well away from the equatorial plane in a region not explored by Voyager. This conclusion is supported by whistler dispersion observations [Gurnett et al., 1981b] which require substantially more columnar electron density than can be accounted for by heavy ions in the equatorial torus. Furthermore, although the plasma science instrument on the Voyager spacecraft could not directly detect thermal H$^+$ ions in the inner torus, significant H$^+$ concentrations (≈ 30%) have been reported by McNutt, Belcher, and Bridge [1981] in the middle magnetosphere ($l \gtrsim 10$), and Hamilton et al. [1980] have discovered energetic H$^+$ and H$^+$ ions in the outer Jovian magnetosphere. Both observations suggest that the ionosphere is an important plasma source.

The injected ionospheric plasma should be rapidly scattered onto trapped orbits in the magnetosphere during the initial transit of the high density plasma torus and subsequently redistributed in radial location by the eddies associated with interchange instability of the heavy ions injected from Io or by corotating ionospheric convection [e.g., Hill, Dessler, and Maher, 1981]. However, the outward flow of thermal heavy ions exhibits no evidence for systematic adiabatic cooling. Some additional heat input is therefore required to maintain the ion temperatures near 100 eV. Plasma waves or secondary electron heat flux from the extended Jovian aurora zone are potential candidates. An important implication of the high thermal ion temperatures in the outer magnetosphere is that subsequent inward transport leads to adiabatic heating to energies comparable to 100 keV in the region of the torus. Rapid inward radial transport can therefore provide a means of maintaining the energy content of the Jovian ring current plasma, which is the reservoir for auroral dissipation. Whether this transport is dominated by interchange eddies, corotating magnetospheric convection or other processes remains to be determined.

ACKNOWLEDGMENTS

The author wishes to thank F. V. Coroniti, A. J. Dessler, A. Evitar, D. A. Gurnett, F. L. Scarf, M. Schulz, G. L. Siscoe, B. T. Tsurutani, and Y. L. Yung for advice and constructive criticism during the preparation of this report. S. R. Church computed the Bessel functions used in the ion radial diffusion solution. The work was supported in part by N.S.F. Grants ATM 81-10517 and ATM 81-19544.
### Symbols and acronyms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g )</td>
<td>local acceleration of gravity at a planet or moon, Euler potential</td>
</tr>
<tr>
<td>( H )</td>
<td>local horizontal field component, scale height</td>
</tr>
<tr>
<td>( h )</td>
<td>distance variable, Planck's constant, Planck's constant/2(\pi)</td>
</tr>
<tr>
<td>( I )</td>
<td>Stokes parameter (total flux density), dip angle, total current (amps)</td>
</tr>
<tr>
<td>( J )</td>
<td>second adiabatic invariant, integral particle flux</td>
</tr>
<tr>
<td>( J^* )</td>
<td>action integral associated with ( j^* ) adiabatic periodicity of motion</td>
</tr>
<tr>
<td>( J_{i\star} )</td>
<td>resonant integral electron flux</td>
</tr>
<tr>
<td>( J_{\star} )</td>
<td>critical proton integral flux for ion-cyclotron instability</td>
</tr>
<tr>
<td>( j )</td>
<td>current density, ( j_1 ) current perpendicular to ( B ), ( j_i ) current parallel to ( B ), field-aligned (Birkeland) current</td>
</tr>
<tr>
<td>( j_d )</td>
<td>differential particle flux, ( j_e ) differential particle flux for electrons, ( j_t ) trapped differential flux</td>
</tr>
<tr>
<td>( j_b )</td>
<td>Birkeland (field-aligned) current density</td>
</tr>
<tr>
<td>( j_t )</td>
<td>current tangential to the current sheet</td>
</tr>
<tr>
<td>( j^d )</td>
<td>current density (amps/m), height-integrated current density</td>
</tr>
<tr>
<td>( K )</td>
<td>Kelvin degrees, energy injection rate, eddy diffusion coefficient</td>
</tr>
<tr>
<td>( K_s )</td>
<td>eddy diffusion coefficient at Jupiter's homopause</td>
</tr>
<tr>
<td>( K_p )</td>
<td>modified Bessel function of the second kind of order ( p )</td>
</tr>
<tr>
<td>( K_s )</td>
<td>thermal energy</td>
</tr>
</tbody>
</table>

