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ABSORPTION OF TRAPPED PARTICLES BY JUPITER'S MOONS

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ABSTRACT

We have included absorption effects of the four innermost moons in the radial transport equations for electrons and protons in Jupiter's magnetosphere. We find that the phase space density n at 2 R_J for electrons with equatorial pitch angles $<69^{\circ}$ is reduced by a factor of 4.2×10^4 when lunar absorption is included in the calculation. For protons with equatorial pitch angles $<69^{\circ}$ the corresponding reduction factor is 3.2×10^6. The effect of the satellites becomes progressively weaker for both electrons and protons as equatorial pitch angles of $\pi/2$ are approached because the likelihood of impacting a satellite becomes progressively smaller. The large density decreases which we find at the orbits of Io, Europa, and Ganymede result in corresponding particle flux decreases that should be observed by spacecraft making particle measurements in Jupiter's magnetosphere. The characteristic signature of satellite absorption should be a downward pointing cusp in the flux vs. radius curve at the L-value corresponding to each satellite.

INTRODUCTION

The Galilean satellites of Jupiter, located deep within its magnetosphere, may play an important role in limiting the fluxes of electrons and protons in Jupiter's radiation belts. The effectiveness with which a moon reduces particle fluxes in its neighborhood by its sweeping effect depends on how rapidly particles move radially across the moon's orbit by diffusion and acceleration processes. Mead and Hess (1973) concluded that if radial diffusion were caused by solar wind-induced magnetic field variations or by fluctuations in the convection electric field in Jupiter's magnetosphere, diffusion would proceed very slowly at low altitudes, and the inner Galilean moons would absorb essentially all radially diffusing particles.

Recent studies by Brice and McDonough (1973), Jacques and Davis (1972), Coroniti (1973), Birmingham et al. (1973), and Stansberry and White (1973) have indicated, however, that if the trapped electrons responsible for Jupiter's decimeter radiation have diffused in from the solar wind, additional low-altitude diffusion mechanisms are needed in order to bring the electrons down to the synchrotron-emitting region in times comparable to their average synchrotron loss lifetimes. Brice and McDonough have suggested that inside about 10 R_J, the diffusion is probably caused by electric fields associated with an upper atmospheric dynamo driven by neutral winds. This type of diffusion is estimated to be much stronger than diffusion generated by magnetopause motions or convection electric fields in the region $R < 10\ R_J$, because of the proximity of its source.

Birmingham et al. (1973; hereafter referred to as BHNBL) have determined a radial diffusion coefficient D by making empirical fits to the observed 10.4-cm radiation from Jupiter (Berge, 1966). A steady-state model of the electron radiation belts was developed. This model assumed injection of particles from the solar wind, radial diffusion, energy degradation by synchrotron radiation, and absorption at Jupiter's surface. A diffusion coefficient of the form

$$D = k\ R^{m} \tag{1}$$

was assumed. The following values of the parameters were in best agreement with the observations:

$$k = 1.7 \pm 0.5 \times 10^{-9}\ R_J{}^2/\mathrm{sec} \tag{2}$$

$$m = 1.95 \pm 0.5$$

$$\mu_o = 770\ \mathrm{MeV/Gauss}$$

where μ_o is the (monoenergetic) magnetic moment at the time of injection. These values of k and m are reasonably consistent with the atmospheric dynamo mechanism.

LUNAR ABSORPTION MODEL

In this paper we estimate the absorption effects of the moons Amalthea ($R = 2.55\ R_J$), Io ($R = 5.95\ R_J$), Europa ($R = 9.47\ R_J$), and

Ganymede ($R = 15.1\ R_J$), by adding loss terms representing these satellites to the BHNBL electron transport equation:

$$-R^{15/2}\frac{\partial}{\partial R}\left[\frac{kR^{m}}{R^{2}}\frac{\partial}{\partial R}\left(nR^{2}\right)\right]-2.5\times10^{-6}\frac{\partial}{\partial\mu}\left[\mu^{3/2}\left(1+\frac{R^{3}}{39\mu}\right)^{1/2}n\right]$$
$$+\sum_{i=1}^{4}\frac{n}{\tau_i}S(R-R_i\pm a_i)=NR_0^{15/2}\delta(R-R_0)\,\delta(\mu-\mu_0) \qquad (3)$$

