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 ($\approx$ 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_3^+ and H_2^+ 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 magnetospheric 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

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APPENDIX A
SYMBOLS AND ACRONYMS

Symbols

A		amps
		collecting area of telescope
		angstroms
		atomic mass number
	A_+	mean atomic number of ions
$\tilde{\mathbf{A}}$		magnetic vector potential
A_p		geomagnetic index
A_0		spin averaged flux
A_1		first order anisotropy in particle flux
A_2		second order anisotropy in particle flux
A_n		n^{th} order anisotropy in particle flux
A_c		critical anisotropy of electrons required for instability
A_e		pitch angle anisotropy of resonant e^-
B		magnetic field
	B_r, B_θ, B_ϕ	right-hand spherical components of **B**
	B_ρ, B_ϕ, B_z	right-hand cylindrical components of **B**
	B_A	magnetic field (strength) at the top of the atmosphere
	B_c	projection of **B** onto Jovigraphic equatorial plane
	B_{eq}	equatorial magnetic field
	B_I	magnetic field at Io
	B_{max}	maximum hourly average magnetic field
	B_T	magnetic field in tail lobes
	$\mathbf{B}_0$	background magnetic field
	$\hat{\mathbf{B}}$	unit magnetic field vector
	$\hat{\mathbf{B}}\hat{\mathbf{B}}$	unit dyadic of magnetic field
b		any magnetic field external to the current sheet, other than the planetary dipole and the planar field of the current sheet itself
$\hat{\mathbf{b}}$		unit vector parallel to **b**
c		speed of light
D		dispersion (units s-$Hz^{1/2}$)

D_{LL}	radial diffusion coefficient
D_0	diffusion coefficient at $L = 1$ ($D_{LL} = D_0 L^n$)
D_{ij}	diffusion coefficient
D_{vv}	energy diffusion coefficient
$D_{\alpha\alpha}$	pitch angle diffusion coefficient
$\mathscr{D}_{\alpha}$	pitch angle diffusion coefficient, bounce averaged
D	length scale for thickness or depth of a region
D_E	Jovicentric declination of the Earth (degrees) angular distance of the Earth from Jupiter's spin equator
D_S	Jovicentric 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)
f	reconnection efficiency = $E_{\substack{magnetospheric\\convection}} / E_{\substack{solar\\wind}}$ dynamic flattening of Jupiter Euler potential magnetic flux function frequency f_c cyclotron frequency f_{ce} electron cyclotron frequency f_{ci} ion cyclotron frequency f_p plasma frequency f_{pe} electron plasma frequency f_{pi} ion plasma frequency f_{LHR} lower hybrid resonance frequency f_{UHR} upper hybrid resonance frequency distribution function f_e electron distribution function f_0 phase-averaged distribution function
G	Newton's gravitational constant geometric factor
g	gravitational acceleration

g	local acceleration of gravity at a planet or moon Euler potential
H	local horizontal field component scale height
h	distance variable Planck's constant
$\hbar$	Planck's constant/2π
I	Stokes parameter (total flux density) dip angle total current (amps)
J	second adiabatic invariant integral particle flux
J_i	action integral associated with i^{th} adiabatic periodicity of motion
J_e^*	resonant integral electron flux
J_p^*	critical proton integral flux for ion-cyclotron instability
$\tilde{\mathbf{j}}$	current density $j_\perp$ current perpendicular to **B** $j_\parallel$ current parallel to **B**, field-aligned (Birkeland) current
j	differential particle flux j_e differential particle flux for electrons j_T trapped differential flux
j_B	Birkeland (field-aligned) current density
$\tilde{\mathbf{j}}_t$	current tangential to the current sheet
j'	current density (amps/m) height-integrated current density
K	Kelvin degrees energy injection rate eddy diffusion coefficient
K_h	eddy diffusion coefficient at Jupiter's homopause
K_ν	modified Bessel function of the second kind of order ν
K_{th}	thermal energy

k — Boltzmann constant
rate coefficient

$\overline{k}$ — wave propagation vector
- $k_\perp$ component of wave propagation vector perpendicular to B
- $k_\parallel$ component of wave propagation vector parallel to B

