Modeling the effect of iron oxides on asteroid radar albedos

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Radar remote sensing is a powerful tool used to image planets, moons, asteroids, and comets with ground-based and orbital instruments. Variations in the backscatter coefficient, or albedo, are related to changes in the near-surface properties. Analyses of radar albedos have revealed polar ice deposits on Mercury (Slade et al., 1992), identified methane lakes on Titan (Stofan et al., 2007), and provided evidence for the ice crusts of Europa, Ganymede, and Callisto (Ostro et al., 1992). Interpretations of radar albedos of asteroids have been used to infer metallic composition, such as for 16 Psyche (Magri et al., 1999), the possible remnant metallic core that is the target of NASA's Psyche mission. Analyses that combine measurements of radar albedos of asteroids with dielectric models have been used to determine the near-surface porosity of asteroids (Magri et al., 2001; Hickson et al., 2020).

In these models, the radar albedo is used to determine the Fresnel reflectivity of the near-surface, which can then be used to determine the complex index of refraction of the near-surface material, \( n = \sqrt{\varepsilon \mu} \). The index of refraction is a function of the complex permittivity, \( \varepsilon \), and the complex permeability, \( \mu \). Most minerals are paramagnetic, with permeabilities approaching that of vacuum. As such, many interpretations of the Fresnel reflectivity of planetary surfaces are predominantly concerned with the permittivity. However, some iron oxide minerals are ferromagnetic, and possess permeabilities that can be significantly greater than that of vacuum. The importance of these minerals in interpreting radar backscatter has been identified for Mars, for which iron oxide minerals such as magnetite, hematite, and goethite have been identified in the regolith (Stillman 2006). Earth-based spectroscopic observations of near-Earth asteroid 101955 Bennu, the target of NASA's OSIRIS-REx mission, hinted at the presence of magnetite on the surface (Cloutis et al., 2013). Spectral data obtained by the OSIRIS-REx spacecraft have recently corroborated these early Earth-based observations (Hamilton et al., 2019). These data, combined with compositional analyses of analogue CI/CM carbonaceous chondrite meteorites, indicate that the surface of Bennu could be comprised up to 10% by magnetite.

In this study, we model the effect of magnetic iron oxides on the radar albedo of asteroids. Since the iron oxide abundance on asteroids is not well understood, we use Bennu as a test case. Laboratory measurements of the magnetic permeability of magnetite have been carried out by several authors, including Pettinelli et al., 2005, Cereti et al., 2007, and Stillman 2006 with application to orbital sounding radar of Mars. The measured permeability in these studies can be extrapolated to a volume fraction of magnetite of 10%, relevant for Bennu as mentioned above, using effective medium approximations. Figure 1 shows the measurements of magnetic permeability of various magnetite mixtures from Pettinelli et al., 2005 and Cereti et al., 2007 fit with the
Bruggeman Symmetric mixing model using a permeability of 5.5 for the magnetite phase.

![Graph showing permeability vs. volume fraction with data points and a line fit.]

Figure 1: Magnetite mixture permeability measurements from the literature fitted with the Bruggeman Symmetric effective medium model.

At 10% magnetite, this model predicts an effective permeability of 1.21. This corresponds to an increase of the index of refraction by a factor of \( \sqrt{1.21} = 1.1 \), or 10%. For a smooth surface at normal incidence, the radar albedo, \( \sigma \), is equal to the Fresnel reflectivity:

\[
\sigma = \text{abs}\left(\frac{\sqrt{\varepsilon \mu - 1}}{\sqrt{\varepsilon \mu + 1}}\right)^2.
\]

Ignoring the imaginary part (which is often significantly lower than the real part), for a permittivity of 3 and permeability of 1 the above equation gives a radar albedo of \( \sigma = 0.072 \). If we further assume that this surface is comprised of 10% magnetite (and assume that the magnetite's permittivity has already been incorporated into the effective permittivity of 3), changing the effective permeability to 1.21 increases the radar albedo to \( \sigma = 0.097 \). In this simple example, considering the magnetic effect of 10% magnetite increased the radar albedo by 35% compared with a strictly dielectric model.

We have shown through laboratory measurements from the literature and electromagnetic modeling that iron oxides can increase radar albedos of asteroids appreciably due to their magnetic properties. These magnetic properties must be better understood in the context of asteroids, and their abundances better characterized, for improved interpretation of planetary radar datasets.

References:

Cloutis, E. A., et al. (2013). Possible Causes of Blue Slopes (\(\sim\) 0.5-2.5 \(\mu\)m) in Carbonaceous Chondrite Spectra. LPI, (1719), 1550.


