

# GPR and Magnetic Minerals at Mars Temperatures

David E. Stillman and Gary R. Olhoeft  
Department of Geophysics, Colorado School of Mines,  
1500 Illinois St., Golden, Colorado, 80401-1887 USA  
[dstillma@mines.edu](mailto:dstillma@mines.edu) or [golhoeft@mines.edu](mailto:golhoeft@mines.edu)

**Abstract**—Orbital and earth-based remote sensing infrared spectroscopy, along with in situ magnet tests, Mössbauer, and thermal infrared emission spectroscopy have determined the presence of magnetic minerals on Mars. The iron oxide minerals magnetite and grey hematite have been confirmed in situ by the Spirit and Opportunity rovers. Elemental compositions including nickel and sulfur have also been observed, which along with titanium can produce a wide range of minerals from paramagnetic through ferromagnetic species. Laboratory measurements of the electrical and magnetic properties of magnetite and grey hematite at Mars ambient temperatures in the ground penetrating radar frequency range have produced surprisingly strong dielectric relaxations, as well as the expected magnetic properties. At the average annual Mars surface temperature of 213 K, magnetite has a strong dielectric relaxation near 10 MHz, and hematite has two strong dielectric relaxations near 15 MHz and 200 MHz. These relaxation processes are strongly temperature dependent, moving about a factor of two lower in frequency with each 10 K decrease in temperature. Thus over the temperature range of a Mars Sol, between day and night, these relaxations will move through the frequency range of the MARSIS orbital radar sounder and other proposed radar systems. Also surprising, the weakly magnetic hematite produced stronger magnetic relaxation losses than the more magnetic magnetite in the radar frequency range. The addition of titanium to this iron oxide mixture can lower the Curie temperature (above which ferromagnetic minerals become paramagnetic) into the Mars day-night temperature range, which would make the magnetic signature of the minerals strong at night and make it disappear in the higher daytime temperatures. This is a problem for a radar orbiter since the ionosphere absorbs the radar energy in the daytime and the magnetic relaxations would be strongest at night, severely limiting the possibilities for depth of penetration. Future ground penetrating radar systems on Mars surface rovers will have to carefully choose frequencies and times of operation to maximize depth of penetration. However, the strong frequency dependence as a function of temperature also implies a broadband radar system might be able to produce a temperature versus depth profile.

**Keywords**—Mars, temperature dependence, frequency dependence, dielectric permittivity, magnetic permeability

## I. INTRODUCTION

Subsurface water on Mars needs to be found for a variety of reasons [3]. Olhoeft [10] suggests electromagnetic methods will be the best methods to locate subsurface water on Mars. However, from Viking through the latest results in 2004 from the Spirit and Opportunity rovers, the presence of magnetic minerals has been confirmed on Mars [5,8,9].

Magnetic minerals will impact EM exploration for water, so those minerals expected to be on Mars must be studied at Martian-ambient temperatures to determine their impact on the search for water with EM. Results from Viking, Pathfinder, and 2004 rovers show that the global dust layer on Mars is magnetic at DC frequencies [5,8,9]. The magnetic mineral most likely present is either titanomaghemite and/or titanomagnetite [9]. When titanium is incorporated into a maghemite or magnetite crystal, the Curie temperature can be significantly reduced [7]. The wide daily temperature range on Mars could pass daily through the Curie temperature. This may result in the global dust layer having widely varying magnetic properties as a function of temperature and time of day – from ferromagnetic at night to paramagnetic during the day.

This analysis of Martian magnetic mineral analogs is required to interpret broadband EM measurements. Certain minerals can be identified by their frequency dependence and/or temperature dependence. MARSIS, an orbital radar with 4 frequency bands between 1.8 and 5.0 MHz with a bandwidth of 1 MHz currently orbiting Mars on Mars Express, and SHARAD, an orbital radar with a frequency range from 15-25 MHz (which will fly in 2005 on Mars Reconnaissance Orbiter)[2], are hoped to probe into the subsurface of Mars. While these systems do not have a broad enough frequency range to detect frequency dependence, they may be capable of identifying temperature dependence.

