The Ionosphere of Europa From *Galileo* Radio Occultations

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Abstract

The Galileo spacecraft performed six radio occultation observations of Jupiter's Galilean satellite Europa (J2) during its tour of the Jovian system. Analysis of data from these occultations revealed the presence in jive of the six instances of a tenuous ionosphere on Europa, with an average maximum electron density of nearly 1×10^4 *cm*$^{-3}$ *near the surface, and a plasma scale height of about 240±40 km. from the surface to 300 km, and 440±60 km above 300 km. Such an ionosphere is consistent with one produced by both solar photoionization and Jovian magnetospheric particle impact in an atmosphere having a surface density of about* 10^8 *cm*$^{-3}$*. If this atmosphere is composed primarily of* O_2*, then the principal ion is* O_2^+*, and the neutral atmosphere temperature implied by the 240 km scale height is about 600 K. If it is composed of* H_2O*, the principal ion is* H_3O^+*, and the neutral temperature is about 340 K. In either case, these temperatures are much higher than those observed on Europa's surface, and an external heating source from the Jovian magnetosphere is required.*

The *Galileo* spacecraft is currently in orbit about Jupiter, executing a "tour" of the Galilean satellites. In the course of the tour, the spacecraft was occulted by Europa (J2) on three occasions. The occultations occurred on December 19, *1996,* and on February 20 and 25, 1997.During the first two the spacecraft was in close proximity of Europa (1,500-5,000 km), while the third occurred when the spacecraft was about 2.8 million kilometers from the satellite (see Table 1).

For a few minutes before and after the occultations the S-band (2.295 GHz, or about 13 cm wavelength) radio signal from the *Galileo* spacecraft traversed regions above Europa's surface in which one may observe the effects of refraction by an atmosphere , or more precisely, an ionosphere, should one exist on Europa. Thus, the three occultations provided six opportunities to search for Europa's ionosphere. This task was made more difficult because we had to use the low-gain antenna to transmit the signal from the spacecraft, as the high-gain antenna failed to deploy properly. This resulted in a signal level received by the NASA/JPL Deep Space Net (DSN) stations at Canberra, Australia (E4, Dec. 19) and Goldstone, California (E6 a and b, Feb. 20 and 25) that was reduced "by almost a factor of 1,000 (30 dB), and only one frequency, S-band, to work with rather than two coherently related frequencies at S-band and X-band (8.41 5 GHz, or 3.56 cm wavelength). The resulting signal-to-noise ratio, even when using the 70 m diameter antennas of the DSN, was of the order of 14 dB in a 1 Hz bandwidth. Five of the six occultation measurements were conducted in the one-way mode, with the downlink frequency referenced to the on-board Ultrastable Oscillator (1) having a stability of about 1 part in 10^{12}, except for the E6a entry, which was done in the two-way mode.

The received signals were downconverted to an audio frequency range, filtered in a bandpass of O to 2,500 Hz, and digitized to 8-bit samples at a rate of 5,000 samples per second. These digital data were then recorded on magnetic tape at the DSN stations and transmitted in near-real time to the Multi-mission Radio Science facility at JPL, and from there to the *Galileo* Radio Science investigators.

The digital data were then processed with a digital phase-locked loop (PLL) program analyzing 1 sec data blocks to obtain time-series of the frequency and signal strength . Removing the Programmable Local Oscillator (PLO) "steering function" results in a time-series of "sky-frequency", which is what one would have observed without a PLO. This . time-series is then compared to a predicted frequency time series computed from a very precise spacecraft ephemeris, and their difference forms the frequency residuals, which are the basic data used in determining the profiles of electron density in Europa's ionosphere. Ideally, these residuals should have a zero mean on the baseline, which is that portion of the data away from the influence of possible ionospheric refraction effects. In reality, because of oscillator drift, effects of propagation through the interplanetary medium, and imperfect knowledge of the frequency transmitted by the spacecraft and of the spacecraft trajectory, this baseline has not only a non-zero mean, but also a slope which over periods of tens of minutes can be approximated by a linear drift. The residuals are therefore "detrended" by fitting a straight line to the baseline data. When this was done, we noticed that the baseline contained many frequency oscillations, some of a magnitude similar to the frequency deviations near the surface that ostensibly were caused by propagation through the ionosphere. When the fitted residuals were integrated to produce phase residuals, we noticed a number of linear features abruptly changing back and forth from positive to negative slopes. These were clearly not random, and were caused by abrupt positive and negative frequency steps of the order of a few millihertz, which probably are caused by gradients in the interplanetary plasma between the spacecraft and the Earth. These frequency steps were computed from the magnitude and duration of the linear phase features, and removed throughout each data set, including those corresponding to the regions where ionospheric effects could be expected. This procedure reduced the peak-to-peak excursions of residual phase on the baselines by approximately a factor of 10, making the final results far less dependent on where on the baseline the detrending function is computed. This step is crucial to the analysis, because the maximum frequency excursions presumably due to an Europa ionosphere are only of the order of 20 to 40 mHz.