L — magnetic field line equatorial crossing distance at R_J
loss rate

$d\overline{L}$ — path element

$\mathscr{L}$ — loss rate

ℓ — distance between points measured along a magnetic field line

M — planetary magnetic dipole moment

M_J — mass of Jupiter

M_A — Alfvén Mach number

M_s — sonic Mach number

m — particle mass
- m_a mass of an ion of species "a"
- m_e mass of electron
- m_i mass of ion
- m_0 particle (rest) mass
- m_p mass of proton

N — total number of ions/unit L-shell
column number abundance of emitting species (per unit area)
total number – as opposed to n: number/volume

n — refractive index
plasma number density or concentration (number/volume) – as distinct from N: total number or column number density (number/area)
- n_e e^- concentration (number/volume)
- n_i ion concentration (number/volume)
- n_p concentration of protons (amu/volume)
- n_H hydrogen concentration (number/volume)

P — pressure
power (in watts)

P_c — degree of circular polarization (sign indicates sense)
P_L — degree of linear polarization

P_e — production rate/unit volume (electrons)
P_i — production rate/unit volume (ions)

$P_n^m(\cos\theta)$ — associated Legendre polynomial

$\mathbf{p}$ — momentum vector

Q — Stokes parameter

q — particle's charge

R — count rate
reflection coefficient

R_J — radius of Jupiter

R_I — radius of Io

R_p — planetary radius

r — axial ratio (sign indicates RH or LH) (characterizes polarization of radiation)
Jovicentric distance

r_m — effective radius of one of Jupiter's moons

S — total flux density
source term with units phase space density/time
column production rate of ions

s — a quantum state corresponding to momentum $p_\parallel$ and $p_\perp$

T — temperature
- $T_\perp$ temperature characterizing thermal motion perpendicular to $\mathbf{B}$
- $T_\parallel$ temperature characterizing thermal motion parallel to $\mathbf{B}$
- T_e electron temperature
- T_i ion temperature

t — time

U — potential
Stokes parameter

V — Stokes parameter (sign specifies polarization sense [– RH, + LH]
magnetic potential

$\mathbf{V}$ — plasma bulk velocity
- V_A Alfvén velocity
- V_I orbital velocity of Io
- V_s solar-wind velocity

v velocity of particle
- $v_{\parallel}$ component of particle velocity parallel to **B**
- $v_{\perp}$ component of particle velocity perpendicular to **B**
- $\bar{\mathbf{v}}_n$ velocity of the neutral atmosphere
- v_C corotation velocity
- v_g average wave group speed
- v_{ph} wave phase velocity

w total particle energy
- $w_{\parallel}$ energy due to particle motion parallel to **B**
- $w_{\perp}$ energy due to particle motion perpendicular to **B**

Y magnetic flux shell density

Z atomic charge in units of e

z altitude

α pitch angle
angle between Jupiter's rotational and magnetic axes ($\sim 10°$)
alpha particle (He nucleus)
polarizability of an atom (in units of Bohr radii cubed) recombination rate
- α_r radiative recombination coefficient

β plasma parameter = particle thermal pressure/magnetic pressure
angle between the centrifugal symmetry surface and the magnetic equator of Jupiter

γ $= 10^{-5}$ Gauss $= 10^{-9}$ Tesla
index in power law spectrum $\sim E^{-\gamma}$
adiabatic index

γ_I Io phase angle

γ_r relativistic contraction factor

θ co-latitude in right-hand polar coordinates

Λ invariant latitude

λ wavelength

λ_D Debye length

λ_{III} system III longitude

μ first adiabatic invariant (magnetic moment)
reduced mass

μ_o magnetic permeability of free space

ρ mass density
particle's cyclotron radius

Σ conductivity
- Σ_p height-integrated Pedersen conductivity
- Σ_A Alfvén conductance

σ cross section

τ characteristic lifetime of particles

τ_b bounce time for travel between magnetic mirror points

Φ electric potential drop
third adiabatic invariant

Φ_{sc} spacecraft potential (volts)

