A Ferroelectric Model for the Low Emissivity Highlands on Venus

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Abstract. A model to explain the low emissivity venusian highlands is proposed utilizing the temperature-dependent dielectric constant of ferroelectric minerals. Ferroelectric minerals are known to occur in alkaline and carbonatite rocks, both of which are plausible for Venus. Ferroelectric minerals possess extremely high dielectric constants (10^5) over small temperature intervals and are only required in minor (<<1%) abundances to explain the observed emissivities. The ferroelectric model can account for: (1) the observed reduction in emissivity with increased altitude, (2) the abrupt return to normal emissivities at highest elevations, and (3) the variations in the critical elevation observed from region to region.

Introduction

One of the most interesting features observed on Venus is the transition from areas of "normal" emissivity (i.e., 0.8-0.9) and radar cross section at wavelengths of 12.6 cm over most of the planet to anomalously low emissivities (as low as 0.3-0.4) above a critical altitude, typically around 6054 km planetary radius [*Pettengill et al.,* 1992]. Because the temperature and pressure are primarily functions only of altitude, one mechanism for this observation is that pyrite (FeS$_2$) becomes thermodynamically stable at higher elevations [*Pettengill et al.,* 1988; *Klose et al.,* 1992]. Pettengill et al. [1988] proposed the loaded dielectric model in which a conductive mineral such as pyrite is dispersed throughout a matrix of a non-conductor such as basalt. The difficulty with the loaded dielectric model in general is that the volumetric fraction of proposed conductive inclusions required [>20%, *Pettengill et al.,*1988] is much higher than that observed in most igneous rocks. In addition, experimental studies by Fegley et al. [1993] show that pyrite rapidly decomposes under the entire range of venusian surface conditions.

Alternatively, Fegley et al. [1992] have proposed that perovskite (CaTiO$_3$) is found only at high elevations on Venus where destruction by reactions involving CO$_2$ and SO$_2$ is kinetically inhibited. Perovskite has a dielectric constant of 170 at radar frequencies and may explain the observed low emissivities; however, a significant amount of perovskite is probably required. (In this paper, reference to dielectric constant or permittivity corresponds to the real part of the complex quantity unless otherwise indicated). Additionally, rates of perovskite destruction by CO$_2$ and SO$_2$ are unknown.

Textural changes have also been invoked to explain low emissivities in the highlands, including decimeter-scale voids interior to the surface which mimic high dielectric permittivities via multiple scattering [*Pettengill et al.,* 1992] or scattering from a matrix of igneous rocks in low loss soils [*Tryka and Muhleman,* 1992]. These explanations are unsatisfying since no mechanism has been proposed to explain why these conditions exist primarily at high elevations.

In this paper, we propose that the low emissivities observed in the highlands of Venus are caused by the presence of ferroelectric

minerals. The dielectric permittivity of ferroelectric minerals behave "normally" below a critical temperature, T$_c$. At and above this temperature the dielectric permittivity takes on values on the order of 10^4 — 10^5 [*Rupprecht and Bell,* 1964]. This mechanism is fundamentally different than those previously proposed because it requires no compositional changes or textural variations with altitude. Furthermore, the model satisfies all observations of low emissivity in the highlands and requires only small quantities (<0.2%) of ferroelectric material.

Properties of Ferroelectrics

Ferroelectric minerals are a subset of the piezoelectric minerals with permanent polarizations that can be reversed upon application of an electric field, analogous to the behavior of ferromagnetic minerals [*Burfoot,* 1967; *Lines and Glass,* 1977]. Also, like ferromagnetic minerals, this behavior disappears above a certain critical temperature which is referred to as the transition temperature [*Burfoot,* 1967]. The term ferroelectric is somewhat misleading in that these minerals are not metallic and the presence of iron is neither required nor common [*Burfoot,* 1967].

Below the transition temperature, the dielectric constant of a ferroelectric mineral is typical of many capacitor ceramics (i.e., 10^2–10^3, *Kingery et al.* [1976]). At the transition temperature, however, the dielectric constant sharply (often discontinuously) increases to values as high as 10^5 and then decays according to the Curie-Weiss equation:

$$\varepsilon_s = \frac{C}{T - T_c} \ \ for \ T > T_c \tag{1}$$

where ε_s is the dielectric constant of the ferroelectric, C is the Curie constant (K$^\circ$) which is a function of the composition of the material, T is the temperature, and T$_c$ is the Curie temperature [*Rupprecht and Bell,* 1964]. In many ferroelectric minerals, the Curie and transition temperatures are equivalent; however, for some minerals they may differ by up to several degrees [*Burfoot,* 1967]. The unusual temperature-dependent dielectric behavior of ferroelectric materials make them very useful for a range of engineering applications [*Kingery et al.,* 1976; *Burfoot,* 1967].