## II. MEASUREMENTS AND ANALYSIS

A variety of analog magnetic mineral samples have been acquired, powdered, vacuum dried, and the EM properties (complex dielectric permittivity, DC conductivity, and complex magnetic permeability) measured as in [4,11].

Seven different materials have been measured to date for their complex EM properties versus temperature and frequency. Of these seven materials, two were quality control experiments using both an empty sample holder and dry quartz sand. That data showed no magnetic or electrical losses for either sample. Five magnetic soils have been tested: hematite, magnetite, maghemite, JSC Mars-1 [1], and grey hematite. The hematite had no magnetic or electrical losses. It had the frequency independent magnetic permeability of free space and a relative dielectric permittivity of 7. Magnetite and maghemite results are shown in Fig. 1. They both showed magnetic polarization at radar frequencies; however, no magnetic losses were

measured since no magnetic relaxations were present and neither showed any significant electrical losses when dry. Even though both these minerals are strongly magnetic, they are low loss minerals at radar frequencies. JSC Mars-1 and grey hematite are also shown in Fig. 2. They are both weakly magnetic at radar frequencies. The JSC Mars-1 had measurable but low electrical losses. The grey hematite had a temperature dependent dielectric relaxation that produced moderate electrical losses. X-ray diffraction confirmed that this grey hematite sample from Keweenaw Peninsula, Michigan is mostly hematite with a minor mineralogical component of goethite.

The frequency dependence of the dielectric relaxation was fit at different temperatures using the Cole-Cole distribution [4,6,11,12]. Data from five different temperatures were fitted to a Boltzmann temperature dependent relaxation process. The Cole-Cole parameters only varied by the time constant of relaxation,  $\tau$ , at each temperature. The independent Cole-Cole parameters are dielectric permittivity at low frequency = 18.9, dielectric permittivity at high frequency = 7.0, and the relaxation distribution parameter is 0.96. The temperature dependence of the time constant was then modeled with the generalized Boltzmann temperature dependence relationship [12] to find the activation energy. Fig. 3 shows the best fit line to four of the five temperature data points. The temperature of the last data point may contain some error, or it may indicate a change in relaxation mechanism. The slope of this line yields an activation energy of 0.0982 eV.

### III. CONCLUSION

As the temperature changes, the structure of the hematite crystal changes. The crystal structure determines the dielectric permittivity, so crystal structure changes with temperature alter the dielectric permittivity with temperature. This temperature dependent dielectric permittivity relaxation has interesting consequences for future Mars EM exploration.

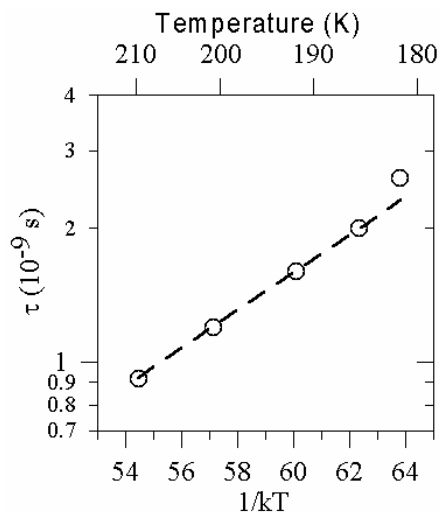


Figure 3. The circles show the grey hematite time constant versus temperature, with the dashed line showing the best fit to a Boltzmann temperature process. The slope of this line is the activation energy.

Since Mars has a high concentration of hematite and a wide temperature range, this temperature dependent relaxation moves widely in frequency on a daily basis. This property can be used to map areas of hematite. If a rover equipped with high bandwidth radar could perform a day-long sounding in a grey hematite area, a temperature profile could also be produced. This profile could be used to estimate shallow heat flow.

The five soil measurements showed that highly magnetic minerals such as magnetite and maghemite may be lower loss materials than weakly magnetic minerals like hematite at Mars ambient temperatures. During the next year, additional types of magnetic mineral samples will be measured and the frequency range of the EM properties measurements will be increased.