χ solar zenith angle

ψ_m magnetic latitude

Ω_J angular frequency of Jupiter

ω frequency (angular)
- ω_c cyclotron frequency of a given species
- ω_{ce} electron cyclotron frequency
- ω_{ci} ion cyclotron frequency
- ω_{pi} ion plasma frequency
- ω_{pe} electron plasma frequency
- ω_{LHR} frequency of lower hybrid resonance
- ω_{UHR} frequency of upper hybrid resonance
- ω_R right-hand cutoff frequency
- ω_L left-hand cutoff frequency

Acronyms

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

BP/WP 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

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_4	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_4	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

O_4	magnetic field model of Acuña and Ness [1976] (same as GSFC O_4)
P10	Pioneer 10
P11	Pioneer 11
P.A.	position angle of the plane of linear polarization
PLS	low-energy plasma instrument
PWS	plasma-wave instrument
RH	right-hand circularly polarized
RP/RD	rocking plane-rotating disc model of Jovian magnetodisc
RSS	radioscience instrument
S/C	spacecraft
SCET	spacecraft event time
SCM	spacecraft maneuver
SKR	Saturn kilometric radiation
SZA	solar zenith angle
TD	tangential discontinuity
TKR	terrestrial kilometric radiation
UT	universal time
UV	ultraviolet
UVS	ultraviolet spectrometer
V1	Voyager 1
V2	Voyager 2

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 (i.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 starting time, Greenwich noon on July 14, 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 50m 30.0034s for System I and 9h 55m 40.6322s for System II). It is the rotation rate that is exact by

* It can be argued that continental drift does not move the land on which the Greenwich transit telescope rests. By definition it is the other land masses that move.

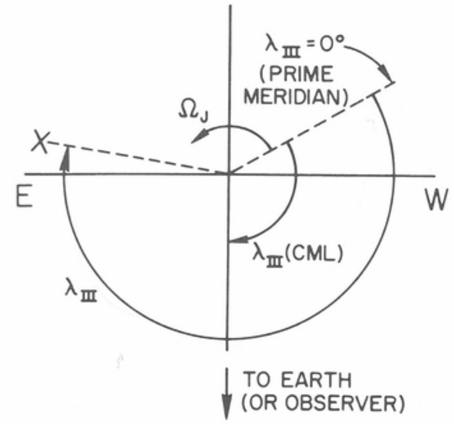


Fig. B.1. Jovian coordinate convention. The view is from above the north pole. The standard astronomical definition of the eastern and western sides of Jupiter as seen from the Earth are indicated by an E and W, respectively. Unfortunately the reverse (or the terrestrial convention), with east on the right and west on the left is also prevalent in the literature. The reader should be wary. The prime meridian rotates counterclockwise at a constant rate Ω_J. Longitude is measured clockwise from this prime meridian. The System III longitude of the Earth, or of any observer, is called the Central Meridian Longitude (CML). This illustration also shows the longitude of some object (a satellite, spacecraft, or phenomenon) marked X. Although this figure shows λ_{III}, the same conventions apply to λ_I and λ_{II} the only difference being the numerical value of Ω_J, which is different for each system, and which causes the three prime meridians to move relative to each other.

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 29.37s (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 10^5, the period being too short by about 1/3 s. The result was that a given radio phenomenon drifted steadily in longitude. This drift amounts to only 3.4×10^{-3} degrees/Jovian rotation, but in a year it grows to $3.4 \times 10^{-3} \times 365$ d/yr $\times$ 2.4 rev/d = 3°/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 10^6 (consistent with the stated uncertainty in the IAU value). This could lead to a drift of 0.19°/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 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 $\lambda_{III}(1957.0)$ to $\lambda_{III}(1965)$ on a given Julian date t is given by Riddle and Warwick [1976], and in a slightly more precise form by Seidelman and Devine [1977], as

$$\lambda_{III}(1965) = \lambda_{III}(1957.0) - 0.0083169\,(t - 2438761.5) \qquad \text{(B.1)}$$