The corrected residuals were then converted to refraction angle by applying the Europa-centered trajectory information derived from the *Galileo* navigation ephemeris with iterative light propagation time corrections between the spacecraft and the limb of Europa, and from the limb to the DSN stations. These data were then inverted using well-known techniques *(2,3,4)* to obtain the refractivity, or $(n-1)\times10^6$, as a function of altitude. This is directly related to the electron density through a constant dependent on the inverse square of the frequency.

The geometry of each measurement is illustrated in Table 1, which lists the date, distance from the limb, latitude, longitude, solar zenith angle, and the magnetospheric ram angle. The ram angle is defined as the angle between the vector pointing from the center of Europa to the "sub-ram" point and the one pointing from the center to the occultation point. Because all occultations occurred at near-equatorial latitudes, this angle can be approximated by the difference in longitude between the occultation point and 270°, the sub-ram longitude.

This geometry is depicted in Figures 1 through 3, which show diagrams giving the location of each occultation point with respect to the ram direction and the terminator, as well as the electron density profiles derived from the entry and exit observations for that occultation.

The locations are widely different because each occultation occurred when Europa was in a different place in its orbit about Jupiter. All occultations occurred within about 5 deg. of the terminator.

The electron density profiles clearly show the presence of ionization in the Europa atmosphere in five of the six measurements. The observation when no ionosphere was observed, E6a exit (Fig. 2), occurred at a ram angle of nearly 180 deg., near the middle of the wake region, where the electron density could be expected to be depleted. In contrast, the observations during the E4 occultation (Fig 1) were made at ram angles close to 90 deg., where the line of sight lay along the wake direction, thus perhaps enhancing the electron density and giving rise to effects caused by lack of spherical symmetry, The maximum electron densities in the other cases range from about 6x1 0^{3} cm^{-3} to about 11x103 cm^{-3} and occur at or near the surface of Europa. The error bars in Figures 1 to 3 represent 3 times the standard deviation of the baseline data computed from the top down to 1000 km.

There are significant differences between individual measurements, so for the purpose of modeling an average electron density profile was computed, which is shown along with the five constituent profiles in Figure 4. The error bars on the plot of the average are derived from the standard deviation of the average, also taking into account the standard deviation of the data along the baseline of each data set. The average electron density profile has a maximum of about 9x103 ± 4x103 cm^{-3} and a plasma scale height of about 2404-40 km. below 300 km. and 440*60 km. above 300 km. altitude. These simple models are represented by the triple solid lines in Figure 4.

The implications of the observed ionosphere for the atmosphere of Europa will now be briefly examined. It can be assumed, based on past observations and theoretical considerations, that the origin of the atmosphere is frozen surface water ice, most likely produced by particle impact (e.g. 5,6). Therefore, the atmosphere must consist of some mixture of H_2O, H, H_2, OH, O_2 and O. Early Pioneer 10 observations suggested an atomic oxygen column density of around 1x1013 cm ‘z (7), but these measurements may have been contaminated. Recent HST observations of the 1304/1 356 lines of atomic oxygen were used to deduce an 0_2 column density of about 1.5x1 O*^{S} cm^{-2} (8). At this time there apparently are no other observations which would place a limit on the abundances of the other potential atmospheric species. Recent Galileo measurements at

Ganymede and Callisto indicated the presence of atomic hydrogen, with densities of the order of 1x104 cm-’, which might be suggestive of similar abundances at Europa *(C. Barth, private communication).*

The radio occultation observations indicate the presence of detectable ionospheres with peak densities of approximately $1x10^4 cm^{-3}$ with apparent electron density scale heights of about 240-440 km depending on altitude. These electron densities may be the result of photoionization, impact ionization, or a combination of both. The various likely scenarios and the resulting implications for the presence of an atmosphere around Europa are discussed in the following paragraphs.

