CHLORIDE SALTS PREVENT DIRECT DETERMINATION OF EUROPA'S ICY SHELL THICKNESS VIA RADAR SOUNDING.

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Abstract: We present a new model of radar attenuation with Europa's icy shell based on salt type, concentration and temperature to predict the effectiveness of radar sounding of the shell. Our model accounts for electrically conductive brine within the liquid vein networks (LVNs; **Fig. 1**) of ice, because brine pockets are now thought to be prevalent within the icy shell. Our modeling predicts that radar will not penetrate through the entire icy shell, because warm ice within the shell attenuates too much energy (**Fig. 2g**). While LVNs within ice increase radar attenuation, our modeling suggests that this phenomenon will be difficult to detect, because of significant attenuation within shallower portions of the shell before the eutectic temperature is reached at greater depths. Our model can be applied to any icy ocean world, assuming chloride (Cl^-) dominates over other ice-soluble impurities.

Introduction: Future Europa flyby missions will image the icy shell of Europa using orbital radar sounding: Radar for Icy Moon Exploration (RIME) onboard the Jupiter Icy Moon Explorer (JUICE) and Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) onboard NASA's Europa Clipper. The motivation for these instruments is to discover the thickness of the icy shell, to detect brine within it and to determine its thermal state. Thus, several studies have modeled attenuation of radar energy through Europa's icy shell [1-3]. Recent spectroscopic evidence suggests that chloride (Cl^-) salts, as opposed to sulfate (SO_4^{2-}) salts, are the dominant salt in the Europan ocean [4-5] and have a modeled oceanic concentration of 10–300 mM Cl^- [6]. While SO_4^{2-} salts do not affect radar attenuation significantly [7-8], Cl^- salts have a major effect because Cl^- ions can substitute directly into the ice lattice. Further, Cl^- salts have a much lower freezing point depression than SO_4^{2-} salts, thus brines also can increase radar absorption via electrolytic conduction. The possible existence of brines within the icy shell has gained traction in recent years due to the interpretation that chaos terrain and double ridges may be actively forming over shallow subsurface water [9-12] and due to observations of plumes emanating from a location with anomalously warmer temperatures [13-16]. Our new radar-attenuation model considers the consequences of briny LVNs within the icy shell.

Dielectric relaxation of ice: Ice possesses a dielectric relaxation that causes radar attenuation. This attenuation increases with temperature and Cl^- concentration [17-19]. We use a laboratory-calibrated Jaccard model [17,18,20] that considers Cl^--partitioning between the lattice and LVNs [21] to estimate the conductivity due to this dielectric relaxation as a function of temperature and oceanic Cl^- concentration.

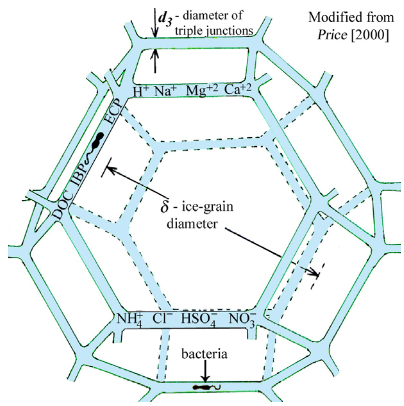

Fig. 1. Ice's liquid vein network (blue). These networks represent briny unfrozen water that – if well-connected – can be detected remotely by their high electrical conductivity. The temperature and Cl^- concentration of the ice affects radar attenuation via the dielectric relaxation of ice.

Conductivity of liquid vein networks: Europa's icy shell may be dominated by marine ice that accreted onto the base of the shell. In this scenario, any LVN brines would drain. Any injected brine from the ocean [10-11] or melted pocket of water [9] will retain LVN brines if the temperature is above the salt's eutectic temperature (**Fig. 1**). We assume that the amount of unfrozen water is low enough that a radar reflection from this ice would not be detectable.

To model the magnitude of the LVN conductivity, we use Archie's law $\sigma_{DC}^{bulk} / \sigma_{DC}^{brine} = \phi^m$ [e.g. 22] combined with our numerous laboratory measurements to find an Archie's law exponent m for ice of 1.8–2.8 with a best-fit of 2.35. The direct-current (DC; zero-frequency) electrical conductivity of the bulk ice sample σ_{DC}^{bulk} is measured experimentally, while the brine's conductivity σ_{DC}^{brine} and ice porosity ϕ are modeled. Our model shows that LVNs cause a non-negligible increase DC conductivity and hence radar attenuation.

Radar attenuation of Europa's icy shell: To calculate the attenuation of the icy shell, we sum the conductivity contributions due to the dielectric relaxation and the LVNs to find the high-frequency (HF) conductivity (**Fig. 2d**). Future measurements will aim to reduce the uncertainty in the Archie exponent, which causes significant uncertainty in the predicted attenuation (**Fig. 2a-c**). In **Fig 2e-g**, we combine the temperatures of a warm upwelling and cold downwelling for an ice-shell thickness of 10 km [23] and a linear temperature gradient for a thinner icy shell containing either LVNs or marine/accretion ice frozen from a 10 mM $MgCl_2$ solution. Only the upwelling and linear temperature profiles show minimal differences when accounting for LVNs (**Fig. 2g**). If the $MgCl_2$ concentration is larger (not shown), less change in the LVNs is detectable because the two-way attenuation exceeds the dynamic range of the radar as saltier ice attenuates more energy dielectrically. $CaCl_2$ shows a yet larger change when including LVNs because its eutectic temperature is much lower (not shown). Thus, to detect LVNs, the salt must have (1) a low eutectic temperature, <240 K, (2) a salt concentration >7 mM to produce an observably greater attenuation and (3) a salt concentration that is <60 mM to prevent the ice relaxation from attenuating all the energy before reaching the eutectic temperature. Finally, even with a small amount of salt present in the icy shell, (10 mM) the planned radar sounders are not predicted to penetrate through the entire icy shell. Their penetration depth is limited by warm ice that occurs at ~35% or 90% depth of the thickness of a convecting or conducting icy shell, respectively.