The number inside the final 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

$$\lambda_{III}(1965) = \lambda_{III}(1957.0) - 3.04T \qquad \text{(B.2)}$$

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 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 $\lambda_{III}(1973.9)$ or $\lambda_{III}(1974.9)$. This usage is in error. Whenever it appears, the reader would probably be safe in assuming that System III(1957.0) is what was used, and the

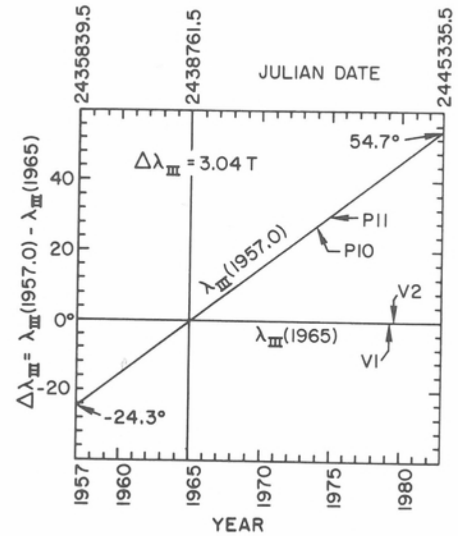


Fig. B.2. Difference between $\lambda_{III}(1957.0)$ and $\lambda_{III}(1965)$. The two longitude systems were in agreement at 00 UT on January 1, 1965. The 1957.0 coordinate system drifts slowly relative to Jupiter's magnetic field. To convert a $\lambda_{III}(1957.0)$ longitude to $\lambda_{III}(1965)$ simply subtract $\Delta\lambda_{III}$ from the 1957.0 value. In the equation, T is the time in years since 1965.0. The times for the Jupiter encounters for Pioneer 10 and 11 are shown on the 1957.0 line and for Voyager 1 and 2 on the 1965 line. (See also Eqs. (B.1) and (B.2).)

referenced 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 Seidelman and Devine [1977],

$$\lambda_{III}(1965) = \lambda_{II} + 81.2 + 0.266\,(t - 2438761.5) \qquad \text{(B.3)}$$

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 flybys), Riddle and Warwick [1976], and particularly Seidelmann and Devine [1977] (contains the final IAU definitions for the 1965 system). Those wishing to calculate values of λ_{III} 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 Alamanac 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 Alamanac*, 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 γ_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

$$\gamma_E = 360° \times 1.6347/3.5541 = 166°$$

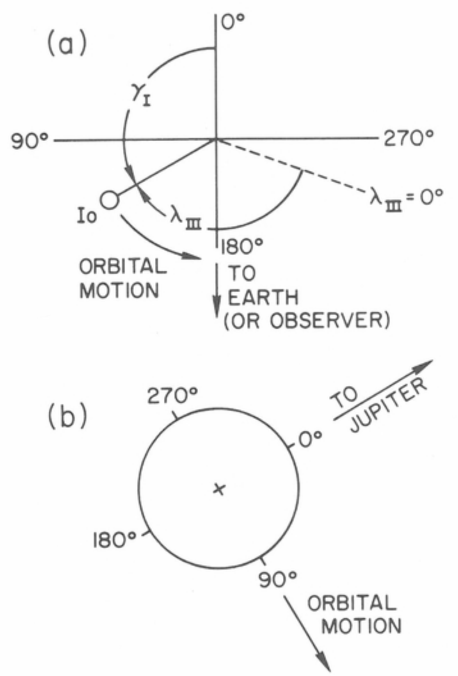


Fig. B.3. Satellite coordinate convention. The view is from above the north pole. *(a)* The orbital phase angle of the satellite (Io in this figure) is γ_I, which is measured counterclockwise starting from geocentric superior conjunction (i.e., the anti-Earth meridian). Note that the phase angle can be similarly defined for an observing point away from the Earth, for example, a spacecraft. $\gamma = 0°$ is always the anti-observer meridian. The value of λ_{III} 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.