### Physical Constants

- \( D_o \) radial diffusion coefficient
- \( D_{1r} \) diffusion coefficient at \( L = 1 \) (\( D_{1r} = D_{L1} \))
- \( D_o \) diffusion coefficient
- \( D_o \) energy diffusion coefficient
- \( D_o \) pitch angle diffusion coefficient
- \( \vartheta_o \) pitch angle diffusion coefficient, bounce averaged
- \( D \) length scale for thickness or depth of a region
- \( D_{1r} \) jovianicentric declination of the Earth (degrees)
- \( D_{i\star} \) angular distance of the Earth from Jupiter's spin equator
- \( D_s \) jovianicentric declination of the Sun
- \( E \) electric field
- \( \hat{e} \) unit vector in the direction of the electric field
- \( E \) energy
  - \( E_a \) energy of ion species \( a \)
  - \( E_e \) electron energy
  - \( E_i \) ion energy
  - \( E_p \) proton energy
  - \( E_m \) magnetic energy per particle
  - \( E_{th} \) thermal energy (of plasma)
- \( e \) fundamental charge (charge of electron = \( -e \))
- \( \eta \) reconnection efficiency = \( E_{\text{magnetic flux function}} / E_{\text{energy}} \)
- \( \eta \) dynamic flattening of Jupiter, Euler potential
- \( f \) magnetic flux function frequency
  - \( f_c \) cyclotron frequency
  - \( f_c^\text{e} \) electron cyclotron frequency
  - \( f_c^\text{i} \) ion cyclotron frequency
  - \( f_p \) plasma frequency
  - \( f_p^\text{e} \) electron plasma frequency
  - \( f_p^\text{i} \) ion plasma frequency
  - \( f_{\text{low}} \) lower hybrid resonance frequency
  - \( f_{\text{high}} \) upper hybrid resonance frequency
- \( G \) Newton's gravitational constant
- \( g \) geometric factor
- \( g \) gravitational acceleration
Appendix A

Symbols and acronyms

\begin{align*}
P_e & \quad \text{production rate/unit volume (electrons)} \\
P_i & \quad \text{production rate/unit volume (ions)} \\
P_e^{(\cos \theta)} & \quad \text{associated Legendre polynomial} \\
p & \quad \text{momentum vector} \\
Q & \quad \text{Stokes parameter} \\
q & \quad \text{particle's charge} \\
R & \quad \text{count rate} \\
R & \quad \text{reflection coefficient} \\
R_j & \quad \text{radius of Jupiter} \\
R_i & \quad \text{radius of Io} \\
R_p & \quad \text{planetary radius} \\
r & \quad \text{axial ratio (sign indicates RH or LH) (characterizes polarization of radiation)} \\
& \quad \text{Jovian-centric distance} \\
r_e & \quad \text{effective radius of one of Jupiter's moons} \\
S & \quad \text{total flux density} \\
& \quad \text{source term with units phase space density/time} \\
& \quad \text{column production rate of ions} \\
s & \quad \text{a quantum state corresponding to momentum } p_1 \text{ and } p_i \\
T & \quad \text{temperature} \\
& \quad \text{temperature characterizing thermal motion perpendicular to } B \\
& \quad \text{temperature characterizing thermal motion parallel to } B \\
T_e & \quad \text{electron temperature} \\
T_i & \quad \text{ion temperature} \\
t & \quad \text{time} \\
U & \quad \text{potential} \\
& \quad \text{Stokes parameter} \\
V & \quad \text{Stokes parameter (sign specifies polarization sense [$-$ RH, $+$ LH] magnetic potential} \\
V & \quad \text{plasma bulk velocity} \\
V_e & \quad \text{Alfvén velocity} \\
V_i & \quad \text{orbital velocity of Io} \\
V_i & \quad \text{Solar-wind velocity}
\end{align*}
Appendix A

Symbols and acronyms

\( \rho \)  
mass density

particle's cyclotron radius

\( \Sigma \)  
conductivity

\( \Sigma_v \)  
height-integrated Pedersen conductivity

\( \Sigma_A \)  
Alfvén conductivity

\( \sigma \)  
cross section

\( \tau \)  
characteristic lifetime of particles

\( \tau_b \)  
bounce time for travel between magnetic mirror points

\( \Phi \)  
electric potential drop

\( \Phi_r \)  
third adiabatic invariant

\( \Phi_s \)  
spacecraft potential (volts)