There are several ferroelectric minerals of interest to this work. The perovskites are a series of phases with the structure ABX$_3$, where the X is typically oxygen. The most common perovskite is CaTiO$_3$, but it is not ferroelectric. However, substitution of Ba, Sr, Cd, or Pb for Ca or the substitution of Sn, Hf, Zr, Ce, Ta, Nb, and Cr for Ti produces a suite of solid-solution ferroelectrics [*Rupprecht and Bell,* 1964; *Kingery et al.,* 1976]. Another group of interesting ferroelectric minerals are the pyrochlores which, like the perovskites, are oxide structures. Table 1 lists several perovskite, pyrochlore, and other oxides which have Curie temperatures in the range of venusian surface temperatures. Experimental work with perovskites and other ferroelectric minerals has shown that both T$_c$ and C are functions of the reduced mass of the mineral, thus providing a way to calculate both constants for a solid-solution mixture of

various cations [*Rupprecht and Bell*, 1964; *Kingery et al.*, 1976; *Burfoot*, 1967; *Lines and Glass*, 1977].

Both the pyrochlores and perovskites are interesting candidates for venusian ferroelectrics because they occur naturally in terrestrial alkaline basalts and carbonatites. Chemical analyses by Venera Landers 8 and 13 suggest alkaline basalts are present on the venusian surface. Fegley et al. [1992] have noted that alkaline rocks can buffer the atmospheric concentrations of CO_2, HCl, and HF. Finally, Kargel et al. [1991] have observed that some of the venusian channels require low viscosity melts and suggested carbonatite flows as one possibility.

Ferroelectric Model for Venus

In this section, we develop a ferroelectric model which can be compared directly to venusian observations of the distribution of emissivity with altitude. We assume that a ferroelectric mineral phase is ubiquitous (although this is not a requirement) in moderate to low concentrations, (i.e., <1%). We also assume that emissivity can be related to the surface dielectric properties by

$$e(\varepsilon,\mu,\theta)= 1 - \rho(\varepsilon,\mu,\theta) \qquad (2)$$

where e is the emissivity, and ρ is the power reflectivity given by Fresnel's equation: a function of ε, the relative dielectric permittivity; μ the relative magnetic permeability; and θ, the emission angle [*Pettengill et al.*, 1988]. To attain the low values of emissivity observed (≤0.4 in some regions), dielectric permittivities must be ≥65, assuming μ ~1 (i.e., most non-ferromagnetic minerals).

The ferroelectric model that we propose is somewhat analogous to the loaded dielectric model in that mixtures of different dielectric materials combine to give a higher dielectric constant than the matrix material. However, the ferroelectric model differs from the loaded dielectric because the ferroelectric inclusions are typically non-conductors. Further, a minor volumetric fraction of a mixture with typical ferroelectric dielectric permittivities of 10^5 can explain the observed emissivities.

A significant body of theory has been developed to calculate the effective dielectric permittivity of a mixture of non-conducting dielectrics (e.g., see the reviews by *Scaife*, [1989]; and *Sihvola and Kong*, [1988]). In this paper, we adopt the Polder-van Santen formula as described in Sihvola and Kong [1988]. The effective dielectric permittivity of a binary mixture is given by:

$$\varepsilon_{eff}= \varepsilon + \frac{f}{3}(\varepsilon_s - \varepsilon) \sum_{i=1}^{3} \frac{\varepsilon_{eff}}{\varepsilon_{eff} + N_i(\varepsilon_s - \varepsilon_{eff})} \qquad (3)$$

where ε_{eff} is the effective dielectric permittivity of the mixture, ε is the dielectric permittivity of the matrix (e.g., basalt), ε_s is the dielectric permittivity of the inclusions (ferroelectrics), f is the volumetric fraction of the inclusions, and N_i are the depolarization factors. It has been shown that the shape of the inclusions will have a significant effect on the effective dielectric permittivity, while changing the magnetic permeability very little [*Sihvola and Kong*, 1988]. In this formulation, the inclusions are modeled as randomly

Table 1. Candidate Ferroelectric Minerals (After *Lines and Glass*, [1977])

Material	Compound Type	Tc (°K)
(Pb(Ba,Sr,Ca))TiO₃	Perovskite	0—760
K(Ta,Nb)O₃	Perovskite	0—705
Na(Nb,Ta)O₃	Perovskite	75—750
Pb₂Bi(Ta,Nb)O₆	Pyrochlore	690—745
Pb(Nb,Ta)₂O₆	Oxide	530—840

oriented ellipsoids, small with respect to the wavelength of incident radiation. N is a three component vector which describes the three orthogonal dipole moments of the inclusions: [1/3, 1/3, 1/3] for spheres, [1/2, 1/2, 0] for "needles" (prolate ellipsoid endmember), and [1, 0, 0] for "discs" (oblate ellipsoid endmember). Note that equation (3) is not in closed form and must be solved iteratively.

