MODELING TRAPPED RADIATION—A COMPARATIVE STUDY OF THE TERRESTRIAL, JOVIAN, SATURNIAN, URANIAN, AND NEPTUNIAN RADIATION BELTS

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1 Introduction

1.1 Objectives

Since the discovery of the Earth’s van Allen radiation belts in the first days of the space program, modeling of the trapped radiation environment surrounding the planets has been an important topic of both scientific and engineering study. Models of the Earth, Jupiter, and Saturn radiation belts have long helped in the design of the radiation shielding for missions such as Galileo, Juno, and Cassini to these planets. Although only limited data from the Voyager 2 spacecraft exist for the radiation environments at Uranus and Neptune, models also exist for these two outer planets. This paper will compare the predictions of these models with each other and will contrast the results—in particular, while the radiation environments at Uranus and Neptune are mild compared to the other planets, their magnetic fields are significantly offset and interact with the solar wind in potentially complex ways making their definition difficult. The latest versions of these extra-terrestrial radiation models are discussed and examples of expected fluxes for missions to each of the outer planets presented.

Figure 1. The Earth's radiation belts in idealized dipole space, according to the AP8 and AE8 models. Average omnidirectional integral fluxes for 1 MeV electrons and 10 MeV protons energy thresholds are shown.

2 Trapped Radiation Environments

First discovered by J. Van Allen and his collaborators on Explorer I, trapped radiation consists principally of energetic protons and electrons, with lesser percentages of heavy ions such as O⁺, contained in toroidal belts by a planetary magnetic field. This toroid at the Earth is commonly known as the "Van Allen belt(s)" [1]. Schematics of the radiation flux contours for the Van Allen belts are illustrated in Fig. 1 (note the difference in scale between the electrons and protons). The detailed mechanism by which particles are entrapped in the belt regions is not well understood nor is the primary source clearly identified. Observations of abundance ratios imply both terrestrial and interplanetary sources. Once captured, however, the motion of charged
particles in the Earth's magnetic field is governed by the Lorentz force (see later). It is this trapped radiation for the other planets which is the thrust of this talk.

As representative of a trapped radiation environment, we first discuss the primary characteristics of the Earth's magnetic field as this is the dominant force controlling the formation and changes associated with these trapped radiation belts. Following this discussion, a brief review of the basic concepts of particle entrapment such as gyro radius, mirror point, and pitch angle will be presented. These concepts are critical to understanding how the radiation belts are modeled. In particular, the concept of why we use B-L coordinates, the basis of almost all modern radiation models, is central in describing the radiation belts.

2.1 Geomagnetic Field

The dominant geophysical environment of interest for trapping is the magnetic field of the planet. For the Earth, it can be crudely modeled in terms of a tilted (-11° from geographic north) magnetic dipole of magnitude \( M = 0.31 \, \text{G} \cdot \text{R}_e^3 \), where \( \text{R}_e \) is the Earth's radius (1 \( \text{R}_e = 6371 \, \text{km} \)).

Fig. 2 is a cross section of the Earth's magnetic field in the noon-midnight meridian showing the structure of the field lines and the Van Allen radiation belts they contain.

![Figure 2. Cross section of the Earth's magnetic field in the noon-midnight meridian showing the structure of the field lines and the plasma regions they contain.](image-url)
2.1.1 Basic Particle Motion

The two main forces \( F_E \) and \( F_M \) acting on charged particles are the electrostatic force:

\[
F_E = qE \tag{1}
\]

and the magnetic (Lorentz) force:

\[
F_M = \frac{q}{c} V \times B \tag{2}
\]

where \( q \) is the particle charge (including sign), \( c \) is the speed of light, \( V \) the velocity vector of the particle, \( B \) the magnetic field vector in space, and \( E \) the electric field vector in space.

Figure 3. Motion of a charged particle (positive in this case) in a magnetic field in the absence of an electric field. The magnetic field is constant in the lower half of the figure and equal to \( B_1 \). It is constant and equal to \( B_2 \) in the upper part of the figure. The figure illustrates the effects of a gradient in a direction perpendicular to the direction of the magnetic field.