\( \chi \)  
solar zenith angle

\( \psi_m \)  
magnetic latitude

\( \Omega \)  
angular frequency of Jupiter

\( \omega \)  
frequency (angular)

\( \omega_c \)  
cyclotron frequency of a given species

\( \omega_e \)  
electron cyclotron frequency

\( \omega_i \)  
ion cyclotron frequency

\( \omega_p \)  
ion plasma frequency

\( \omega_{pe} \)  
electron plasma frequency

\( \omega_{h\perp} \)  
frequency of lower hybrid resonance

\( \omega_{h\parallel} \)  
frequency of upper hybrid resonance

\( \omega_{cl} \)  
right-hand cutoff frequency

\( \omega_l \)  
left-hand cutoff frequency

Acronyms

BP-HD  
bent plane/hinged disc model of Jovian magnetodisc

BP/WD  
bent plane/wave-propagating-outward model of Jovian magnetodisc

BS  
bow shock

bKOM  
broadband component of KOM

CA  
closest approach

CIR  
corotating interaction region

CML  
central meridian longitude

velocity of particle

\( e_x \)  
component of particle velocity parallel to \( B \)

\( e_y \)  
component of particle velocity perpendicular to \( B \)

\( v_n \)  
velocity of the neutral atmosphere

\( v_c \)  
corotation velocity

\( v_w \)  
average wave group speed

\( v_m \)  
wave phase velocity

\( w \)  
total particle energy

\( w_x \)  
energy due to particle motion parallel to \( B \)

\( w_y \)  
energy due to particle motion perpendicular to \( B \)

\( \gamma \)  
magnetic flux shell density

\( Z \)  
atomic charge in units of \( e \)

\( \alpha \)  
altitude

\( \alpha \)  
pitch angle

angle between Jupiter’s rotational and magnetic axes (\( \sim 10^\circ \))

alpha particle (He nucleus)

polarizability of an atom (in units of Bohr radii cubed) recombination rate

\( \alpha_r \)  
radiative recombination coefficient

\( \beta \)  
plasma parameter = particle thermal pressure/magnetic pressure

angle between the centrifugal symmetry surface and the magnetic equator of Jupiter

\( \gamma \)  
\( = 10^{-7} \) Gauss = \( 10^{-8} \) Tesla

index in power law spectrum \( \sim E^{-\gamma} \)

adiabatic index

\( \gamma_i \)  
Io phase angle

\( \gamma_r \)  
relativistic contraction factor

\( \theta \)  
co-latitude in right-hand polar coordinates

\( \Lambda \)  
invariant latitude

\( \lambda \)  
wavlength

\( \lambda_D \)  
Debye length

\( \lambda_0 \)  
system III longitude

\( \mu \)  
first adiabatic invariant (magnetic moment)

\( \mu_r \)  
reduced mass

\( \mu_0 \)  
magnetic permeability of free space
Appendix A

Symbols and acronyms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>O,</td>
<td>magnetic field model of Acuña and Ness [1976] (same as GSFC O,)</td>
</tr>
<tr>
<td>P10</td>
<td>Pioneer 10</td>
</tr>
<tr>
<td>P11</td>
<td>Pioneer 11</td>
</tr>
<tr>
<td>P.A.</td>
<td>position angle of the plane of linear polarization</td>
</tr>
<tr>
<td>PLS</td>
<td>low-energy plasma instrument</td>
</tr>
<tr>
<td>PWS</td>
<td>plasma-wave instrument</td>
</tr>
<tr>
<td>RH</td>
<td>right-hand circularly polarized</td>
</tr>
<tr>
<td>RP/RD</td>
<td>rocking plane-rotating disc model of Jovian magnetodisc</td>
</tr>
<tr>
<td>RSS</td>
<td>radioscience instrument</td>
</tr>
<tr>
<td>SC</td>
<td>spacecraft</td>
</tr>
<tr>
<td>SCET</td>
<td>spacecraft event time</td>
</tr>
<tr>
<td>SCM</td>
<td>spacecraft maneuver</td>
</tr>
<tr>
<td>SKR</td>
<td>Saturn kilometric radiation</td>
</tr>
<tr>
<td>SZA</td>
<td>solar zenith angle</td>
</tr>
<tr>
<td>TD</td>
<td>tangential discontinuity</td>
</tr>
<tr>
<td>TKR</td>
<td>terrestrial kilometric radiation</td>
</tr>
<tr>
<td>UT</td>
<td>universal time</td>
</tr>
<tr>
<td>UV</td>
<td>ultraviolet</td>
</tr>
<tr>
<td>UVS</td>
<td>ultraviolet spectrometer</td>
</tr>
<tr>
<td>V1</td>
<td>Voyager 1</td>
</tr>
<tr>
<td>V2</td>
<td>Voyager 2</td>
</tr>
</tbody>
</table>