Using equation (3), the amount of a ferroelectric required to increase the dielectric permittivity of the surface to 65 from the typical value of 4-5 is ~900 ppm (0.09%) by volume, assuming a dielectric permittivity of 10^5 for the ferroelectric and a disc or tabular shape for the inclusions. If the inclusions are acicular (needle shaped), ~0.2% is required, and spherical inclusions require more than 20%. For volumes <10%, the dielectric permittivity is approximately a linear function of ferroelectric abundance; for the above example, slopes are ~690 (dielectric constant) per vol % for tabular inclusions and 370 per vol% for acicular inclusions.

Elemental abundance constraints required for ferroelectrics can be taken from Vega 2 lander measurements (obtained at 0.4 km elevation). Fegley et al. [1992] list these abundances as: Pb <0.3%; Sr, Y, Zr, Nb < 0.1%. If these limits are representative of the highlands, our model requires the ferroelectric phases to be tabular or acicular. However, recent experimental work with $BaTiO_3$ powder in a polyethylene matrix indicates that equant phases may behave more like acicular inclusions than the spherical ones [*Takeuchi*, 1991]. Additionally, because the model only assumes the size of the inclusions to be less than the wavelength, aggregations of equant minerals in columnar, foliating, or radiating structures should behave more like tabular or acicular inclusions than spherical ones.

Discussion

Figure 1(a) shows a Magellan SAR image (C-MIDR mosaic) of the Ovda Regio region, a highland area containing tesserae (highly tectonized terrain) and evidence of volcanism. Figure 1(b) shows an enlargement (F-MIDR) of the box outlined in Figure 1(a). Figure 1(c) is an enlargement of the box shown in 1(b) and was one of two images utilized to create the digital elevation model (DEM) shown in Figure 1(d). Figure 1(e) shows an emissivity map of the same area contained in Figs. 1(c) and 1(d).

The DEM was derived from stereophotogrammetric analysis [e.g., *Leberl et al.*, 1992] of cycle 1 and 3 Magellan radar backscatter mosaics (F05S098;1 and F05S099;301). The horizontal resolution of the DEM is similar to the radar resolution (~150 m) and much higher than the altimeter footprint resolution (~10 x 20 km). Additionally, the DEM does not suffer from the vertical uncertainties found in the altimeter data over rough highlands which are caused by multiple reflections from complex topography. For the data shown in Figure 1, the DEM was calibrated to units of planetary radius by comparing DEM and elevations derived from Magellan altimetry data, using locations where the altimeter measurements were considered accurate. The contour on the DEM demarcates a planetary radius of 6056 km.