Let us first consider the case of an ionosphere with an electron density of $1x10^4 cm^{-3}$ near the surface. The photoabsorption cross sections at extreme ultraviolet wavelengths for H_2O, 0_2, 0, H_2,0H and H, the likely neutral atmospheric constituents, are not very different; a value of ~ 3x10-17 cm’ is a reasonable approximation. Therefore, if the ionosphere is in a region where the optical depth is less than unity, the column density above the surface needs to be less than about 3x1016 cm^{-2}. If the atmospheric scale height is about 20 km, as suggested by ***Ip*** (6), then the surface density has to be less than 1.5x1010 cm^{-3} in order to assure an optical depth of less than unity. An upper limit on the optical depth of about 3x1015 cm^{-2} was also suggested by ***Johnson (5).*** If the atmosphere is created by slow (- 100 eV) ion sputtering of the surface, then these ions must be able to reach the surface, thus setting an upper limit on the column density. The HST observations suggest that a predominantly 0_2 atmosphere should be considered first, under the assumption that chemical processes dominate at the altitude region of the peak electron density. Assuming dissociative recombination as the dominant loss process for the 0^+_2 ions, the neutral density required to produce an electron density of n_e at zero optical depth is:

$$[O_2] = n_e^2 \alpha / \xi$$

where α is the dissociative recombination rate and ξ is the ionization frequency. Taking the terrestrial photoionization frequency of about 9x10-7 see-l (9), adjusted for Jupiter (-3 .3x1 0^{-8} see-l), a recombination rate constant of 1x10“7 $cm^3 see^{-1}$,and an electron density of lx 104 cm^{-3}, one gets an O_2 density of ~ 3 x 108 cm^{-3}. This required density is reduced if additional ionization due to electron impact is considered. *Schreier et al.* (10) used measured plasma parameters from Voyager and estimated a total electron impact ionization rate of 1.88x10-7 see-l. This ionization rate is more than a factor of five larger than the one for photoionization and thus leads to a required molecular oxygen density which is smaller, namely -5x10^7 cm^{-3}.

Before addressing the problems associated with this requirement, let us ask how different would the atmospheric density requirement be if the major neutral constituent is not molecular oxygen. As indicated earlier, the other likely candidate constituents are H_2O, H, H_2, OH and O. Any of the other three molecular candidates will not change the above requirement significantly, because neither the dissociative recombination rate coefficients nor the ionization frequencies are significantly different. For example, if H_2O is taken to be the dominant neutral molecular species, which leads to H_3O^+ as the main ion species, the required neutral density is still of the order of 108 cm^{-3}. If the neutral atmosphere consists of a mixture of atomic and molecular species, the conclusion is very similar, because both H^+ and 0^+ can charge-exchange rapidly with one of the molecular neutral species, forming molecular ions.

The measured electron density scale height, as mentioned earlier, is of the order of *240* km. in the lowest 300 km., which implies a neutral gas scale height of 120 km in a chemically controlled region. This neutral scale height corresponds to a gas temperature of about *340* K for H_2O and 610 K for 0_2. These temperatures are significantly higher than the apparent surface temperatures, therefore they require further consideration. (A first order estimate for the energy required, as a topside heat inflow, to maintain this elevated atmospheric temperature is of the order of 10^{10} eV cm^{-2} see-l, which is more than a factor of one hundred less than that which could be obtained from the surrounding magnetospheric region. This does not necessarily imply the presence of such a heat source, but it is energetically well within the realm of possibility. We also note that the upper limit of the solar column heating rate is about 1x109 eV cm^{-2} see-l.)

