Vertical Structure of the Callisto Ionosphere from Galileo Radio Occultation Data and Its Implication on the Moon's Interior.

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Abstract

Using the magnetic field observed by Galileo during two flybys of Callisto, Khurana et al. (1998) demonstrated that Callisto generates a strong induction response to the time-varying primary field, indicative of the presence of a subsurface ocean. In contrast, Hartkorn and Saur (2017) modeled the atmosphere and ionosphere of Callisto and suggested that the ionosphere could be responsible for a significant part of the observed magnetic fields. Thus, they concluded that the water ocean might be located much deeper than previously thought or might not exist at all. While Khurana et al. (1998) did not account for the induction within a conductive ionosphere, Hartkorn and Saur (2017) overestimated the conductivity of the ionosphere by using Cowling conductivity which is not applicable for the situation at Callisto. In this paper, we re-analyzed the S-band open-loop one-way Doppler data of the Galileo spacecraft with the aim to derive the electron density (ED) and neutral density (ND) profiles of Callisto and address its implication in terms of moon's conductivities and interiors. Using modern orbit determination software, MONTE, and the most up-to-date information on the Jovian system, we reconstructed the Galileo orbit with a full dynamical approach. The estimated rms values of the Doppler residuals for baseline measurement vary from 0.01-0.08 Hz, well within the expected noises of the radio signals. We used these residuals to derive the ED profiles using the technique discussed in Verma et al., (2019). We found an appreciable ionosphere for C22 and C23 Ingress occultations with peak densities of 15600±900 cm-3 and 17700±600 cm-3, respectively. For other cases, the detections do not exceed the 3-σ level. While the general features of the EDs are consistent with Kliore et al. (2002), our estimated 1-σ formal uncertainties are 2-3 times better presumably because of the constrained Galileo's orbit. Assuming O2 as the major component of the Callisto's atmosphere, the estimated ND (weighted mean) at the surface is 2.0±0.33 x10-10 cm-3 which corresponds to a column density of 3.9±0.35 x10-16 cm-2 (see Figure). Finally, we will use these density profiles to constrain the ionospheric conductivities and address their implications in terms of the presence of a subsurface ocean.

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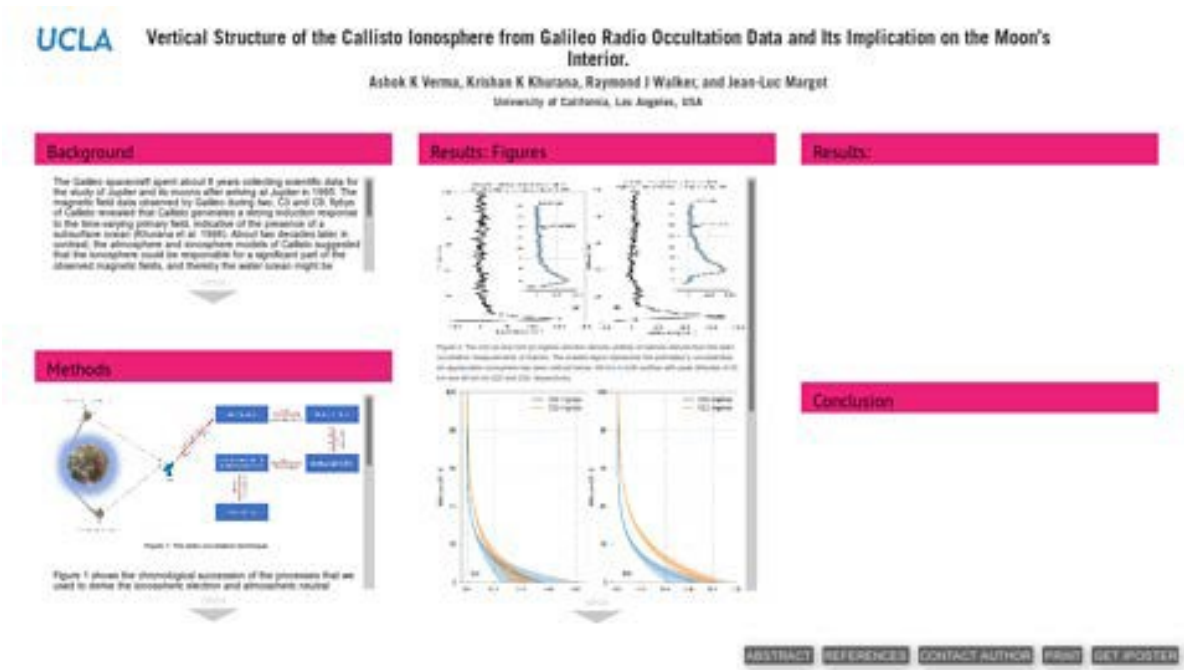