Setting the electric field to zero and using the definition of the cross product, equation (2) implies that the force on a charged particle is always perpendicular to both the particle's instantaneous velocity vector and the magnetic field vector. This means that a particle must, in the absence of another force and in the presence of a uniform magnetic field, move in a circle in the plane perpendicular to the magnetic field vector. It may additionally move freely (without any acceleration) along the magnetic field, mapping out a helix around its "center of motion" (Figs. 3, 4, and 5). The radius \( R_c \) (called the cyclotron or gyro radius) of this circle is found by equating the centripetal force, \( mV_\perp^2/R \), to the Lorentz force. In this expression \( m \) is the particle mass and \( V_\perp \) is the component of the velocity perpendicular to \( B \). The expression is:

\[
R_c = \frac{mV_\perp c}{qB} \tag{3}
\]
The frequency with which the charged particle gyrates, the cyclotron frequency, $\omega_c$, is given by:

$$\omega_c = \frac{qB}{mc}$$  \hspace{1cm} (4)

Figure 4. Motion of a charged particle in a converging magnetic field in the absence of an electric field. $F_\|$ is the force along the magnetic field that results from the field convergence (or divergence) and is responsible for the mirroring effect (see text).

Figure 5. Motion of a Charged Particle in a Dipole Magnetic Field.

According to equation (2), any particle motion parallel to $B$ is unaffected by $B$. The particle's motion can be described in terms of a velocity parallel to the field, $V_\parallel$, or perpendicular to the field, $V_\perp$, and a quantity called the particle pitch angle, "$\alpha$", the angle the particle motion makes relative to the $B$ direction:
\[ \alpha = \sin^{-1}(V_\perp/V) \]
\[ \alpha = \cos^{-1}(V_\parallel/V) \]  

The motion of the particle can be pictured as spiraling along the magnetic field direction, executing cyclotron motion around the field while moving along the field (Fig. 5). A charged particle will deviate from these simple motions if there is an electric field or if the magnetic field has temporal changes. As an example, consider the case where the magnetic field increases with distance in a direction perpendicular to the direction of B. In this case as the particle moves from the region of low field strength to high field strength and back again, \( R_c \) decreases and increases correspondingly, and the particle traces out a cycloid configuration (Fig. 3). Under the combined influence of both the Earth's electric field (this field is radially directed close to the Earth and points from dawn to dusk at greater distances) and the radial gradient of its magnetic field, charged particles will slowly trace a similar cycloid around the Earth (electrons drifting towards the east and high energy ions towards the west).

The gradients along the magnetic field are responsible for the "trapping" of radiation particles in the magnetic field. If the magnetic field converges, then the particle will feel a small force along the direction of the field line. This will cause the particle to decelerate (accelerate) as it moves into the converging (diverging) region (Fig. 4). Eventually (unless the particle has collisions with atmospheric particles—i.e., the mirror point is below some critical altitude which we will define by the magnetic field strength at that position, \( B_c \)), the particle will have its motion parallel to the field stopped. However, due to the particle's circular motion (perpendicular to the field), it still experiences the decelerating force which reflects the particle back along the field line. This occurs at the "mirror" point, as determined by the strength of the magnetic field. This point is designated by "\( B_m \)" (Fig. 5). The particle is "trapped" on a magnetic field line defined by its equatorial crossing (L-shell) and where it is reflected by the magnetic field \( B_m \).

2.1.2 B and L Coordinates

For most planetary magnetic fields \( E \) and B field generally change very slowly in time and space compared to the characteristic motions of radiation particles. We can then describe the particles' group motions in terms of so-called characteristic invariants of the motion (realizing that they do indeed change slightly) rather than having to calculate each particle trajectory. In particular, a particle which mirrors at a field strength of \( B_m \) (that is, \( \alpha=90^\circ \)) has a pitch angle at an arbitrary B (\( B_m \geq B \)) given by:

\[ \sin^2(\alpha) = \frac{B}{B_m} \]  

A planetary magnetic field can be crudely represented by a tilted dipole with components:
\[ B(r) = \frac{-2 M \sin(\lambda)}{r^3} \]  
\[ B(\lambda) = \frac{M \cos(\lambda)}{r^3} \]