As in BHNBL, n is the number of electrons with magnetic moments between μ and $\mu + d\mu$ (μ is in units of MeV/Gauss), with longitude invariants between 0 and ΔJ, contained in a (dipole) magnetic field flux tube which crosses the jovimagnetic equatorial plane a distance R (in units of Jovian radii) from the center of the planet and which has a cross-sectional area of $R\,dR\,d\phi$ in that plane ($d\phi$ is an element of longitude). The first term on the left side is the radial diffusion term, the second term represents synchrotron energy loss, and the third term represents absorption by the satellites. The source, located at R_0 with the source strength N, is represented by the term on the right. (The position of the source, so long as it is further out than Ganymede, has no effect on the radial shape of n at $R < 15.1\ R_J$; we have taken $R_0 = 35\ R_J$.) The four satellites, $i = 1$ to 4, are centered at distances R_i from the center of the planet and have radii a_i. The step function $S(R-R_i \pm a_i)$ is unity over the region $R_i - a_i < R < R_i + a_i$ and zero elsewhere. The average "lifetimes" τ_i depend on the electron energy and equatorial pitch angle as well as the satellite by which the electron is being absorbed. Implicit in

Equation 3 is the assumption that a single form of D is valid out to the radius of Ganymede's orbit.

As in BHNBL, Equation (3) is solved by a numerical finite difference technique with the boundary conditions that n vanish at the surface of Jupiter $[n\ (R=1) = 0]$ and at the magnetopause $[n(R=R_m) = 0]$ and that the sole source of electrons be that shown explicitly on the right hand side (we thus demand that $n(\mu > \mu_o) = 0$ so that there is no flow of electrons into the system through boundaries in μ-space).

RESULTS

Equation (3) has been solved for several different combinations of parameters. In all cases we have taken μ_o = 770 MeV/Gauss at injection. Populations of electrons with $\mu < \mu_o$ are formed, however, due to energy degradation caused by synchrotron radiation. The upper curve in Figure 1 is a plot of the density of the highest-energy electrons ($\mu = \mu_o$) vs. R for m = 1.95 and k = 1.7 x 10^{-9} $R_J{}^2$/sec. (Electrons with $\mu = \mu_o$ occur at radii other than the injection radius R_o because of the finite difference method of solution; cf. discussion in BHNBL.)

The lower curve of Figure 1 shows the effect of lunar absorption on electrons with equatorial pitch angles everywhere less than 69^o (mirror latitudes greater than 10^o). These electrons undergo Case 2 or snowplow absorption (Mead and Hess, 1973). That is, since their mirror latitude is always greater than the jovimagnetic latitude of the absorbing moon, and since the relative longitudinal motion with respect to the moon during one bounce period is less than a lunar diameter, the characteristic absorption time τ_i at each moon is roughly equal to the lunar corotation period, i.e., the apparent (retrograde) period of revolution of each moon in a frame of reference rotating with Jupiter's decametric rotation period (Mead and Hess, 1973). The trapped particles are assumed to corotate with the planet at least out to 16 R_J. This lunar corotation period is 2.4 days at Amalthea, 0.54 days at Io, 0.47 days at Europa, and 0.44 days at Ganymede.

A significant absorption effect occurs at the positions of Io, Europa, and Ganymede (due to its tiny size, Amalthea exerts a negligible effect). The effect is seen as a discontinuity in the slope of the electron density at each of the satellite positions, producing a downward-pointing cusp.

Due to the 10° tilt of Jupiter's dipole with respect to its rotation axis, electrons with equatorial pitch angles greater than 59° will have longer average absorption lifetimes at each satellite. The Galilean satellites oscillate between $\pm\ 10^{\circ}$ jovimagnetic latitude in one corotation period, and low-latitude-mirroring particles are less likely to collide with a satellite than are high-latitude-mirroring particles (Mead and Hess, 1973). The middle curve of Figure 1 shows the density of electrons with an equatorial pitch angle of 87° (mirror latitude of 1.5°) at $R = 1.85\ R_J$, the heart of Jupiter's synchrotron radiation region. These electrons would contribute significantly to the emission observed at Earth. The equatorial pitch angle varies from 87° to 84.9° in the region out to 16 R_J under μ and J conservation. The absorption lifetimes for a $\mu = 770$ MeV/Gauss electron as calculated from Equation 37 of Mead and Hess (1973) are 25 days at Amalthea, 5.8 days at Io, 5.1 days at Europa, and 5.0 days at Ganymede. The effects of absorption are clearly greatly reduced for these near-equatorial particles.