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ABSTRACT

Using the magnetic field observed by Galileo during two flybys of Callisto, Khurana et al. (1998) demonstrated that Callisto generates a strong induction response to the time-varying primary field, indicative of the presence of a subsurface ocean. In contrast, Hartkorn and Saur (2017) modeled the atmosphere and ionosphere of Callisto and suggested that the ionosphere could be responsible for a significant part of the observed magnetic field. Thus, they concluded that the water ocean might be located much deeper than previously thought or might not exist at all. While Khurana et al. (1998) did not account for the induction within a conductive ionosphere, Hartkorn and Saur (2017) overestimated the conductivity of the ionosphere by using Cowling conductivity which is not applicable to the situation at Callisto.

In this paper, we re-analyzed the S-band open-loop one-way Doppler data of the Galileo spacecraft with the aim to derive the electron density (ED) and neutral density (ND) profiles of Callisto and address its implication in terms of the moon's conductivities and interiors.

Using the modern orbit determination software, MONTE, and the most up-to-date information on the Jovian system, we reconstructed the Galileo orbit with a full dynamical approach. The estimated rms values of the Doppler residuals for baseline measurement vary from 0.01-0.08 Hz, well within the expected noises of the radio signals. We used these residuals to derive the ED profiles using the technique discussed in Verma et al., (2019).

We found an appreciable ionosphere for C22 and C23 Ingress occultations with peak densities of 15400±550 cm^{-3} and 17500±550 cm^{-3}, respectively. For other cases, the detections do not exceed the 3-σ level. While the general features of the EDs are consistent with Kliore et al. (2002), our estimated 1-σ formal uncertainties are 2-3 times better, presumably because of the constrained Galileo's orbit.

Assuming that Callisto's atmosphere mainly consists of O_2 yields the surface neutral density of 5.4±3 x 1e10 cm^{-3} and 4.5±1.2 x 1e10 cm^{-3} derived respectively from C22 and C23 Ingress electron density profiles. The corresponding estimated column densities for C22 and C23 Ingress profiles are 6.5±2.5 x 1e16 cm^{-2} and 8.0±1.5 x 1e16 cm^{-2}, respectively.

Finally, we will use these density profiles to constrain the ionospheric conductivities and address their implications in terms of the presence of a subsurface ocean.

BACKGROUND

The Galileo spacecraft spent about 8 years collecting scientific data for the study of Jupiter and its moons after arriving at Jupiter in 1995. The magnetic field data observed by Galileo during two, C3 and C9, flybys of Callisto revealed that Callisto generates a strong induction response to the time-varying primary field, indicative of the presence of a subsurface ocean (Khurana et al. 1998). About two decades later, Hartkorn and Saur (2017) using their models of ionospheric conductivity suggested that all or a large part of the induction may be occurring in the ionosphere, and thereby the water ocean might be located much deeper than previously thought or might not exist at all. While Khurana et al. 1998 did not account for the induction within a conductive ionosphere, Hartkorn and Saur (2017) overestimated the conductivity of the ionosphere by using Cowling conductivity which does not apply to the situation at Callisto. Thus, the existence of a subsurface ocean beneath the Callisto surface is still in question.

