approximately a factor of 20. The D-G model places the high latitude peaks at higher latitudes than observed. A detailed analysis is necessary to estimate the error in the D-G model for specific locations in Jupiter's inner radiation belts.

Jupiter's synchrotron radiation exhibits temporal variability on time scales of weeks to years [*Klein et al.*, 1989; *Bolton et al.*, 1989]. The differences evident from the comparison of simulated maps using the D-G model and the VLA observations are much greater than the modest variability observed over the last few decades. Furthermore, no observations have shown spatial or intensity characteristics similar to the D-G model (including those during the SL-9 impacts).

Conclusions and Future Work

Our results indicate that the Divine-Garrett model does not accurately describe the high energy ($> 1MeV$) electron population present in Jupiter's inner radiation belts ($< 4R_J$) and that substantial modifications to the model are required. Simulated synchrotron emission maps generated with the Divine-Garrett model do not reflect the basic characteristics of the Jovian synchrotron emission such as the total flux density, spatial distribution, polarization and variability with Jupiter rotation. Current observations are sufficient to improve the model, however, further work is required to constrain the electron distribution energy spectrum and detailed radial profile. Results from the Galileo probe data suggest the energy spectrum may be different for the equatorial (pancake) and high latitude (less anisotropic) components [*Mihalov et al.*, 1998]. If the energy spectrum of either component is softer than assumed by Divine and Garrett, the results reported here represent a minimum error in the D-G model.

The difference between synchrotron emission observation and the D-G model varies spatially as shown in Figure 4. In most regions, the D-G model underestimates the radiation environment (electron number density) by a factor of 5 - 20. However, in small regions, the error increases substantially and in a few select regions the D-G model overestimates the radiation. Our results indicate the region of maximum error (underestimation) is close to the planet ($< 2R_J$) at the equator and near latitudes 55-75 degrees. This can be seen from the peak differences in Figure 4.

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