The effectiveness of each satellite in wiping out electrons which mirror at latitudes greater than 10° is also evident from the first column of Table 1. The reduction factor is the ratio of n at adjacent points midway between satellites. The cumulative effect of the satellites on these same electrons is seen from the second column of Table 2. The ratio listed here is the value of n without moons (upper curve of Fig. 1) divided by n with moons (lower curve of Fig. 1) at the same R.

The error limits quoted in Equation (2) result from uncertainties in fitting the Berge (1966) data. The dependence of satellite wipe-out on these uncertainties has been estimated by also solving Eq. (3) for high latitude mirroring electrons for the following pairs of m and k: 1) $m = 1.45$, $k = 1.7 \times 10^{-9}$ sec^{-1}; 2) $m = 2.45$, $k = 1.7 \times 10^{-9}$ sec^{-1}; 3) $m = 1.95$, $k = 1.2 \times 10^{-9}$ sec^{-1}; and 4) $m = 1.95$, $k = 2.2 \times 10^{-9}$ sec^{-1}. Results for Cases 1 and 2 are shown in Fig. 2. We show both high-μ (μ=770 MeV/gauss) and low-μ (μ=0.48 MeV/gauss) electrons. (The dotted curves are the m = 1.95 results without moons.) Uncertainties in n resulting from this m variation are of the order of a factor of 20 at each satellite for the μ = 770 MeV/gauss electrons. They are even larger for the low-μ electrons. In no way, however, do these uncertainties negate the conclusion that the satellites are very effective in wiping out high latitude mirroring electrons. Uncertainties in n due to the k-variation are of the order of a factor of 2 at each satellite and hence considerably smaller than those shown in Fig. 2. Values of the reduction factor at each satellite for μ = 770 MeV/gauss electrons are also listed in Table 1 for Cases 1-4.

The Galilean satellites can be similarly important in limiting the fluxes of energetic protons. We have studied this effect by solving Eq. (1) with the synchrotron energy loss term eliminated. (Because of their mass, protons are far poorer synchrotron radiation emitters than are electrons of the same μ.) The values of μ_o and D were taken to be the same as were determined for the electrons. Figure 3 shows the results for protons mirroring at latitudes greater than 10^o. The lifetimes of these particles (0.14 days at Amalthea, 0.28 days at Io, 0.38 days at Europa, 1.13 days at Ganymede) were calculated in the same way as for electrons, the one difference being that proton energies close in to Jupiter's surface are so large that gradient-curvature drifts strongly dominate co-rotational $\vec{E}x\vec{B}$ motions. Shown for comparison is the lower electron curve of Fig. 1.

The generally greater effectiveness of the satellites in removing protons, as seen in Fig. 3 and Tables 1 and 2, results from the shorter absorption lifetimes of protons. The precipitous fall-off of the electron density inside of Io is partly the strong effect of electron synchrotron energy loss in this region. The cumulative effect of the satellites is to reduce the proton density near R = 2 by a factor of 3.2×10^6 from what it would be without moons.

DISCUSSION

Because the Galilean satellites have such a large effect on the electron density, it is legitimate to question the use of m = 1.95 and $k = 1.7 \times 10^{-9}$ sec^{-1} which were obtained by BHNBL without considering satellite absorption. We have repeated the synchrotron calculation of BHNBL with these same values of m and k and with satellite absorption included in the electron transport equation. We find that the fit to the observed radial profile of synchrotron radiation is only slightly poorer with satellite absorption than without: the RMS residual U is 0.0049 with satellites and 0.0027 without satellites. (For the same injection strength, the intensity of sychrotron radiation is, however, orders of magnitude weaker with satellites than without.) We have therefore continued to use $m = 1.95$, $k = 1.7 \times 10^{-9}$ sec^{-1}.