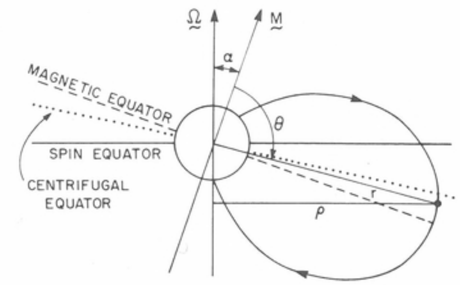
Next we find the Central Meridian Longitude. From page 383, $\lambda_{II} = 219.5°$ at 00 UT on August 24. (Note that System III CML is not listed in the *Almanac* until 1981. The *Alamanac* is not quick to adopt the latest fads.) The Julian date of 00 UT August 24 is 2443014.5 (from page 17). We convert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

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 γ is measured counterclockwise (as viewed from north of the ecliptic) from superior geocentric conjunction. This is a right-handed system with $\gamma = 0°$ when the satellite is directly behind Jupiter as seen from the Earth. The specific satellite is indicated by a subscript, such as γ_I for Io's phase angle. Like CML, γ is sometimes referenced to an extraterrestrial observer (for example, a spacecraft) instead of to Earth. In such a case, $\gamma = 0°$ at the orbital meridian that is 180° from the observer's meridian.

Longitude 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.)

Fig. B.4. Jovian dipole equators. 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 $\tilde{\Omega}$. 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 the maximum distance (or where ρ is a maximum) from the spin axis for given lines of force. If Jupiter's magnetic dipole is tilted at an angle $\alpha = 10°$ toward $\lambda_{III} = 200°$, the centrifugal equator is tipped 7° 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° toward $\lambda_{III}(1965) = 200°$, and the southern end is, of course, tilted 10° toward $\lambda_{III} = 20°$ (values given for the tilt differ by about $\pm 1°$ and values of λ_{III} by about $\pm 3°$, 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 λ has been usurped to signify Jovian longitude, whereas λ is commonly used to designate latitude on the Earth. In this book we have selected ψ for the Jovigraphic latitude symbol, and ψ_m for magnetic latitude.

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

$$-\alpha = \Delta\psi = \psi_m - \psi = 10° \sin(\lambda_{III} - 110°) \qquad \text{(B.4)}$$

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° 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

$\psi_m = \psi + \Delta\psi = \psi - \alpha$

$\sin\alpha = \sin 9.6° \sin(\lambda_{III} - 292°)$

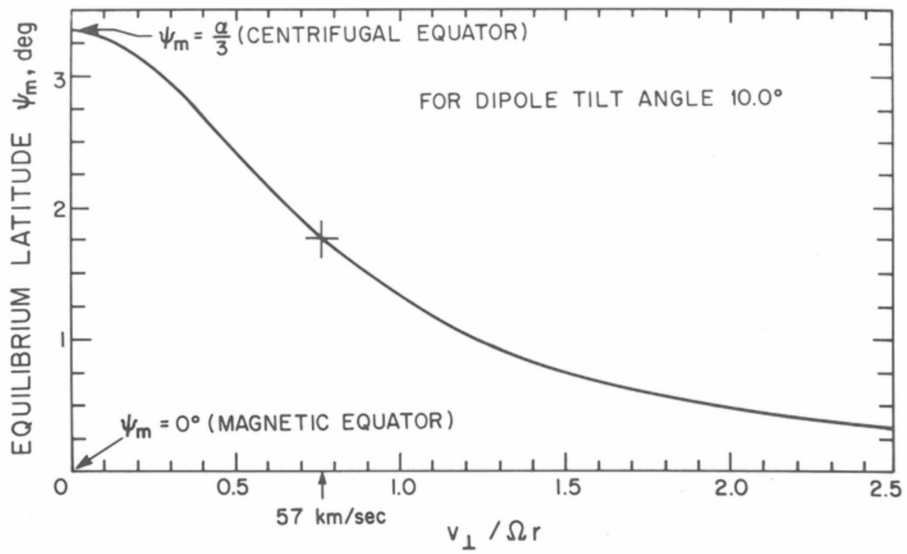


Fig. B.5. The equilibrium latitude of a charged particle as determined by centrifugal and magnetic-moment forces. The abscissa is the particle speed perpendicular to the magnetic field ($v_\perp$) in units of corotation speed (Ωr) where Ω is the corotation angular velocity and r is the Jovicentric distance to the particle. The $v_\perp$ of an ion freshly injected from Io is indicated (57 km/s). The plane of equilibrium latitude for such particles is tilted about 1.8° from the magnetic equator. Note that the equilibrium latitude depends only on particle speed, not charge or mass [after Cummings et al., 1980].