Callisto is unusual from other Galilean icy satellites in that it possesses a near-collisional atmosphere. The measurements from the Hubble Space Telescope detect O I 1304 A and O I 1356 A emissions from Callisto and indicated that Callisto's atmosphere primarily consists of O_2 molecules with a measured column density of 4e15 cm^{-2} in the leading/Jupiter facing hemisphere (Cunningham et al. 2015). On the other hand, two of the eight Galileo's radio occultation measurements indicated an order of magnitude denser atmosphere with an estimated column density varying from 3 to 4 x 1e16 cm^{-2} (Kliore et al. 2002). Such a thick atmosphere would be able to sustain an appreciable ionosphere (Strobel et al. 2002), and indeed two (out of eight) Galileo radio occultation measurements provided positive evidence of substantial electron densities, peak > 17000 cm^{-3}, (Kliore et al. 2002). However, the error bars in the radio occultation measurements of electron densities are very large, and these densities have never been archived as a function of altitude. It limits the precise computation of the ionospheric conductance and its contribution to the observed magnetic field. To discover the plausible origin of the observed magnetic field of Callisto, we revisited Galileo's radio occultation and magnetic field observations.

METHOD

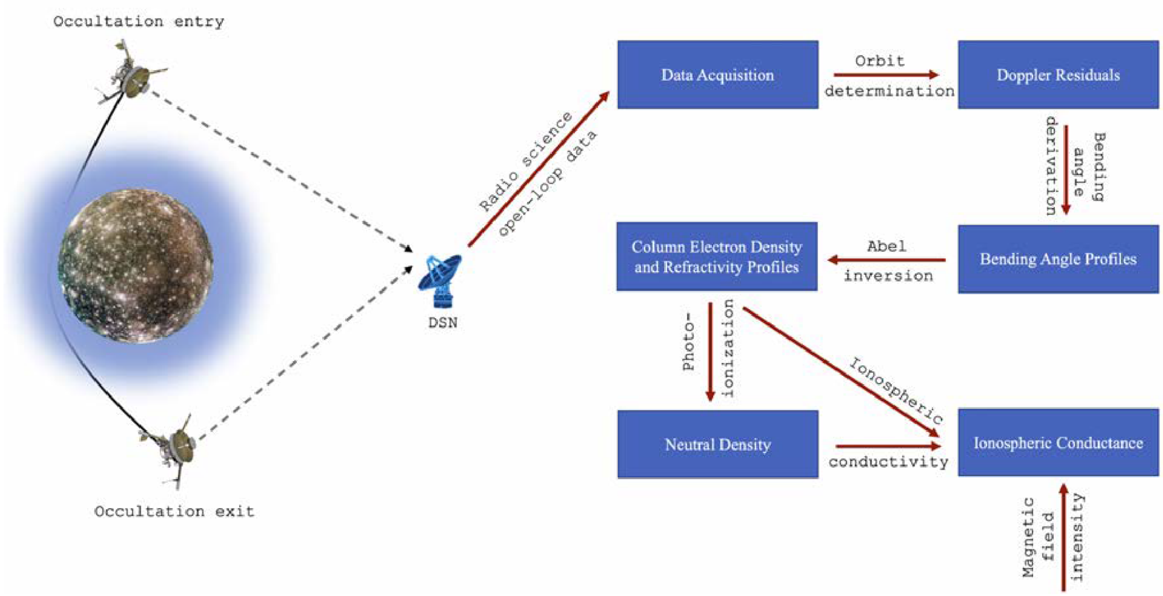

Figure 1: The radio occultation technique.

Figure 1 shows the chronological succession of the processes that we used to derive the ionospheric electron and atmospheric neutral density profiles of Callisto.