The large density drops in electrons and protons at Ganymede, Europa, and Io should manifest themselves in corresponding flux reductions as observed by satellites traversing Jupiter's magnetosphere. The flux $F(E, \Omega)$ of particles differential in total energy $E = \gamma m_o c^4$ and solid angle Ω is related to n by (Northrop and Teller, 1960)

$$F = \frac{(E^2 - m_o{}^2 c^4)}{\pi m_o c^2} \frac{n R^2}{a_o} \tag{4}$$

at a near-equatorial point R in the field of a dipole of strength a_o. In crossing the orbits of Ganymede, Europa, and Io, F in Eq. 4 is most critically affected by the change in n.

The fluxes of protons and high energy electrons ought to exhibit the behavior of n as shown in Figures (1-3) with a downward pointing cusp (indicating a discontinuity in $\partial n/\partial R$) at the position of each of the three effective satellites. The drop in flux should be most pronounced at jovimagnetic latitudes $>10^o$ because (cf. Fig. 1) particles mirroring near the magnetic equator have a greater chance of escaping absorption than do those mirroring at higher magnetic latitudes.

Our conclusions are based on the simplest model of Jupiter's magnetosphere containing what we consider the essential physics. The possible failure of spacecraft to see the flux jumps which we predict would indicate to us that one or more of our premises are in error: 1) the Galilean satellites may be sufficiently conducting that field distortions allow particles to slip around and past moons rather than impact them; 2) the form of D obtained by BHNBL in the 1-4 R_J region may be invalid at the larger R positions of the satellites; or 3) the source of energetic charged particles may not be the solar wind but local acceleration in the vicinity of one or more of the satellites themselves (Hubbard et al., 1973).

The era of active exploration of Jupiter's magnetosphere which is now beginning should answer the question of the correctness of our model.

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TABLE 1

Reduction Factor per Moon*

		ELECTRONS					PROTONS
		Best Fit Parameters	$+\Delta m$	$-\Delta m$	$+\Delta k$	$-\Delta k$	Best Fit Parameters
IO	$\frac{N(R=7.7)}{N(R=4.2)}$	64.9	16.6	336.7	40.8	114.9	38.9
EUROPA	$\frac{N(R=12.3)}{N(R=7.7)}$	21.6	6.62	84.0	16.0	31.0	36.7
GANYMEDE	$\frac{N(R=19)}{N(R=12.3)}$	23.4	5.75	123.1	17.2	33.8	83.3

* These values are for $\mu = 770$ MeV/Gauss the highest magnetic moment particles present and also they are for particles of equatorial pitch angle $\alpha_e < 69°$ so that these particles bounce far enough off equator to always reach the moon's orbit.

TABLE 2
Total Reduction Factor*

R/R_J	ELECTRONS $\frac{N(\text{no moons})}{N(4\text{ moons})}$	PROTONS $\frac{N(\text{no moons})}{N(4\text{ moons})}$
2.0	41700	3.23×10^6
4.2	39600	1.10×10^6
7.7	1694	18000
12.3	72.0	331.0
19.0	2.40	2.70

* These values are for $\mu = 770$ MeV/Gauss the highest magnetic moment particles present and also they are for particles of equatorial pitch angle $\alpha_e < 69°$ so that these particles bounce far enough off equator to always reach the moon's orbit.