Where \( r \) is the radial distance from the center of the planet; \( B(r) \), \( B(\lambda) \), and \( B(\phi) \) are the field components in polar coordinates (\( \lambda \) is the latitude relative to the equator and \( \phi \) is the longitude). For reference, a field line for this dipole field is defined by:

\[ r = r_0 \cos^2 \lambda \]  

where \( r_0 \) is the radial distance at which the field line crosses the magnetic equator and a field line is the line that would be traced by always moving in the direction of the B vector. The dimensionless quantity \( L \) can be defined where:

\[ L = \frac{r_0}{R_e} \]  

The value of \( L \) is, by the definition of \( r_0 \), the equatorial crossing point of a magnetic field line in terms of \( R_e \). As a radiation particle drifts, it traces out a cycloid around the Earth's equator and bounces between the two mirror points defined by \( B_m \) along the field line. It follows a well defined surface. This surface is called the "L shell" of the particle and the two mirror points. This fact has given rise to the use of the McIlwain B-L coordinate system in which a particle population is completely described in terms of the particle flux as a function of B and L values—this is the fundamental underpinning of most existing trapped radiation models in use today and allows the development of simple time-averaged models of the radiation particle fluxes.

The use of the McIlwain B-L coordinates have led to a standardized means of representing the time-averaged features of the trapped radiation environment. For example, the AE/AP radiation models have been the principle source of a uniform set of practical models of the Earth's trapped radiation environment [2, 3] for decades. The AE8/AP8 model fluxes are parametrically represented by:

\[ I(>E,B,L,t,T) = N(>E,L)\Phi(>E,L,t)G(B,L) \]  

Where \( I \) is the integral omnidirectional flux, \( >E \) means for all energies above \( E \), \( t \) is the local time, and \( T \) is the epoch (or date) of the model. Data are averaged in discrete B and L bins to determine the B-L variation \( G \); in energy, \( L \), and (for the Earth) local time to determine the local time variation \( \Phi \); and in energy and L bins to determine the energy variations \( N \). Fig. 1 for 1 MeV electrons and 10 MeV protons illustrates the basic structure of the radiation belts as predicted by the AE8 and AP8 models.
2.2 Extraterrestrial Trapped Radiation

As in the case of the Earth, several other planets in the solar system have been observed to have trapped radiation belts. The species, abundances, energies, and time variations of particles that are trapped in these radiation belts vary greatly depending upon the planet and its magnetic field. Planetary magnetic fields influence the particle spectrum that is observed near a planet in two ways—first, the magnetic field of the planet shields the planet from solar flare particles and from the GCR and, second, it allows particles to be trapped near the planet in radiation belts. Table 1 compares properties of the Earth, Jupiter, Saturn, Uranus, and Neptune. The Earth, for its size, has proportionally one of the most intense magnetic fields in the solar system. Jupiter and Saturn are roughly 10 times the size of the Earth while their magnetic moments are ~2x10⁴ and ~10³ larger. This implies that as the magnetic field at the equator is proportional to the magnetic moment divided by the cube of the radial distance, Saturn’s magnetic field/magnetosphere scales proportionally to Earth’s while Jupiter’s magnetic field/magnetosphere is 20 times larger than the Earth’s and Saturn’s. As the maximum energy and flux levels of trapped particles in a magnetosphere are proportional to the magnetic field strength, the Jovian system can maintain much higher particle energy densities than those at Saturn and the Earth. Subsequent flybys of Jupiter and Saturn have indeed born this out with Jupiter having much more intense radiation belts whereas Saturn’s are roughly equal to Earth’s. Uranus and Neptune on the other hand have relatively weaker magnetic fields and hence radiation belt intensities. Mercury, Mars, and Venus have very weak magnetic fields and therefore no radiation belts.

Table 1. Physical properties of the planets with radiation belts. Values are based on the HORIZON system [13].