DAM  Jupiter radiation component with spectral peak at wavelengths of decameters  
DIM  Jupiter radiation component with spectral peak at wavelengths of decimeters  
DOY  day of year  
D  magnetic field model for Jupiter of Smith, Davis, and Jones [1976] - offset, tilted dipole  
E-E  limited amplitude wave model of Eviatar and Ershkovich for Jovian magnetodisc  
GSFC O, Goddard model of Jupiter's magnetic field  
HG  heliographic  
HOM  Jupiter radiation peaking in the hectometer wavelengths (between 100 m and 1000 m)  
IFT  Io flux tube  
IMF  interplanetary magnetic field  
IRIS  infrared spectrometer  
KOM  Jupiter radiation component with spectral peak at kilometer wavelengths (subdivided nKOM and bKOM)  
LCFL  last closed field line  
LECP  Low Energy Charged Particle detector  
LEMPA  Low Energy Magnetospheric Particle Analyzer  
LEPT  Low Energy Particle Telescope  
LET-B  proton detector  
LH  left-hand circularly polarized  
LT  local time  
LTE  local thermodynamic equilibrium  
MS  magnetosheath  
MP  magnetopause  
nKOM  narrow band component of KOM  
OTD  offset, tilted dipole
APPENDIX B
COORDINATE SYSTEMS

A. J. Dessler

Jovian coordinate systems are not complicated or cabalistic, but they are different. The following is a description of these systems, as relevant to this book. I will also try to explain why things are as they are. There is logic behind the present system, even if some of the results seem curious or unfortunate.

B.1. Jovian longitude conventions

Latitude and longitude coordinates are usually established relative to some solid surface. Because Jupiter does not have a solid surface (at least none that is visible through the clouds), arbitrary, but convenient, coordinate grids have been prescribed. A spin equator is rather easily made out from observations of cloud motion, so the direction of the planetary spin axis is determined with relatively good accuracy. However, the determination of longitude is an entirely different matter.

Longitudes on a planet are fixed relative to an arbitrary, but well defined, prime or zero-longitude meridian. For example, the Earth’s prime meridian is the one that passes through the central cross-hair of the transit telescope at the Greenwich Royal Observatory. Its location is unique, and it stays put*. The selection of this meridian as the prime or zero-longitude meridian was initially arbitrary, but the selection, once made, fixes the longitude grid with precision. The problem immediately faced in establishing a Jupiter longitude system is that the mean rotation period of the clouds is a function of latitude. The equatorial region rotates faster than the temperate and polar regions, as is common in all planetary upper atmospheres. The difference is large enough that a cloud feature near the equator completely laps a cloud feature at higher latitude in about 120 Jupiter rotations, or 50 days. (Unless otherwise stated, “day” refers to a 24-hour terrestrial day.) Thus, a single longitude system cannot conveniently be used to keep track of motions of cloud features at different latitudes.

The solution selected was to define two separate longitude grids. System I applies to cloud features within about 10° of the equator. System II applies to higher latitudes. Rotation rates were established and a Central Meridian Longitude (t.e., sub-Earth longitude, commonly abbreviated CML) was selected for each of these systems. All of this was done some time ago, as evidenced by the staring time (14 July, 1897) that was used to define the locations of the prime meridians for Systems I and II.