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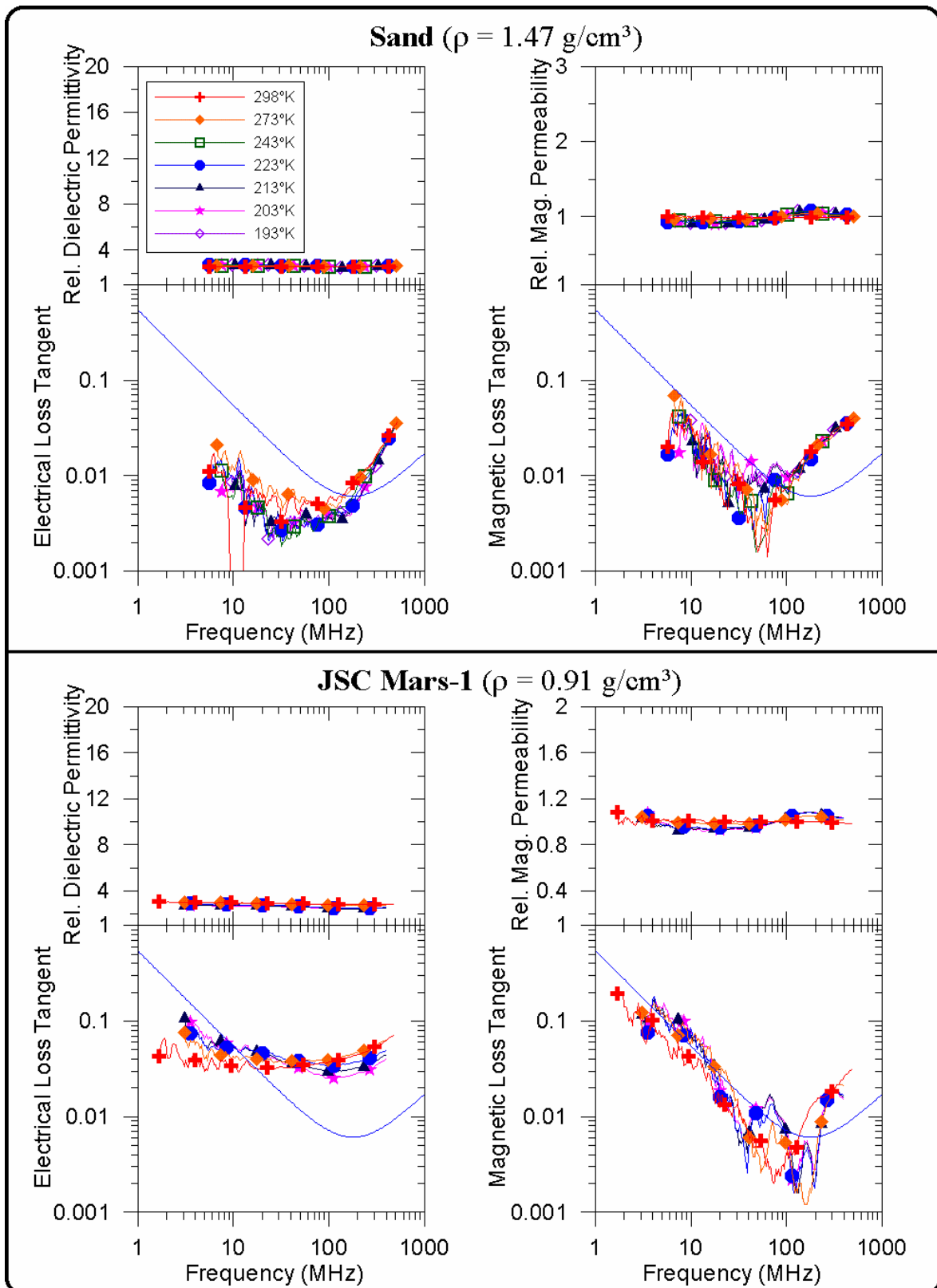


Figure 1. These plots show the dielectric and magnetic properties of vacuum dried powder sand, and JSC Mars-1 as a function of frequency and temperature. The relative dielectric permittivity and electric loss tangent are top and bottom on the left, and the magnetic properties are on the right in each plot. The common blue line (with no symbols) in the loss tangent plots is roughly the minimum measurable loss in the measurement system.