Next, let us look at the issue of optical depth and column density in light of the atmospheric density values that have just been obtained. If the larger number density requirement is imposed, corresponding to photoionization (3x10^8 cm-3), column densities of about 6x10^{14} cm and 3.6x10^{15} cm^{-2} are obtained for assumed scale heights of 20 and 120 km, respectively. Even the larger column density, if reduced by the factor of five corresponding to additional electron impact ionization, brings the required column density very close to the *Hall et a/.* (8) value.

It should also be pointed out that these column densities do lead to an optical depth of less than unity, which was assumed to start this discussion. It is now appropriate to address the validity of the assumption of chemical equilibrium conditions. The chemical time constant near the surface {-500 see}, given the observed scale height, is significantly smaller than the diffusive one {-104 see}, thus the assumption is a good one.

The near-surface atmospheric densities and temperatures which were found to be consistent with the ionospheric observations, namely a number density of approximately 108 cm^{-3} and a temperature of about 600 K correspond to a surface pressure of less than 0.1 nanobars. This value is slightly larger than the limit set by the Voyager ultraviolet spectrometer for Ganymede (cf. 11), but no comparable limits are available for Europa and the impact ionization rate is believed to be significantly higher at Europa than at Ganymede.

It should be mentioned that a very unlikely scenario would lead to a density requirement which is significantly lower than any discussed here so far . This is the case of an atmosphere which consists solely of atomic hydrogen or oxygen, with no molecular species present. The required atmospheric density is very different in this case, because the loss of atomic ions by either radiative recombination, corresponding to a lifetime of about 107 sec., or diffusion to the surface, with a lifetime of about 10^6 sec., are both very slow processes . In this scenario, transport processes related to Europa's interaction with Jupiter's magnetosphere are likely to be most important.

Finally it should be pointed out that the external magnetospheric thermal plasma and magnetic pressures on Europa's ionosphere are about $2x1\ 0^{-8}$ and 10^{-7} N m^{-2} respectively. Even if the electron and ion temperatures are allowed to be four times greater than the neutral gas temperature, the peak ionospheric thermal plasma pressure, calculated with the measured peak electron density, is still significantly less than the external one. This means that the ionosphere will be strongly magnetized and coupled to the magnetosphere.

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Table 1. Geometry of *Galileo* Occultations by Europa

Ohs.	Date	Distance (km)	Lat. (deg)	W. Long. (deg)	SZA (deg)	Ram Angle (deg)
E4 entry	Dec 19, 1996	1,600	-2	346	95	76
E4 exit	"	4,000	-4	167	85	103
E6a entry	Feb 20, 1997	1,500	-24	281	86	11
E6a exit	"	4,400	-21	102	94	168
E6b entry	Feb 25, 1997	2,777,500	-14	56	85	146
E6b **exit**	"	2,776,700	-14	236	95	34