The rotation of the longitude grid is defined in terms of a rotation rate (877.90°/day for System I and 870.27°/day for System II). The rotation period (which is usually quoted) is derived from these rotation rates. This explains the seemingly meaningless number of significant figures in the quoted rotation periods (9h 55m 30.00346 for System I and 9h 55m 40.63225s for System II). It is the rotation rate that is exact by definition; the rotation period is only a numerical approximation. These rotation periods have never been revised, and the 1897 convention is still the adopted one.

A third longitude system became necessary when, a half-century later, radio signals were detected that gave evidence for a planetary magnetic field that rotates at a rate intermediate between Systems I and II (although only about 0.3°/day faster than System II). After about five years of observations, a rotation period of 9h 55m 29.3h (not a rate as for Systems I and II) was selected, and a starting time of 00 UT on January 1, 1957 was picked. This system is called System III(1957.0). It is System III, which describes the rotation of the Jovian magnetic field, that is of primary use to magnetospheric physics.

Within less than a decade, it became apparent that the defined period for System III(1957.0) was in error by less than 1 part in 10⁶, the period being too short by about 1/5 s. The result was that a given radio phenomenon drifted steadily in longitude. This drift amounts to only 3.4 × 10⁻⁸ degrees/Jovian rotation, but in a year it grows to 3.4 × 10⁻⁶ × 365 days = 2.4 rev/d = 5°/yr.

The direction of drift is determined by the sense of the longitude system, which is left-handed, as illustrated in Figure B.1. That is, looking down on Jupiter from above the north pole, longitude increases in a clockwise direction. In a Mercator projection, longitude is usually shown increasing from left to right. However, for Jupiter, longitude is usually shown increasing from right to left, as, for example, figure 1.1 or 1.3. The advantage of a left-handed coordinate system is that, as viewed from the Earth (or from any other distant or slowly moving observation point), the longitude directly beneath the observer (the Central Meridian Longitude), increases with time. It should also be noted that east and west on Jupiter are usually (but not always) defined in terms of their direction on the Earth. Thus, for an observer in the Earth’s northern hemisphere looking at Jupiter in the southern sky, the western side of Jupiter is on the observer’s
right (or terrestrial west), and the eastern side of Jupiter is on the observer's left (or terrestrial east). This is standard astronomical usage. However, the reader should be cautioned that the opposite convention is frequently used where east on Jupiter is the direction that an observer standing (or floating) on Jupiter would see the Sun rise, and west is the direction the observer would see the Sun set. The usage of east and west is inconsistent as applied to the planets (other than Earth); if the direction is important, be sure you know the convention being used in each individual paper.

The outstanding problem with a coordinate system that does not rotate at the same rate as the planet arises when one wishes to compare one data set with another. One must know the epoch of each data set, that is, the time when each were obtained, and make a correction for the drift (i.e., correct for the cumulative error in the inaccurately defined planetary spin period). For example, if one wished to compare Pioneer 10 flyby data (obtained in December 1973) with radio astronomy data obtained in, say, 1960, a correction of approximately 45° of longitude must be introduced. At best, this is an inconvenience (one must remember whether to add or subtract the correction), but, if the date (epoch) the data were obtained is not given, useful comparison is difficult or impossible.

In 1976, the International Astronomical Union (IAU) adopted a new longitude system, known as System III (1965). A more accurate rotation rate was selected so that the drift in longitude of magnetically related phenomena has been effectively stopped. Undoubtedly, some small error is still present in the selected value of the spin rate. For example, May, Carr, and Desch [1979] conclude the IAU period may be in error by about one part in 10⁴ (consistent with the stated uncertainty in the IAU value). This could lead to a drift of 0.1° year, or less than 2°/decade, which is a drift rate that can be safely ignored by magnetospheric physicists for decades to come.

It is often necessary to compare System III (1957.0) data with data from System III (1965) data, not only to be able to compare older radio data with more recent measurements, but to compare spacecraft data. Pioneer 10 and 11 data were reported in 1957.0 coordinates, whereas Voyager data were reported in 1965 coordinates, and a correction of about 30° is required if magnetic longitudes between these two missions are to be correlated.