<table>
<thead>
<tr>
<th>PHYSICAL PROPERTIES</th>
<th>Earth</th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equatorial radius (km)</td>
<td>6378</td>
<td>71492</td>
<td>60268</td>
<td>25559</td>
<td>24766</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>5.97E+24</td>
<td>1.90E+27</td>
<td>5.68E+26</td>
<td>8.68E+25</td>
<td>1.02E+26</td>
</tr>
<tr>
<td>Semi-major axis (AU)</td>
<td>1</td>
<td>5.2</td>
<td>9.54</td>
<td>19.19</td>
<td>30.07</td>
</tr>
<tr>
<td>Sidereal day (hr)</td>
<td>23.93</td>
<td>9.89</td>
<td>10.61</td>
<td>17.14</td>
<td>16.7</td>
</tr>
<tr>
<td>Dipole tilt (deg)</td>
<td>11.3</td>
<td>9.6</td>
<td>0</td>
<td>58.6</td>
<td>47</td>
</tr>
<tr>
<td>Dipole offset (rp)</td>
<td>0.0725</td>
<td>0.131</td>
<td>0.04</td>
<td>0.3</td>
<td>0.55</td>
</tr>
<tr>
<td>Magnetic moment (gauss Rp³)</td>
<td>0.305</td>
<td>4.28</td>
<td>0.21</td>
<td>0.228</td>
<td>0.133</td>
</tr>
</tbody>
</table>

Another key feature of the outer planets is that they rotate extremely rapidly (~10-17 hours versus 24 hours for the Earth). At Jupiter, because of the very dense plasma torus associated with volcanic Io, the magnetic field of Jupiter is dragged out into a pronounced disk beyond L~16 (at Saturn, Titan generates a plasma disk but it is much farther out and much lower density then the jovian plasma sheet)—see Figs. 6 and 8. This outer radiation region is marked by significantly lower radiation levels and is dependent on radius R and distance Z rather than B and L. At the
Earth, Jupiter, Uranus, and Neptune the observed radiation rapidly varies sinusoidally at the equator as their magnetic fields are tilted relative to the spin axis. As a result, more complex magnetic field models are required and the spatial dependence of the radiation is similarly more difficult to model. Saturn, in contrast, has the peculiarity that its magnetic field is precisely aligned with its spin axis so that its radiation does not vary with spin.

![Schematic representation of Jupiter's magnetosphere illustrating the various plasma regions and particle flows](image)

**Figure 6.** Schematic representation of Jupiter's magnetosphere illustrating the various plasma regions and particle flows [4].

### 2.2.1 Jupiter

The strongest magnetic field in the solar system is that of Jupiter. Since the ability to trap particles magnetically is a function of the magnetic strength, it is little wonder then that it has the most intense radiation belts yet observed. These belts are so intense in fact that they rival the man-made saturated nuclear environment at the Earth—the most intense environment space systems will likely have to fly in. To date, the principle engineering models of these radiation belts are the JPL Divine family of models [5, 6] and the European Salambo and Jose models [7, 8]. Some of the key references to the JPL models are listed in Table 2. The trapped versions of these models have many of the characteristics of the AE8/AP8 radiation models and thus can be reviewed in terms of B and L.

Jupiter was known to have radiation belts since 1960 [12] when, in analogy with early spacecraft observations of the Earth's radiation belts, it was realized that the Jovian UHF radio emissions could be interpreted in terms of trapped energetic electrons [10]. Fig. 7A shows ground based measurements of this jovian synchrotron radiation at 1400 Mhz. Pronounced wave-like variations in the high energy particle fluxes led to the proposal that the Jovian magnetosphere was distorted into a thin disc—the so-called magnetodisc theory (Fig. 8 [11, 14])—and that this thin disc was populated by a cold plasma consisting of heavy ions originating from Io. The passage of
the Voyager 1 and 2 further refined the particle and field observations. Subsequently, theoretical models have further helped to interpret the observations and have led to the development of Jovian radiation models capable of making practical predictions about the environment around Jupiter (see [5-9]). The JPL Divine models will be described here as they have been the standard design tool for US Jupiter missions.

Figure 7. A) Earth-based observations of jovian synchrotron radiation at 1400 Mhz [9]. B) Simulated jovian synchrotron radiation at 1400 Mhz using the Divine family of jovian electron radiation models [9].