The breakdown of these cognitive operations is as follows:

- Analysis of the ODR formatted open-loop radio science data to obtain observed sky frequency and Doppler shift measurements.
- Reconstruction of Galileo's orbit by means of modern techniques and an orbit determination software (MONTE).
- Ascertain the characteristics of the excitation geometry such as bending angle and impact parameter, and invert them using the well-established technique (e.g., Fjeldbo et al. 1971) to retrieve the refractive index, and subsequently to derive the electron density profile of an ionosphere.
- Derive the neutral density profile using the photo-ionization method, assuming the photochemical equilibrium ionosphere and an atmosphere primarily composed of O_2 (Kliore et al. 2002, Liang et al. 2005, Cunningham et al. 2015).
- Estimate ionospheric conductivity using density patterns of electrons and neutral numbers and magnetic field intensity.

RESULTS: FIGURES

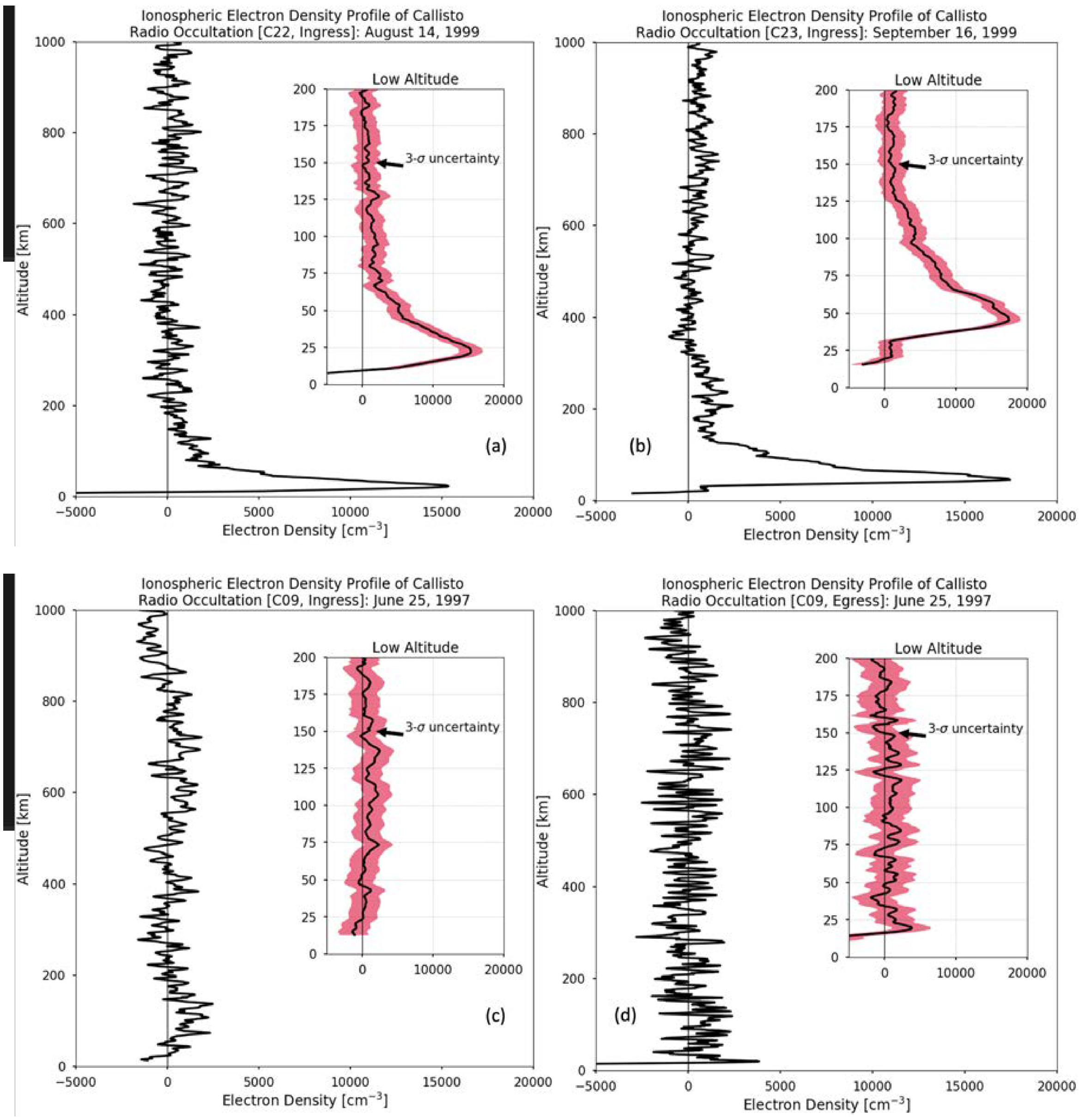

Figure 2: The C22-Ingress (a), C23-Ingress (b), C09-Ingress (c), and C09-Egress (d) electron density profiles of Callisto derived from the radio occultation measurements of Galileo. The shaded region represents the estimated 3-σ uncertainties. An appreciable ionosphere has been noticed below 100 km in C22 and C23 profiles with peak altitudes of 23 km and 46 km for C22 and C23, respectively, while no detection for C09 pass.

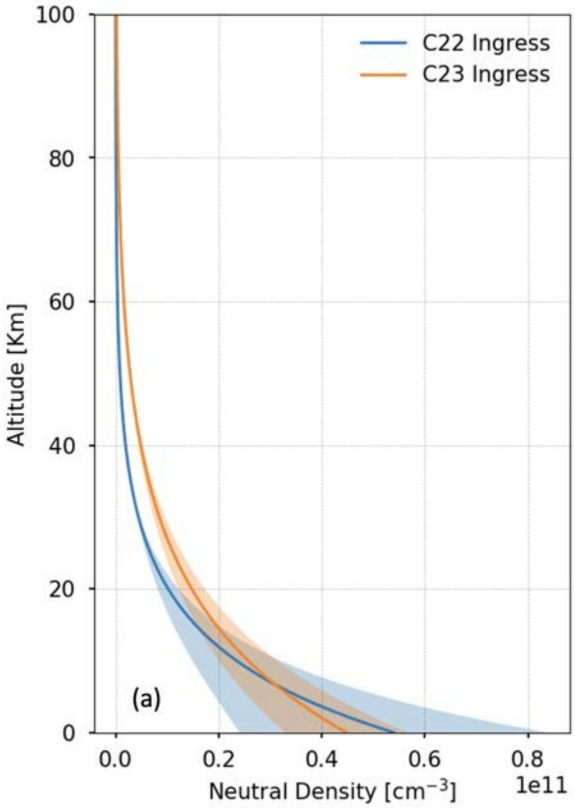

Figure 3: The neutral (a) and column (b) density profiles of Callisto derived from the C22 and C23 Ingress radio occultation measurements of Galileo. The shaded region represents the estimated 1-σ uncertainties.