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LIST OF ILLUSTRATIONS

Fig. 1

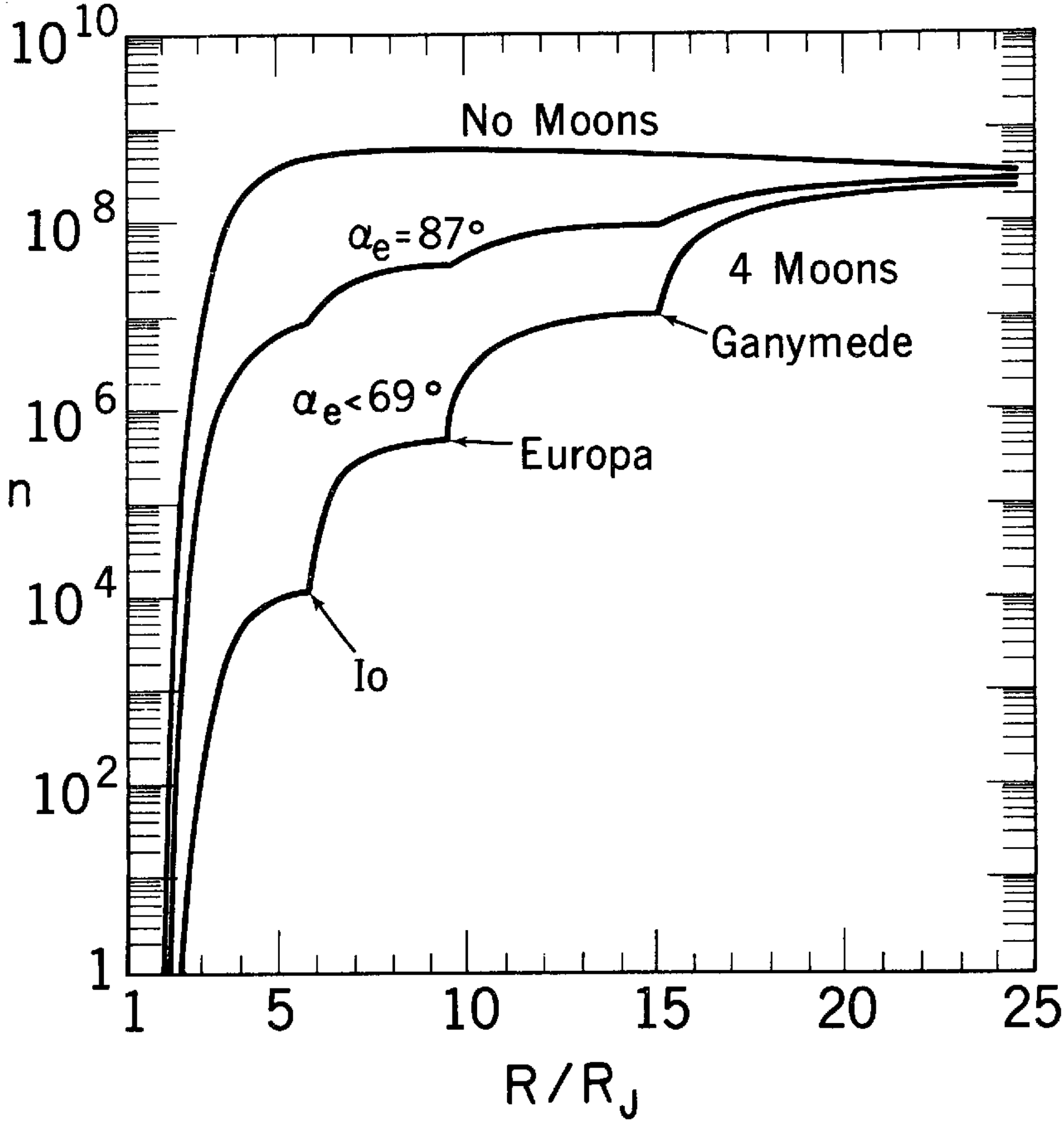
The phase space density of electrons with magnetic moment $\mu = 770$ Mev/gauss obtained by solving Eq. 3. The top curve does not include lunar absorption. The middle curve is for electrons which have an equatorial pitch angle of 87° at 1.85 R_J. The bottom curve is for electrons which everywhere have an equatorial pitch angle $<69^{\circ}$.

Fig. 2

The phase space density of electrons with equatorial pitch angles $<69^{\circ}$. The effect of the uncertainties in m (Eq. 2) on both high and low μ particles are evident.

Fig. 3

The phase space density of protons with equatorial pitch angles $<69^{\circ}$, with and without lunar absorption. The electron curves are repeated for comparison.