Table 2. Current JPL radiation model references:

Figure 8. Magnetic field lines at Jupiter for the VIP4 magnetic field model [15, 16] showing the 11° tilt of the dipole moment and the extended magnetic field resulting from the Io plasma dragging out the field beyond L~16.
As for the Earth, the independent variables used to define position for the magnetic field and charged particles are jovianentric distance $r$ (commonly in km or R$_J$), latitude $\lambda$ (deg or rad), longitude $l$ (deg in System III (1965) [11, 17]), distance $z=r \sin \lambda$ from the rotational equatorial plane, and distance $R=r \cos \lambda$ from the rotation axis. There are several detailed magnetic field models of Jupiter. An example of the inner dipole structure of the trapped magnetic field is the VIP4 [15, 16]. This model accounts for the pronounced jovian plasma sheet and its distortion of the magnetic field beyond ~16 L (Fig. 8). Outside of ~16 L, a more recent Khurana magnetic field model [18] has been developed to model the effects of outer, plasma sheet magnetic field. The inner dipole is offset about 0.1 R$_J$ and tilted about 10° (note: the magnetic field of Jupiter and Saturn are both oriented 180° to that of the Earth’s).

The principle radiation belt populations included in the jovian models are electrons (E>0.06 MeV) and protons (E>0.6 MeV). For the Divine/GIRE models, the range of applicability of the model extends to the Jovian magnetopause. The Divine and GIRE electron models currently include a pitch angle dependency within L=16 but are considered isotropic beyond that point. The proton model includes a pitch angle dependency within L=6. For the inner electron and proton models, the independent variables magnetic L shell, local field strength $B$, pitch angle $\alpha$ with respect to the field line, and particle kinetic energy $E$ were utilized ($B$ and $L$ are of course functions of $r$, $\lambda$, and $l$). The model populations are assumed independent of time, longitude, and direction azimuth about the field line, as appropriate for stably trapped populations.

At each value of L, analytic expressions have been developed (these values are tabulated in Divine and Garrett [5]), based on fits to the spacecraft and radio data, that allow evaluation of the particle integral and differential intensities $I$ and $i$ in terms of $\alpha$, $B$, and $E$. That is, $I$ has been fit to an analytic expression in $\alpha$, $B$, and $E$ at discrete values of L such that:

$$I_L = A_L(\alpha,B,E)$$ (11)

Variations at other values of L are derived by interpolating between the relevant values. The corresponding differential intensity (in units of cm$^{-2}$ s$^{-1}$ sr$^{-1}$ MeV$^{-1}$) is then given by:

$$i = -\frac{dI}{dE}$$ (12)

Electron and proton omnidirectional fluxes are obtained by integration

$$J = 4\pi \int_0^{\pi/2} I(\sin \alpha) d\alpha$$ (13)

In the middle and outer Jovian magnetosphere (i.e., beyond L=16), the energetic particle fluxes are extremely time-dependent and are, as a result, difficult to model. Currently, to estimate radiation effects in the outer jovian radiation belts, simple, omnidirectional models for the energetic electron fluxes were developed based on Pioneer, Voyager, and Galileo observations, varying in R and $Z_K$. The European JOSE model and the latest versions of the GIRE model
assume that the peak equatorial fluxes can be described by a function of the form for $R>16-20 \text{ R}_J$ to $50 \text{ R}_J$:

$$J(E,R,Z_K,t) = J_0(E)e^{\left(\frac{Z_K-Z_0}{H_Z}\right)}G(R)$$

(14)

Where

- $J =$ Omni-directional electron flux; Function of $E$, $R$, $t$, and $Z_K$
- $E =$ Energy
- $R =$ Radial distance from Jupiter
- $G =$ Functional variation of flux with radius $R$ (e.g., $G(R) \sim e^{-A_0 R}$)
- $Z_0$, $H_Z$, $A_0 =$ Constants
- $J_0 =$ Functional variation of Flux with energy $E$
- $Z_K =$ Distance normal to the plasma sheet magnetic plane; currently estimated using the Khurana magnetic field model which is dependent on the date and time given by $t$
- $t =$ Date/time of observation

Here the electron kinetic energy $E$ has units MeV, $R$ has units $\text{R}_J$, and the omnidirectional integral flux $J$ has units of $\text{cm}^{-2} \text{s}^{-1}$. Fig. 9 illustrates a meridional cut based on the JPL GIRE2 model.