about the point) that is a maximum distance from the spin axis. The locus of such points defines the centrifugal equator. The centrifugal equator lies between the magnetic and spin equators, as illustrated in Figure B.4. It is the locus of points for which ρ is a maximum. If the magnetic field is that of a simple dipole, the centrifugal equator is tipped away from the magnetic equator and toward the spin equator by 1/3 of the dipole tilt angle α. If the field is not dipolar, the angle between the magnetic equator and the centrifugal equator is $\alpha r_c / L$ where r_c is the radius of curvature of the field line at the centrifugal equator, and L is the equatorial crossing distance of the field line.

A warm particle having a nonzero magnetic moment experiences a mirroring force that pushes it toward the magnetic equator. Such a particle has an equilibrium position somewhere between the centrifugal and magnetic equators, as illustrated in Figure B.4. The displacement of this equilibrium position from the magnetic equator as a function of the particle's cyclotron speed, normalized in terms of the corotation speed, is shown in Figure B.5. Note that, in this presentation, the equilibrium latitude is independent of particle mass or charge.

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APPENDIX C

JUPITER AND IO: SELECTED PHYSICAL PARAMETERS

Jupiter

Heliocentric distance	5.20 AU = 7.78×10^8 km
Sidereal period	11.86 years
Synodic period	398.88 days = 13.10 months = 1.092 years
Mean orbital speed	13.06 km/sec = 15.7 R_J/day
Equatorial radius (1 R_J)	7.14×10^4 km = 1 R_J (by definition)
Polar radius	6.68×10^4 km
Practical radius (nearly the mean and easily remembered)	7×10^7 m
Mass	317.8 $M_\oplus$ = 1.901×10^{27} kg
Escape speed	61 km/sec
Gravitational acceleration	25.9 m/sec^2 = 2.64 $g_\oplus$
Escape energy for Hydrogen atom	19.4 eV
System III (1965) sidereal spin period	9 hr 55 min 29.71sec (derived from angular velocity) = 3.573×10^4 sec = 9.925 hr
System III (1965) angular velocity	1.76×10^{-4} rad/sec = 870.536°/day (by definition)
System I (equatorial clouds) sidereal spin period	9 hr 50 min 30.00 sec = 9.842 hr
System II (polar clouds) sidereal spin period	9 hr 55 min 40.63 sec = 9.928 hr
Rotational (spin) kinetic energy	3.6×10^{34} J
Spin equator inclined to orbital plane	3° 5′
Main magnetic-dipole moment	4.2×10^{-4} TR_J^3
Magnetic dipole tilt	9.8° ± 0.3°
Tilt toward	λ_{III} = 200° ± 2°
Dipole displaced	0.12 ± 0.02 R_J toward λ_{III} = 149° ± 6°

Io

Jovicentric distance	5.91 R_J = 4.216×10^5 km
Sidereal period	1.769 days = 42.46 hr
Mean orbital speed about Jupiter	17.34 km/sec
Angular velocity about Jupiter	4.112×10^{-5} rad/sec
Radius	1.82×10^3 km = 2.55×10^{-2} R_J
Mass	8.91×10^{22} kg
Escape speed	2.56 km/sec
Gravitational acceleration	1.80 m/sec^2 = 0.184 $g_\oplus$
Corotation speed at Io's orbit	74.2 km/sec
Angular velocity of corotation relative to Io	1.35×10^{-4} rad/sec
Speed of corotation relative to Io	56.8 km/sec
Corotation electric field at Io	0.113 V/m outward from Jupiter
Max potential across Io	411 kV