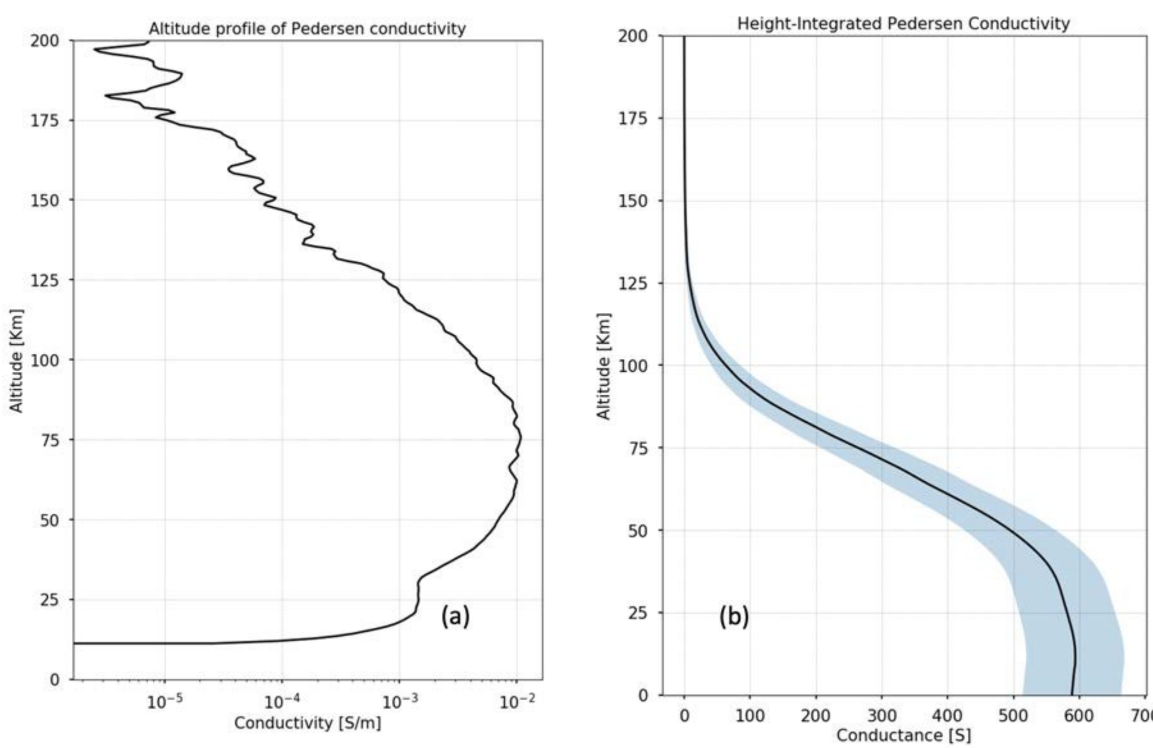

Figure 4: Altitude profile (a) and height-integrated (b) Pedersen conductivity derived from the mean density profiles of the C22 and C23 Ingress occultations. The shadedregion represents the estimated 1-σ uncertainties.

RESULTS: KEY POINTS

Callisto’s Radio Occultation Results

Type	C23 (Ingress)	C22 (Ingress)
Peak Electron Density	17500±550 cm^{-3}	15400±550 cm^{-3}
Peak Altitude	~46 Km	~23 Km
Topside Plasma Scale Height	18±1.2 Km	12±1.6 km
Surface Neutral Density (O_2)	$4.5\pm1.2 \times 10^{10}$ cm^{-3}	$5.4\pm3 \times 10^{10}$ cm^{-3}
Column Density (O_2)	$8.0\pm1.5 \times 10^{16}$ cm^{-2}	$6.5\pm2.5 \times 10^{16}$ cm^{-2}
Pedersen Conductance (mean)	588±75 S	
Moon’s Interior	Research In Progress	

Table 1: Ionospheric and atmospheric properties derived from Galileo's radio occultation measurements. The mean Pedersen conductance value was calculated using C23 and C22 density profiles for which a significant ionosphere was detected.

CONCLUSION

- We revisited Galileo's radio occultation and magnetic field observations and reconstructed Galileo's orbits using modern orbit determination software.

- Two Galileo radio occultation measurements (of eight) provided positive evidence for significant electron densities (Figure 2). In other cases, detection does not exceed or barely exceeds level 3-σ.

- The general characteristics of the electron density profiles are consistent with Kliore et al. 2002, our estimated 1-σ formal uncertainties are 2-3 times better, presumably because of the constrained Galileo's orbit.

- Assuming Callisto's atmosphere consists primarily of O_2, our results indicate a dense atmosphere with inferred column density ranging from 4 to 9.5 x $1e10^{16}$ cm^{-2}.

- We used electron and neutral number densities to calculate ionospheric conductivity. Assuming 35±5 nT as the magnitude of the magnetic field, we derived the elevation profile of the Pedersen conductivity (Figure 4) and obtained the height integrated value of the conductivity as 588±75 S.

- To investigate its implication on the Moon's interior, we are revisiting Galileo's magnetic field data. This investigation is underway.

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