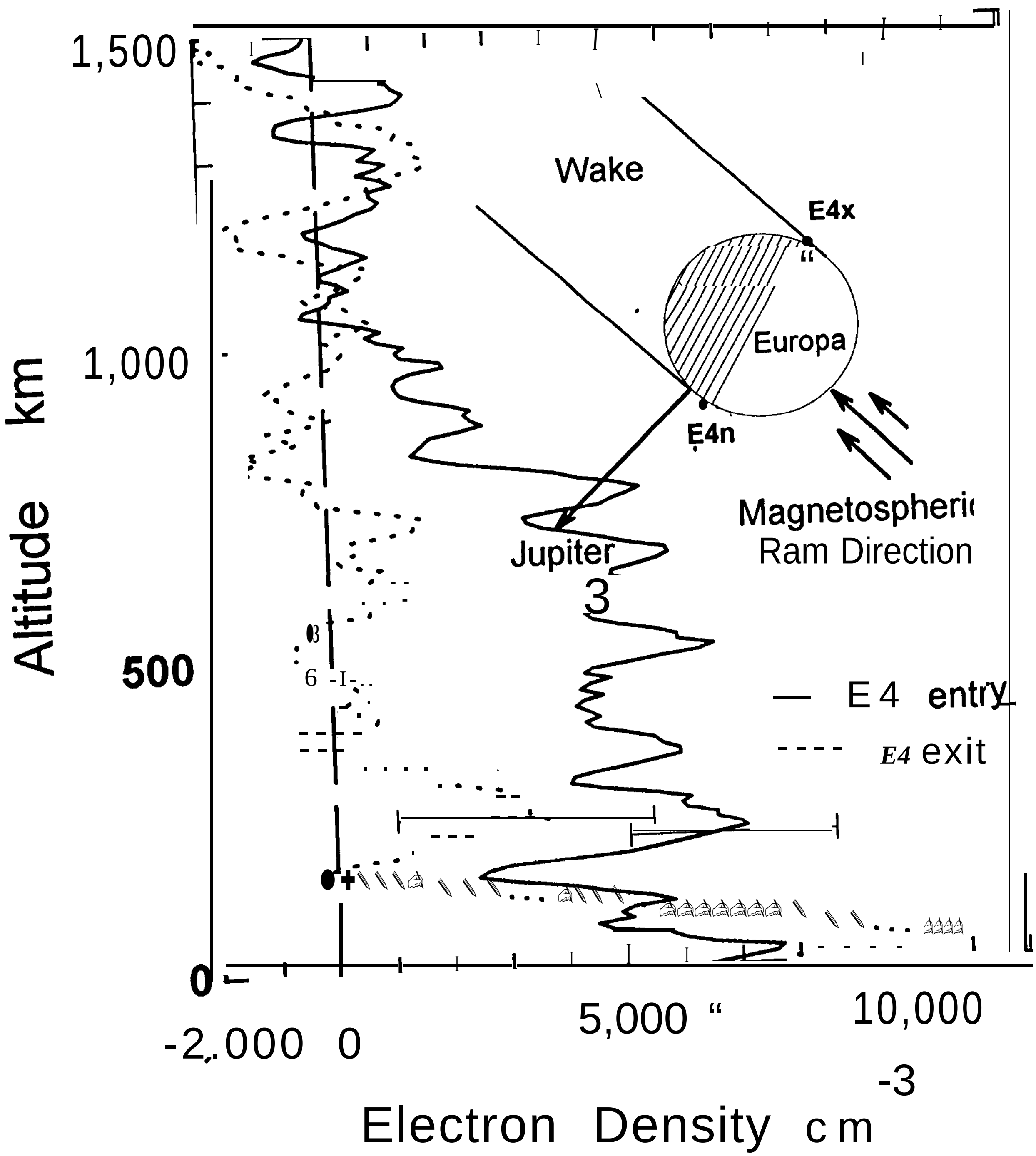
Figure Captions

Figure 1. The E4 occultation of *Galileo* by Europa. The location of the occultation points relative to the **magnetospheric** ram direction and the terminator are shown by the inset diagram. The apparent enhancement of ionization up to about 500 km. in the entry observation maybe an effect of looking along the wake direction. The error bars represent three standard deviations of the random fluctuations on the baseline.

Figure2. The E6a occultation. The lack of an observable ionosphere in the exit observation is most probably due to its location, which is almost in the middle of the anti-ram wake region, which maybe depleted of ionization.