The transformation from \( \lambda_{1957.0} \) to \( \lambda_{1965} \) on a given Julian date \( T \) is given by Riddle and Warwick [1976], and in a slightly more precise form by Sjekelman and Devine [1977], as

\[
\lambda_{1965} = \lambda_{1957.0} - 0.0083169 (T - 2438761.5) \quad (B.1)
\]

The number inside the parentheses on the right is the Julian date for January 1, 1957 at 00 UT. Equation (B.1) may be written more conveniently (although with slightly less accuracy) as

\[
\lambda_{1965} = \lambda_{1957.0} - 3.04T \quad (B.2)
\]

where \( T \) is the time in years and decimal fraction of a year since 00 UT on January 1, 1965. For example, Pioneer 10 made its closest approach to Jupiter on December 4, 1973. Thus, \( T = 8.9 \), and from Equation (B.2) we find that we must subtract 3.04 \times 8.9 = 27° from longitudes related to the Pioneer 10 flyby to convert them to System III (1965). In cases where an approximate correction is adequate, the value of the correction can be scaled from Figure B.2.

Much of the early literature for the Pioneer 10 and 11 encounters contains reference to \( \lambda_{1973.9} \) or \( \lambda_{1974.9} \). This usage is in error. Whenever it appears, the reader would probably be safe in assuming that System III (1975.0) is what was used, and the

referred observations were obtained in 1973.9, 1974.9, or whatever year is given in parentheses. By 1978, System III (1965) was in common usage. As far as I am aware, all of the 1979 Voyager encounter data (even the cloud imaging data) and the subsequent analyses are presented in System III (1965) coordinates. Papers published before 1977, with exceptions, use System III (1957.0).

Finally, it is sometimes necessary to convert a System II longitude to System III longitude. The conversion is, from Sjekelman and Devine [1977],

\[
\lambda_{1965} = \lambda_{1957.0} + 81.2 + 0.266 (T - 2438761.5) \quad (B.3)
\]

Readers interested in or requiring more detailed information on Jovian System III longitudes are referred to the explanatory papers by Mead [1974] (covers 1957 coordinates and the Pioneer flyby), Riddle and Warwick [1976], and particularly Sjekelman and Devine [1977] (contains the final IAU definitions for the 1965 system). Those wishing to calculate values of \( \lambda_{1965} \) for satellites or for the Central Meridian will need to consult the Astronomical Almanac. Before 1981 these volumes were published as The American Ephemeris and Nautical Almanac and The Nautical Almanac and Astronomical Ephemeris. These volumes are produced annually and are sold in the United States by the U.S. Government Printing Office and in the United Kingdom by Her Majesty's Stationery Office. There is also an Explanatory Supplement to the Astronomical Ephemeris and the American Ephemeris and Nautical Almanac, which contains explanations and derivations relevant to the Astronomical Almanac and its predecessors.

The following is a specific example of how to use the Almanac to find the phase angle and System III longitude of a specific satellite (T. D. Carr, private communication). For this example we will find the position of Europa at 1720 UT on August 24, 1976. Page references are to the American Ephemeris and Nautical Almanac, 1976.

First we calculate Europa's orbital phase \( \gamma_e \) (see next section for definitions). From page 393 of the Almanac we see that Europa, Satellite II was a Superior Geocentric Conjunction \( \gamma_e = 0° \) at 0206 UT on August 23. Using Europa's period from page 390, we find that by 1720 on the 24th the satellite has moved

\[
\gamma_e = 360° \times 1.6347/3.5541 = 166°
\]
Fig. B.3. Satellite coordinate convention. The view is from above the north pole. (a) The orbital phase angle of the satellite (in this figure is $\gamma$, which is measured counterclockwise starting from geocentric superior conjunction i.e., the anti-Earth meridian). Note that the phase angle can be similarly defined for an observing point away from the Earth, for example, a spacecraft. $\gamma = 0^\circ$ is always the anti-observer meridian. The value of $\lambda_{so}$ for the satellite is determined as in Figure B.1. (b) The longitude on a satellite is measured from its prime meridian, which is the sub-Jupiter meridian. This meridian is fixed on the Jovian satellites because the same face of each always points toward Jupiter. This is a left-handed coordinate system (longitude increases in a clockwise direction as viewed from above the north pole) so that, as seen from the Earth, longitude increases with time.