Figure 2 is a scatterplot of emissivity versus elevation for the Ovda region. Emissivity was obtained from the Magellan high gain antenna in a passive mode [*Pettengill et al.*, 1992] and topographic data were taken from smoothed altimetric results, together with the DEM. Using equations (1), (2) and (3), and the assumption of a constant quantity of ferroelectric inclusions, we generated a model curve (shown as a line in Figure 2) to match the observed behavior of emissivity versus altitude. Similar behaviors are found in most of the highland regions [c.f. *Klose et al.*, 1992] and model fits to these will be published in a subsequent paper. Scatter about the model curve is believed to be caused by uncertainties in the altimetry and emissivity measurements, variations in ferroelectric abundance and Curie temperature, and the fact that the data come from a large area and
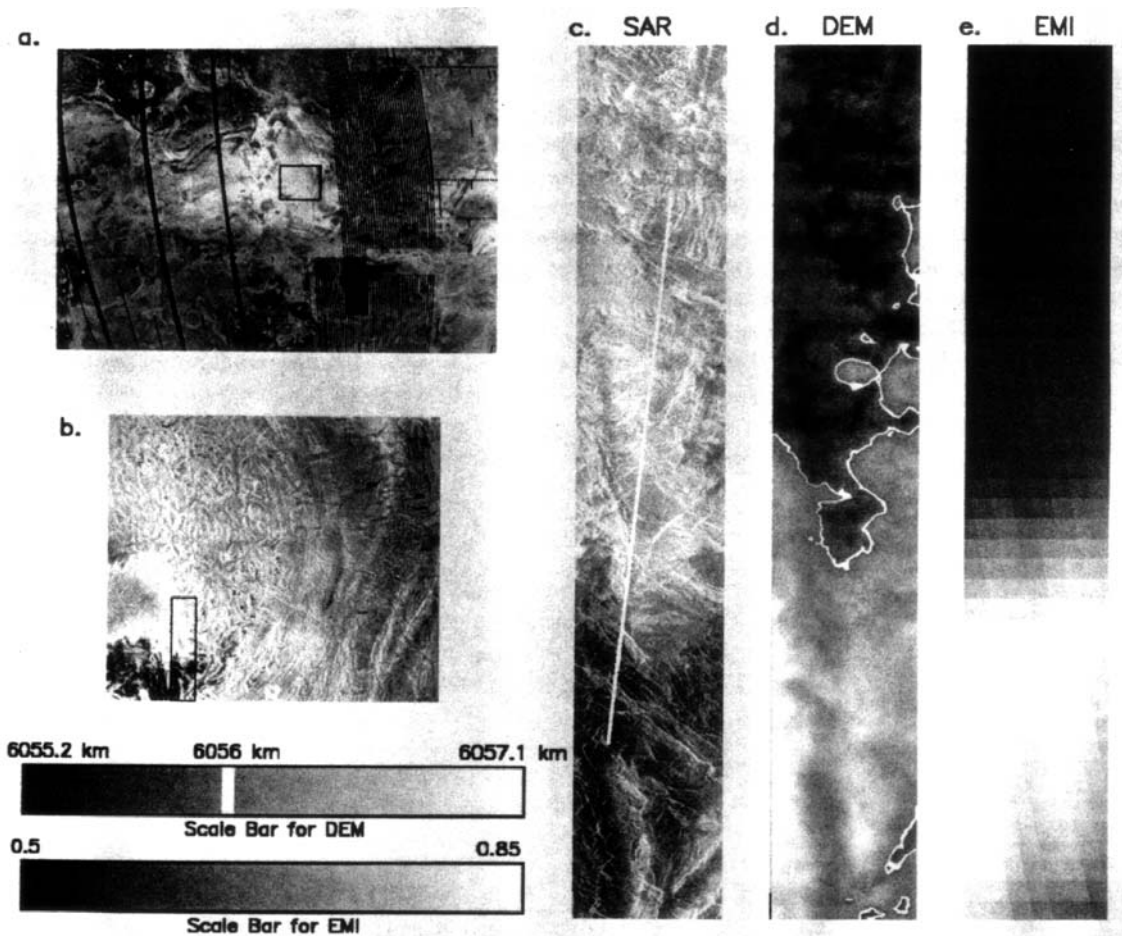
Figure 1. (a) Magellan SAR image of Ovda Regio (C-MIDR mosaic, latitude -45° to 45°, longitude 53° to 127°). (b) F-MIDR of outlined box in C-MIDR image (F05S098;1). (c) Enlargement of outlined box in F-MIDR (SAR backscatter). (d) Gray-scale digital elevation model (DEM) of Figure 1(c). (e) Emissivity map (EMI) of area in (c) and (d). Figures 1(c)-1(e) are ~200 km long. White line in 1(c) indicates transect along which elevation data were extracted from DEM. Bars at bottom of figure shows correspondence of gray-scale to elevation on DEM and emissivity in 1(e). White contour on DEM corresponds to planetary radius 6056.0 km. Note the correspondence of radar bright regions below 6056 km in (c) and emissivity lows (dark) in (e). This transition is quantitatively displayed in Figure 2.

therefore represent the average properties of many different types of terrain.

In addition to explaining the observed emissivity/elevation behavior in the highlands, several other observations are explained with the ferroelectric model. For example, one prediction of the ferroelectric model is that at higher elevations, corresponding to temperatures just below the ferroelectric T_c, the emissivity should abruptly return to normal values. This behavior is difficult to test with altimeter data because of the small areas covered by the highest elevations and the presence of multiple reflections from rough topography. Thus, to examine this phenomenon more closely, we studied portions of Ovda using the high resolution DEM data. Figure 2 shows a series of elevation/emissivity data points (circles) where the DEM data were taken along the profile shown in Figure 1(c). Elevations along this profile were averaged to correspond to the footprint sizes of the emissivity observations. These additional points show an extremely sharp transition from very low emissivity (0.35) to more normal emissivity (0.8), consistent with the model prediction.