![Contour plot](image)

**Figure 9.** Contours for electron fluxes above 1 MeV and protons above 10 MeV at Jupiter [5,6].

### 2.2.2 Saturn

Fig. 10 [19] is a schematic illustration of the Saturn magnetosphere. As in the case of Jupiter, Divine [20, 21] developed a first order radiation model for Saturn similar to that for Jupiter. Based on high energy data from Pioneer 11, Voyager 1, and Voyager 2, the model covers the distance from 2.3 to $13 \text{ R}_S$. It describes the electron distribution at energies between 0.04 and 10 MeV and the proton distribution between 0.14 and 80 MeV. As in the Jupiter model, the first step in the model is to specify the Saturnian magnetic field. Estimates for this field and other relevant quantities are listed in Table 1. Next, the integral and differential intensities for the electrons and protons, as functions of the magnetic field and $L$, are specified by algorithms very similar to the
Jupiter model. The integral omnidirectional flux $J$ is then calculated as before by Eq. 13. The output of the SATRAD model is presented in Fig. 11. The integral omnidirectional flux for the Saturn model at 1 MeV (electrons) and 10 MeV (protons) are shown. The dropouts are typically associated with the orbits of the Saturnian moons or rings.

Figure 10. A schematic representation of Saturn's magnetosphere in the r-z (trajectory) plane as revealed by the LECP data [19]. Tick marks on the trajectory are at 6-hour intervals from day 318 to 320. Note the Titan-associated mantle region outside 17 $R_s$, and the presence of closed field lines in the tail lobe region. The phase of the second-order anisotropies relative to the magnetic field ($B$) is shown for both electrons (e) and protons (p). R, Rhea: T, Titan: MP, magnetopause.

Figure 11. Sample output for the SATRAD model: The integral omnidirectional flux for electrons at 1 MeV (right) and protons at 10 MeV (left) are shown. The dropouts are typically associated with the orbits of the Saturnian moons or rings [19, 20].
2.2.3 Uranus and Neptune

Voyager 2 flew by Uranus and Neptune on January 24, 1986 and Aug. 25, 1989 respectively. While very short, these flybys did resolve the magnetic fields and radiation belts at both planets. The magnetic fields that Voyager detected proved to be surprisingly complex, however. While the Uranian interaction with the solar wind (because its spin axis is tilted ~90° to the ecliptic plane) was expected to yield unusual results, the fact that both planets’ magnetic poles were highly inclined and displaced relative to their spin axes was a major discovery. Fig. 12 by Bagenal [22] illustrates this complexity. As presented in Table 1, the Uranian field is displaced by 0.3 Rₚ and tilted by ~59°. Neptune’s axis is similarly displaced by 0.55 Rₚ and tilted by ~47°. These offsets lead to very strange interactions with the solar wind and its plasma. Here our main concern is in modeling the fields sufficiently accurately to compute the B and L coordinates.

![Uranian Magnetospheric Variations with Rotation**](image)

Figure 12. Schematic representations [22] of the offset/tilted magnetic fields of the Uranian (top) and Neptunian (bottom) magnetospheres. Note the large differences between the spin and magnetic axes. Neptune’s magnetospheric tail actually bifurcates as the planet rotates.

As for Jupiter and Saturn, the Voyager electron and proton trapped radiation belts were modeled by estimating the differential flux spectra along the magnetic equators of the 2 planets and then extrapolating along the L-shell. The procedure, though based on limited data, yielded models of both planetary radiation belts from around an L of ~6 to 15 for Uranus (note: there was insufficient data inside ~6 L to construct a model) and ~1.4 L to ~28 L for Neptune. The resulting meridional plots in idealized magnetic dipole coordinates (R,λ) are presented in Figs. 13 and 14. Given the complexity of these highly eccentric magnetic fields, it is difficult to illustrate them in
the normal “geographic” coordinates we used for the Earth, Jupiter, and Saturn. The Uranian UMOD is available from the authors [23]. The Neptunian NMOD is still under development but should be available from the authors by the end of the summer.