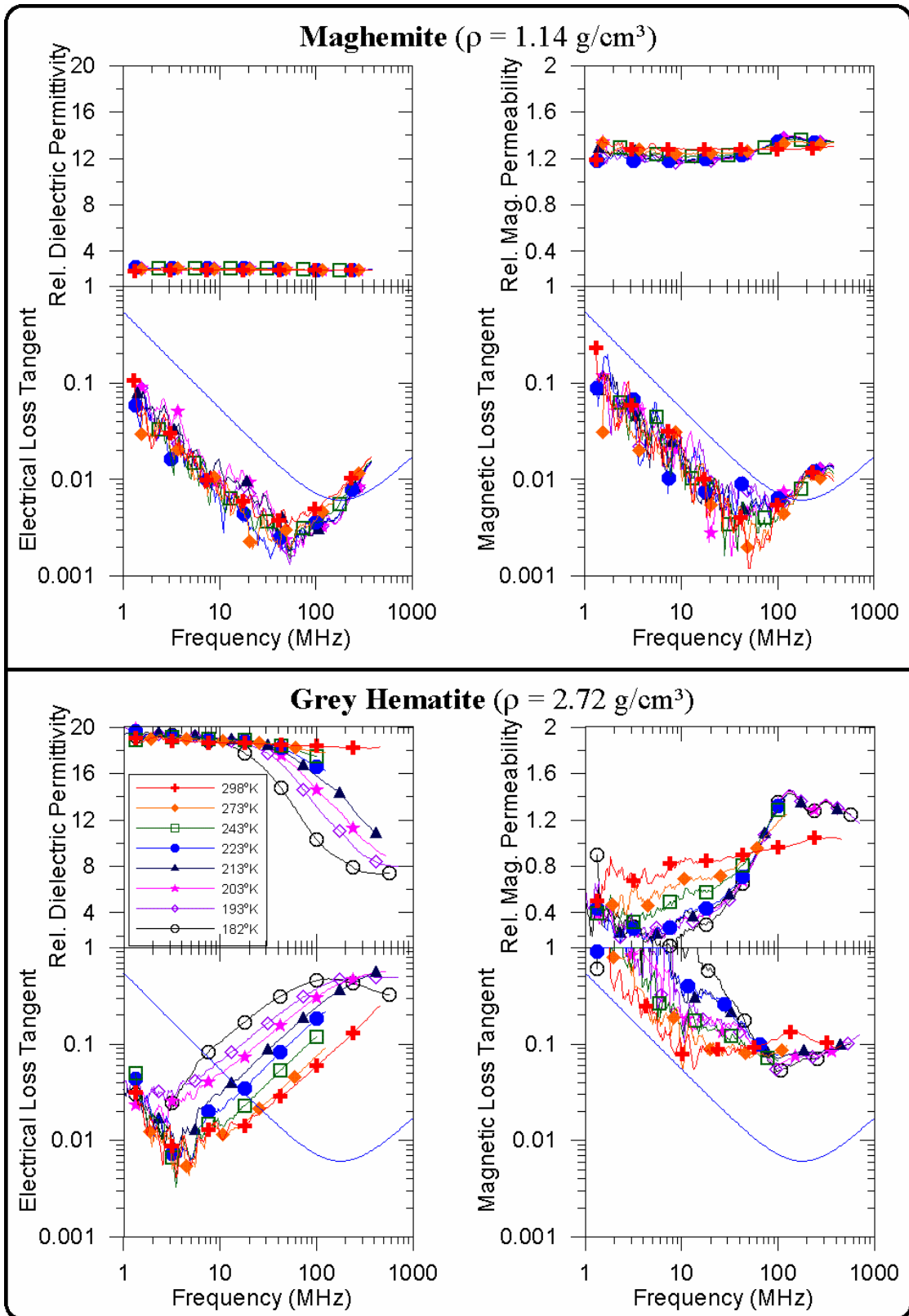


Figure 2. These plots show the dielectric and magnetic properties of vacuum dried maghemite and grey hematite as a function of frequency and temperature. The relative dielectric permittivity and electric loss tangent are top and bottom on the left, and the magnetic properties are on the right in each plot. The common blue line (with no symbols) in the loss tangent plots is roughly the minimum measurable loss in the measurement system.