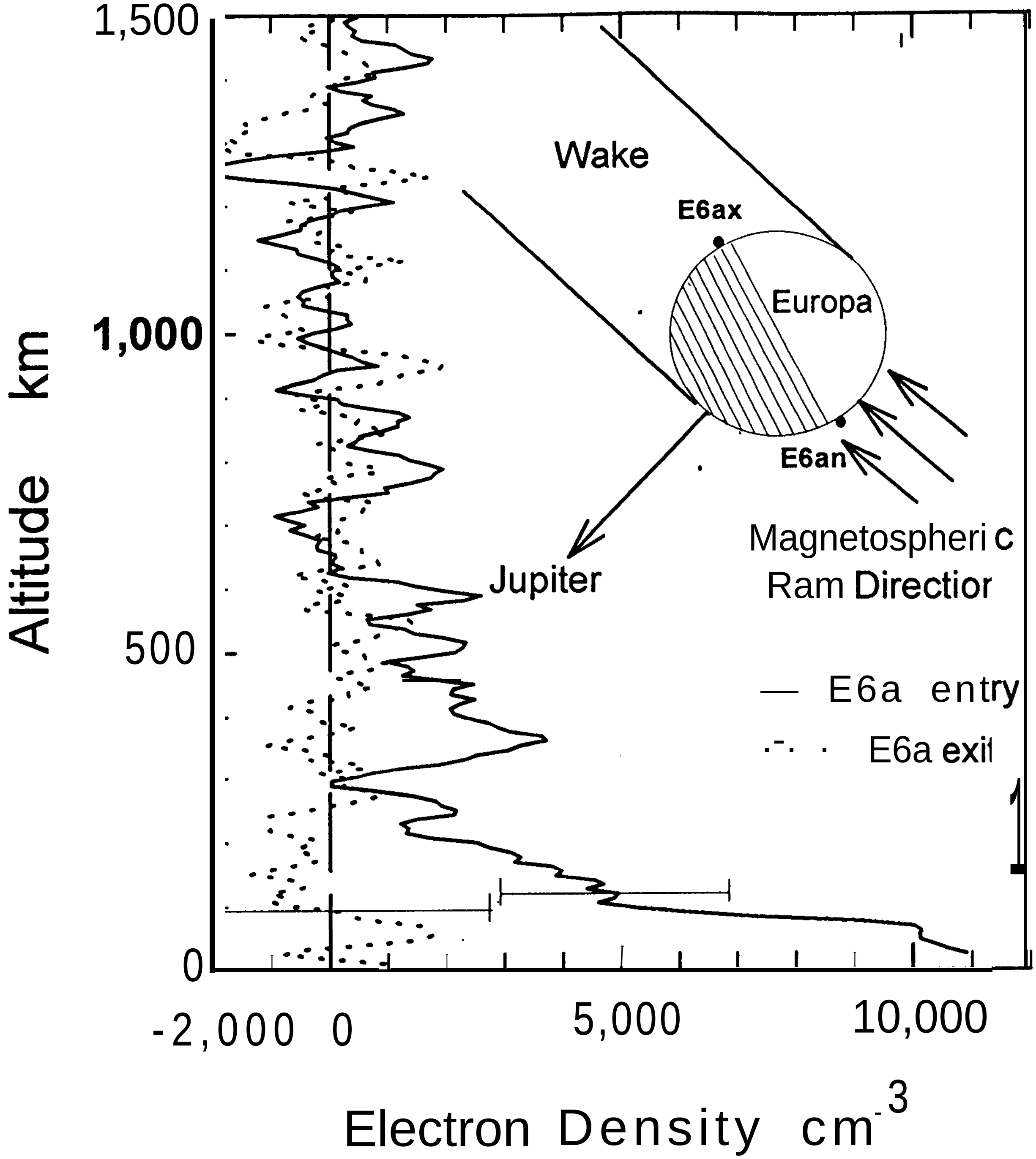
Figure3. The E6b occultation. The similarity of the entry and exit observations is puzzling, since the former lies on the ram side, and the latter well within the wake region.

Figure 4. Average electron density profile computed from the five observations in which an ionosphere was detected, along with the five individual profiles. The average profile is best described by a model having a plasma scale height of 240 ± 40 km. below 300 km. and 440 ± 60 km. above that altitude (smooth solid lines). The error bars represent the standard deviation of the mean combined with the **3-σ** data uncertainties of the individual profiles.