![Graph of Uranus radiation belts](image1)

**Figure 13.** Integral omnidirectional flux for electrons at 1 MeV (right) and protons at 5 MeV (left) based on the JPL Uranian UMOD [23].

![Graph of Neptune radiation belts](image2)

**Figure 14.** Integral omnidirectional flux for electrons at 1 MeV (right) and protons at 5 MeV (left) based on the new JPL Neptunian NMOD.

2.2.4 Radiation Belt Comparisons

Figs. 15A and 15B compare the integral omnidirectional proton and electron fluxes (n#/cm²-s) for our trapped radiation models along their magnetic equators. Jupiter’s radiation belts dominate the other planets by several orders of magnitude over most of its range. While the Earth appears to be slightly higher than Saturn, the two radiation belts for the protons appear to follow each other’s general shape while for the electrons, the Earth exhibits a large drop out around 2 R (the so-called Slot Region). As might be expected because of their complex variations and significant offsets, the Uranian and Neptunian belts show more structure and, in the inner regions, much lower fluxes than the other planets. Interestingly, the beyond ~5-6 L the Earth, Saturn, Uranus, and Neptune electron fluxes appear to approach similar levels.
Figure 15. Integral omnidirectional A) proton and B) electron fluxes (n#/cm²-s) for our trapped radiation models along their magnetic equators. Numbers are based on Figs. 1, 9, 11, 13, and 14.

Fig. 15 illustrates the fact that Jupiter’s radiation belts are dominated at high energies by electrons. In contrast, both at the Earth and Saturn there are comparatively significant high energy proton belts in their inner regions (1.5-3 L). This is an important distinction as it means that the dominant radiation effects can vary between regions. For example, high energy protons can cause SEUs and damage to solar arrays whereas electrons are a major source of TID and IESD. Fig 16 (courtesy Allan Johnston) plots the normalized (i.e., flux is assumed to be 1.0 at 0.1 MeV) proton and electron spectra for the Earth and Jupiter in their inner belts. Earth has a very “hard” proton environment whereas Jupiter has a very “hard” electron environment.
Figure 16. Normalized spectra for protons and electrons in the Earth’s and Jupiter’s inner radiation belts. Note that at Earth the proton environment dominates at high energy while at Jupiter it is the high energy electrons.

Figure 17 summarizes our findings in terms of the dose rate in rads(Si)/s behind 100 mils of aluminum shielding. As expected, Jupiter dominates the planetary radiation belt environment by a factor of ~100. The Earth and Saturn interestingly have similar levels though the Earth shows the AE/AP model characteristic slot region. Beyond about 6 R, Earth, Saturn, Uranus, and Neptune appear to have roughly similar levels on the order $10^{-5}$ rads(Si)/s.

Figure 17. The dose rates in rads(Si)/s behind 100 mils of aluminum shielding for the trapped radiation belts of the Earth, Jupiter, Saturn, Uranus, and Neptune versus L-shell.
3 Summary

This paper has defined to first order the radiation environment at 5 of the Solar System’s major planets: Earth, Jupiter, Saturn, Uranus, and Neptune. The best defined of these environments are at the Earth and Jupiter whereas we only have limited high energy data for the other 3 planets. Even so, several definite trends have been noted. First, Jupiter’s electron belts are by far the dominate radiation environment in the Solar System. Second, the Earth and Saturn also have distinctive electron and proton belts. Third, although we have only limited data from Voyager 2 flybys, both Uranus and Neptune have measurable (though low flux) radiation belts. These belts, however, are of particular scientific interest as their planets’ magnetic fields are significantly offset and tilted leading to complex interactions with the Solar Wind plasmas. Finally, the models (in the form of FORTRAN models) are available from the authors through the Jet Propulsion Laboratory.

4 Acknowledgements

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References