Next we find the Central Meridian Longitude. From page 383, $\lambda_s = 219.5^\circ$ at 00 UT on August 24. (Note that System III CML is not listed in the Almanac until 1981. The Almanac is not quick to adopt the latest fads.) The Julian date of 00 UT August 24 is 2443014.5 (from page 17). We convert to $\lambda_{so}$ using equation (B.3), which yields $\lambda_{so} = 1432.0^\circ$ or $\lambda_{so}(1965) = 352^\circ$. The elapsed time from 00 UT to our desired time is 0.7222 day. The change in $\lambda_{so}$ is $\Delta \lambda_{so} = 870.536^\circ$ day $\times 0.7222$ day = 629$^\circ$. Therefore at 1720 UT, $\lambda_{so}(1965)$ of Europa is 352 + 629 = 981$^\circ$ or $\lambda_{so}(1965) = 261^\circ$.

**B.2. Orbital phase angle and longitude conventions for satellites**

The position of a satellite in its orbit around Jupiter is described by an orbital phase angle. In addition, the larger satellites have longitude systems of their own (these two coordinates are illustrated in Fig. B.3). Because of its popularity in magnetospheric circles, Io is the satellite in the Figure B.3(a), but the system is the same for all of Jupiter's satellites. The orbital phase angle $\gamma$ is measured counterclockwise (as viewed from north of the ecliptic) from superior geocentric conjunction. This is a right-handed system with $\gamma = 0^\circ$ when the satellite is directly behind Jupiter as seen from the Earth. The specific satellite is indicated by a subscript, such as $\gamma_I$ for Io's phase angle. Like CML, $\gamma$ is sometimes referenced to an extraterrestrial observer (for example, a spacecraft) instead of to Earth. In such a case, $\gamma = 0^\circ$ at the orbital meridian that is 180$^\circ$ from the observer's meridian.

Longitudes is measured clockwise around each satellite starting from the meridian that points toward Jupiter. This definition of a prime meridian is possible for the Jovian satellites because the same side of a given satellite always faces Jupiter, as does the Earth's Moon. (The actual definition of the prime meridian is more complex than indicated here because slight ellipticity of a satellite orbit causes some periodic (libration) motion of the sub-Jupiter meridian. However, the above definition, illustrated in Fig. B.3(b), should be adequate for magnetospheric study.)

**Coordinate systems**

Fig. B.4. Jovian dipole equator. The spin equator is a plane that passes through the center of the planet and is perpendicular to the spin axis, which is shown here having an angular velocity $\Omega$. The magnetic equator is the surface defined by the locus of points of minimum magnetic field strength along a magnetic line of force from dipole moment $M$. This point is located where $r$ reaches its maximum value. The centrifugal equator is the surface defined by the locus of points that are at the maximum distance (or where $\rho$ is a maximum) from the spin axis for given lines of force. If Jupiter's magnetic dipole is tilted at an angle $\omega = 10^\circ$ toward $\lambda_{so} = 200^\circ$, the centrifugal equator is tipped 7$^\circ$ toward this same longitude.

**B.3. Latitude conventions**

There are, as for the Earth, two latitude systems for Jupiter. There is the conventional Jovigraphic system with latitude measured positive northward from the spin equator. In addition, there is a magnetic latitude system defined by a centered tilted dipole. The northern end of this dipole is tilted 10$^\circ$ toward $\lambda_{so}(1965) = 200^\circ$, and the southern end is, of course, tilted 10$^\circ$ toward $\lambda_{so} = 20^\circ$ (values given for the tilt differ by about $\pm 5^\circ$ and values of $\lambda_{so}$ by about $\pm 3^\circ$, see Tables 1.2 and 1.3). The magnetic equator is the plane that is perpendicular to the centered dipole and passes through Jupiter's center. Latitude is measured positive northward.

A possible source of confusion is that the symbol $\lambda$ has been usurped to signify Jovian longitude, whereas $\lambda$ is commonly used to designate latitude on the Earth. In this book we have selected $\psi$ for the Jovigraphic latitude symbol, and $\psi$, for magnetic latitude.