1,500
1,000
500
0
Altitude km
Wake
E4x
Europa
E4n
Magnetospheric
Ram Direction
Jupiter
— E4 entry
- - - - E4 exit
-2,000 0
5,000
10,000
Electron Density cm-3

Figure 1



1,500
1,000
500
0
Altitude km
Wake
E6ax
Europa
E6an
Magnetospheric
Ram Direction
Jupiter
— E6a entry
E6a exit
-2,000 0
5,000
10,000
Electron Density cm-3

Figure 2

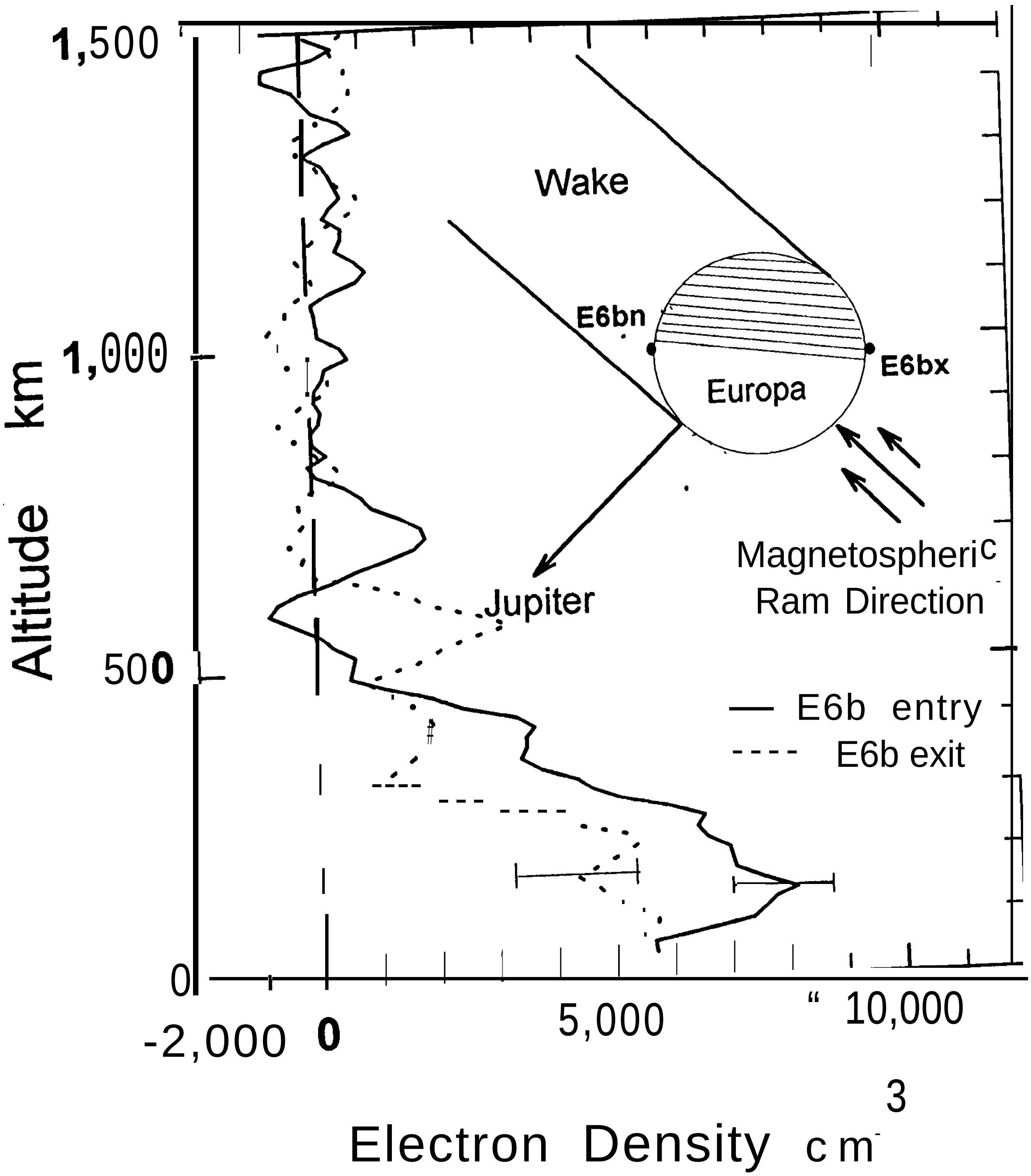

1,500
1,000
500
0
Altitude km
-2,000
0
5,000
10,000
Electron Density cm-3
Wake
E6bn
E6bx
Europa
Jupiter
Magnetospheric
Ram Direction
E6b entry
E6b exit