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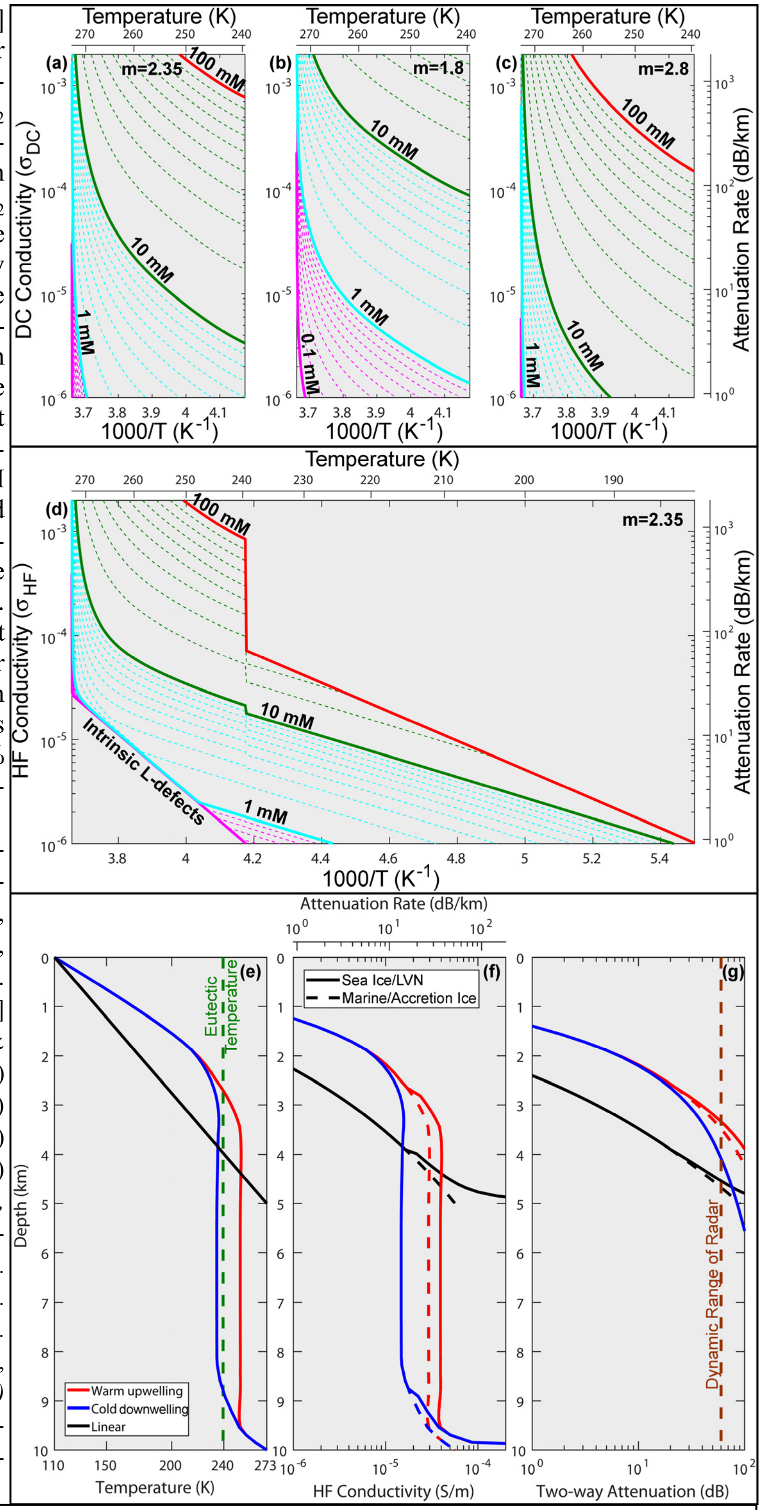

Fig. 2. (a,b,c) Ice conductivity models based on Archie's Law exponents *m* of 2.35 (best-fit), 1.8 and 2.8 for $MgCl_2$ solutions. **(d)** Radar attenuation as a function of temperature dependence and $MgCl_2$ concentration. The jump at 239 K is due to LVN brine melting at the eutectic temperature of $MgCl_2$. Below 7 mM, the increased conductivity due to LVNs is similar to that of the dielectric relaxation. Below the eutectic temperature, high concentration curves merge into the ice-saturated Cl^- curve. **(e)** Three modeled temperature profiles. **(f)** Attenuation rate of sea ice with LVNs and marine/accretion ice without LVNs frozen from a 10-mM $MgCl_2$ liquid solution. **(g)** Two-way attenuation vs. depth, indicating where the returned energy from a perfect reflector (0 dB) equals the dynamic range of the radar sounders.