Magnetic and Jovigraphic latitudes agree where the two equators cross ($\lambda_{so} = 110^\circ$ and 290$^\circ$). Near the equator, the difference between magnetic and Jovigraphic latitude as a function of System III longitude is approximated by

$$-\delta \psi = \phi_x - \psi = 10^\circ \sin \theta_{so} - 110^\circ$$

(B.4)

Because the Io plasma torus is important, and because it consists principally of relatively heavy ions with low energies, one other "equator" is necessary to fully describe the Jovian magnetosphere, and that is the "centrifugal equator." Energetic charged particles bounce (mirror) about the magnetic equator. An energetic particle with 90$^\circ$ pitch angle will drift along the magnetic equator. Because of the large quadrupole and octupole moments in Jupiter's magnetic field, particles close to Jupiter drift along a more complex path, the "particle drift equator," shown in Figure 1.12. Note that at distances of only 6 $R_j$, the drift equator (shown as the dotted line) is essentially that of a simple dipole.

Particles of sufficiently low energy are affected by centrifugal force in Jupiter's large, rapidly rotating magnetosphere. They do not follow the magnetic equator. Consider first a particle of zero magnetic moment (or perpendicular energy) in the corotating frame. It will slide along a magnetic field line and settle at the point (or oscillate

$$\sin \varpi = \frac{1}{17} (\cos \varpi - 292\)
APPENDIX C
JUPITER AND IO: SELECTED PHYSICAL PARAMETERS

**Jupiter**
- Heliocentric distance: $5.20 \text{ AU} = 7.78 \times 10^8 \text{ km}$
- Sidereal period: $11.86 \text{ years}$
- Synodic period: $398.88 \text{ days} = 13.10 \text{ months} = 1.092 \text{ years}$
- Mean orbital speed: $13.06 \text{ km/s} = 15.7 R_J/\text{day}$
- Equatorial radius ($1 R_J$): $7.14 \times 10^4 \text{ km}$ = 1 $R_J$ (by definition)
- Polar radius: $6.68 \times 10^4 \text{ km}$
- Practical radius (nearly the mean and easily remembered): $7 \times 10^4 \text{ m}$
- Mass: $317.8 M_J = 1.901 \times 10^{27} \text{ kg}$
- Escape speed: $61 \text{ km/s}$
- Gravitational acceleration: $25.9 \text{ m/sec}^2 = 2.64 g_J$
- Escape energy for Hydrogen atom: $19.4 \text{ eV}$
- System III (1965) sidereal spin period: 9 hr 55 min 29.71 sec (derived from angular velocity) = $3.573 \times 10^4 \text{ sec} = 9.925 \text{ hr}$
- System III (1965) angular velocity: $1.76 \times 10^{-6} \text{ rad/sec} = 870.536/\text{day}$ (by definition)
- System I (equatorial clouds) sidereal spin period: $9 \text{ hr} 50 \text{ min} 30.00 \text{ sec} = 9.842 \text{ hr}$
- System II (polar clouds) sidereal spin period: $9 \text{ hr} 55 \text{ min} 40.63 \text{ sec} = 9.928 \text{ hr}$
- Rotational (spin) kinetic energy: $3.6 \times 10^{33} \text{ J}$
- Spin equator inclined to orbital plane: $3^\circ 5^\prime$
- Main magnetic-dipole moment: $4.2 \times 10^{16} T \cdot R_J^3$
- Magnetic dipole tilt: $9.8^\circ \pm 0.3^\circ$
- Tilt toward: $\lambda_J = 200^\circ \pm 2^\circ$
- Dipole displaced: $0.12 \pm 0.02 R_J$, toward $\lambda_J = 149^\circ \pm 6^\circ$

**Io**
- Jovianentric distance: $5.91 R_J = 4.216 \times 10^5 \text{ km}$
- Sidereal period: $17.34 \text{ km/sec}$
- Mean orbital speed about Jupiter: $4.112 \times 10^{-1} \text{ rad/sec}$
- Angular velocity about Jupiter: $1.82 \times 10^{-4} \text{ km} = 2.55 \times 10^{-7} R_J$
- Mass: $8.91 \times 10^{24} \text{ kg}$
- Escape speed: $2.56 \text{ km/sec}$
- Gravitational acceleration: $1.80 \text{ m/sec}^2 = 0.184 g_J$
- Corotation speed at Io's orbit: $74.2 \text{ km/sec}$
- Angular velocity of corotation relative to Io: $1.35 \times 10^{-3} \text{ rad/sec}$
- Speed of corotation relative to Io: $56.8 \text{ km/sec}$
- Corotation electric field at Io: $0.113 \text{ V/m outward from Jupiter}$
- Max potential across Io: $411 \text{ kV}$

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