Figure3

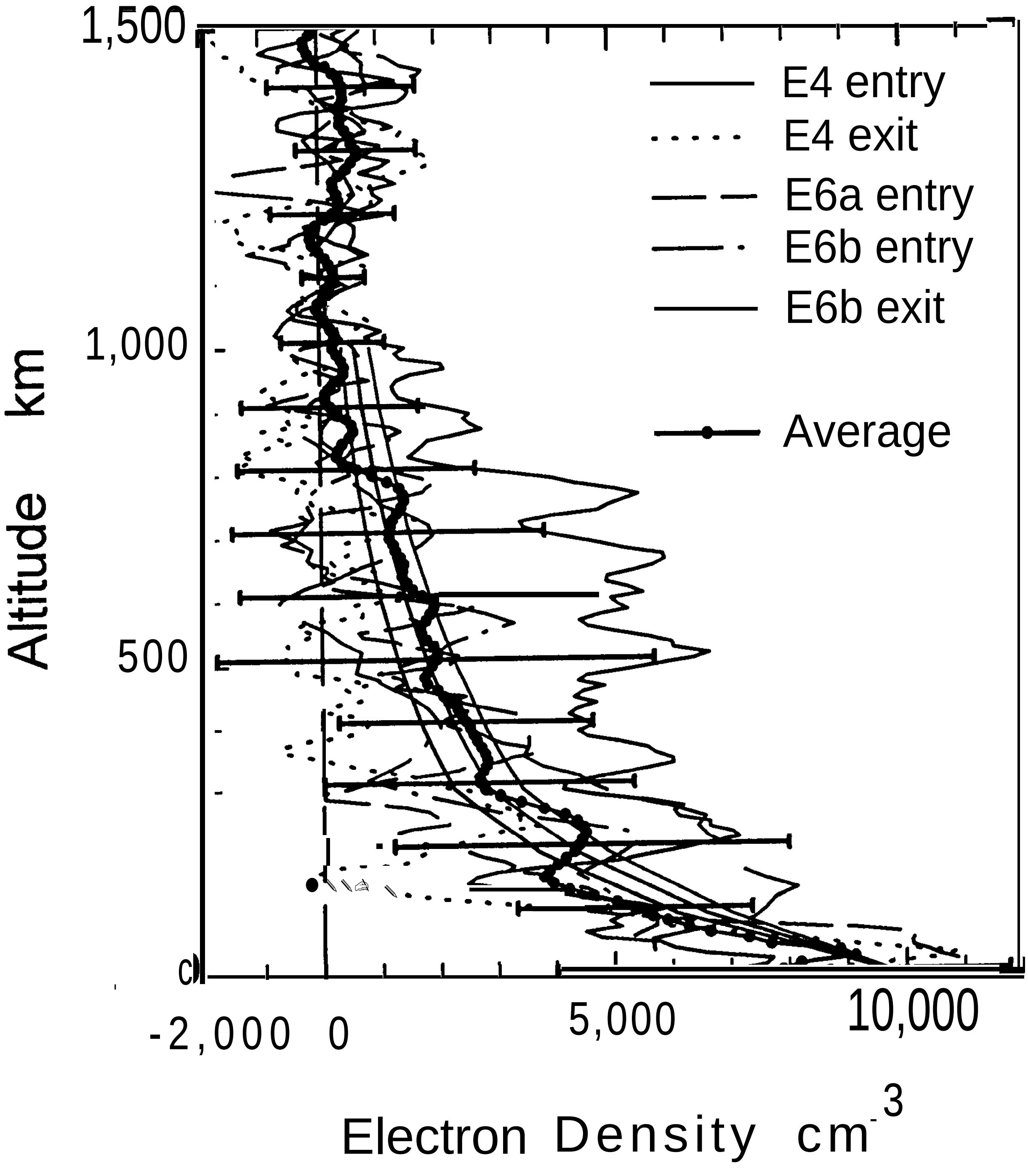

1,500
1,000
500
0
Altitude km
E4 entry
E4 exit
E6a entry
E6b entry
E6b exit
Average
-2,000 0
5,000
10,000
Electron Density cm-3

Figure 4