No Moons
$\alpha_e = 87°$
4 Moons
Ganymede
$\alpha_e < 69°$
Europa
Io
n
10^{10}
10^8
10^6
10^4
10^2
1
1
5
10
15
20
25
R/R_J

Figure 1

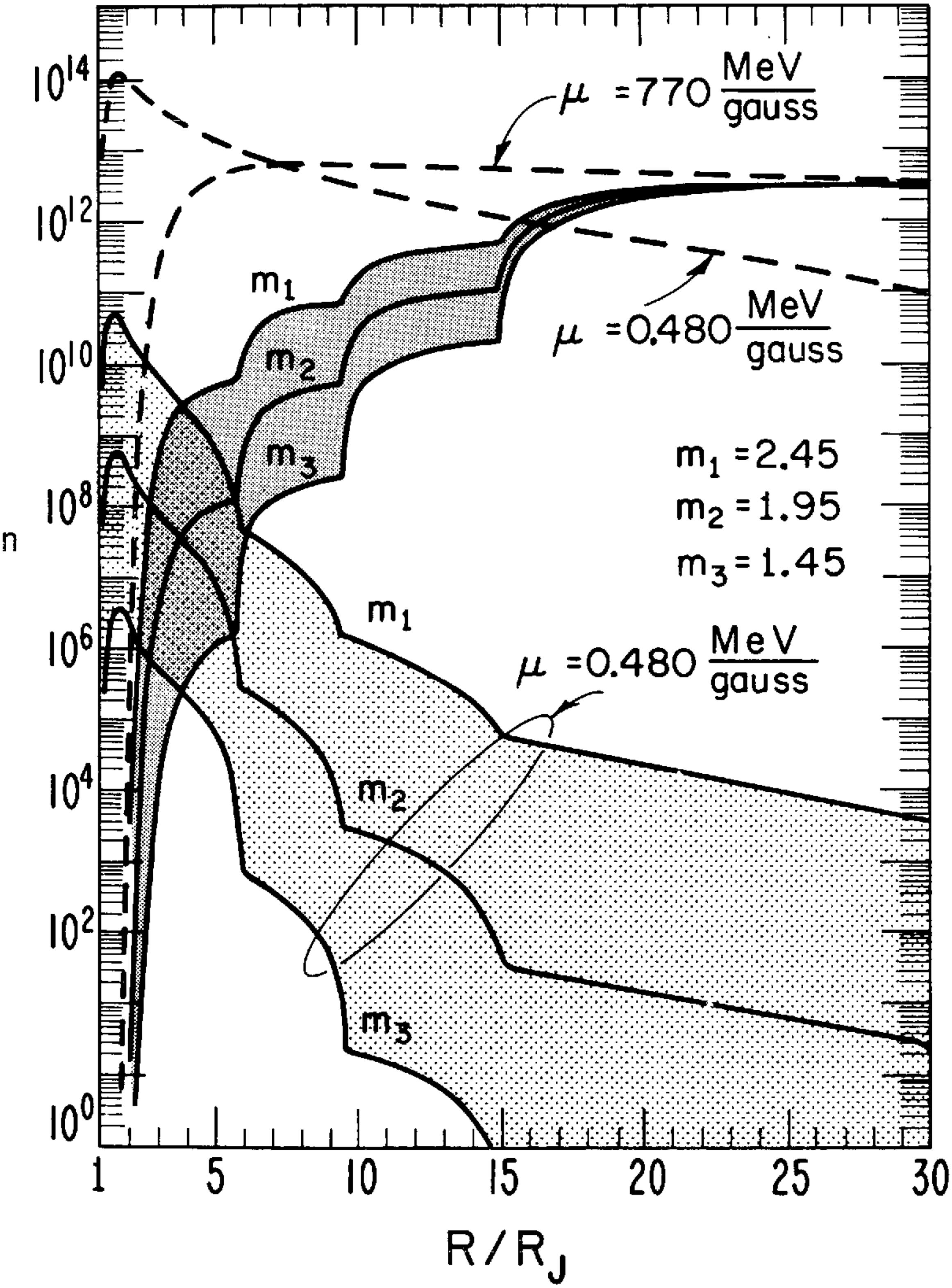
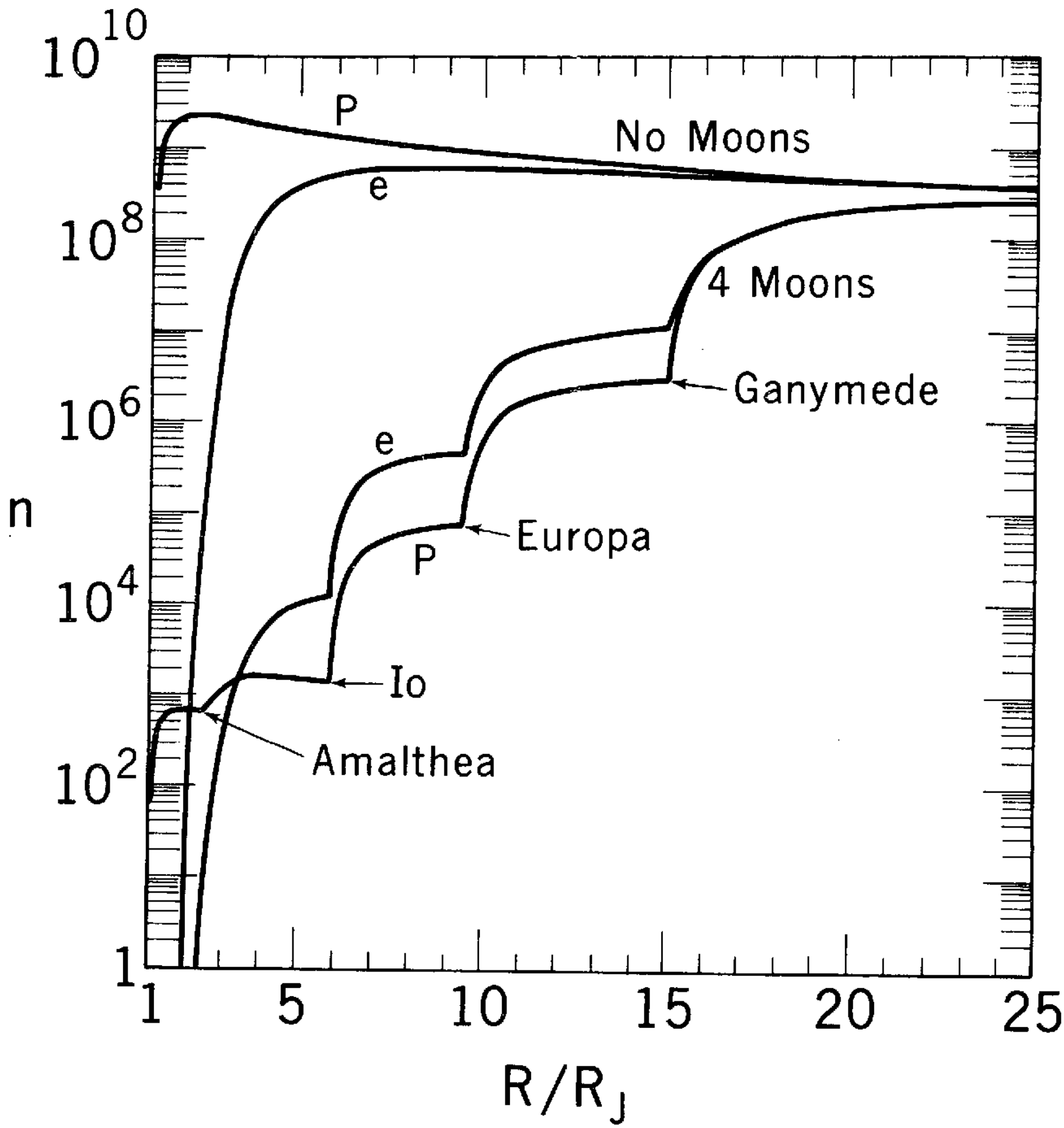

μ =770 MeV/gauss
μ =0.480 MeV/gauss
m_1 =2.45
m_2 =1.95
m_3 =1.45
μ =0.480 MeV/gauss
m_1
m_2
m_3
n
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
1
5
10
15
20
25
30
R/R_J

Figure 2



10^{10}
10^8
10^6
10^4
10^2
1
n
P
No Moons
e
4 Moons
Ganymede
e
Europa
P
Io
Amalthea
1
5
10
15
20
25
R/R_J

Figure 3