The variation in the critical altitude or "snow" line from region to region [*Klose et al.*, 1992] can be explained by slight variations in the solid-solution composition of the ferroelectric. As an example, consider the ferroelectric $(Pb_{0.9}Ca_{0.1})TiO_3$. A 1% change in the Pb abundance from 0.91 to 0.92 changes the Curie temperature from 700° K to 708° K, equivalent to a 1 km change in the critical altitude [*Rupprecht and Bell*, 1964]. The lack of low emissivity regions above the 6054 planetary radius for Maat Mons [*Klose et al.*, 1992] can be explained by the absence of ferroelectric minerals e.g., flows other than alkaline. Alternatively, if there are ferroelectrics in these regions, their Curie temperature must be significantly different from the venusian surface temperature (therefore constraining their compositions).

Finally, we would like to address the reported correlation of high values of depolarized reflectivity (LL/LR ratios as high as 1.2) with high altitude regions [*Tryka and Muhleman*, 1992; B. Campbell, person. comm., 1994; D. Campbell, unpublished data]. The two interpretations most frequently cited are that either surface roughness (e.g., models dominated by small-scale or dihedral surface scattering)
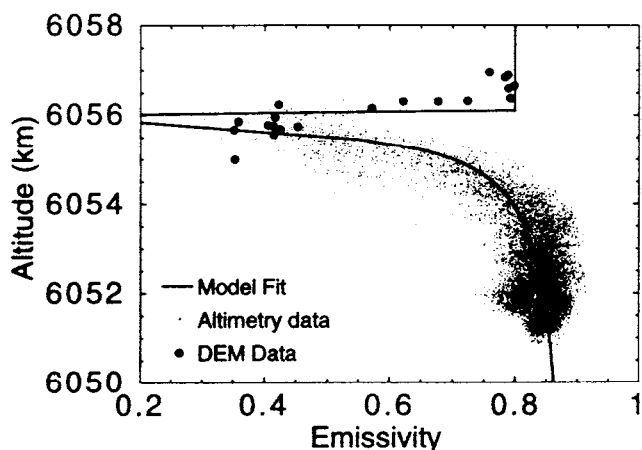
Figure 2. Scatterplot of emissivity versus altitude for Ovda Regio. Emissivity and altimetry data were extracted from area latitude -20° to 7°, longitude 60° to 113°. Altimeter data are dots and the ferroelectric model (assuming tabular inclusions) is the line. Circles on Ovda plot are DEM data extracted from a transect shown in Figure 1(c). The higher resolution DEM topography shows a sharp transition from low emissivity (0.35) to normal emissivity (0.8) at higher elevations. Model parameters: $T_c = 701.5$ °K, $C = 10^5$ K*, inclusion abundance = 0.07%, matrix $\varepsilon = 3.5$.

or textural changes (e.g., lossy soil matrix with imbedded scatterers or other models dominated by volume scattering) are responsible [*Tryka and Muhleman*, 1992].

We have noted in AIRSAR (polarimetric C,L,P band synthetic aperture radar) observations of the Lunar Crater Volcanic Field, Nevada, that LL/LR ratios are often correlated with topography (values up to 0.8 in The Wall, a densely welded rhyolitic ash deposit). The most reasonable explanation is that topographic highs are more prone to erosion and talus or colluvium roughens the surface. Campbell and Campbell [1992] report high (up to ~1.0) LL/LR ratios for many a'a and blocky lava flows where surface scattering is thought to dominate. Additionally, Campbell and Campbell [1992] note that increased surface reflectance (due to increased dielectric permittivity) increases the LL/LR ratio as second and higher-order reflections become more important. For example, a typical surface with reflectance of 0.1 (emissivity 0.9) would have second order reflectances of 0.01 and third order 0.001 (essentially negligible) whereas a surface with a reflectance of 0.5 (emissivity of 0.5) would have second order reflectances of 0.25 and third order ~0.06, both of which are significant. Therefore, we believe the high values of LL/LR noted in the highlands are caused primarily by an increase in the dielectric permittivity of the surface and secondarily by initial surface roughness or increases caused by weathering and erosion.

Future Work

A remaining unanswered question to be addressed by this model is the specific ferroelectric mineral(s) responsible for the low emissivity observations. Because of the lack of knowledge about venusian trace element chemistry and the wide range of possible ferroelectric solid solutions, we cannot choose any one phase as a definitive candidate. For similar reasons, we have not considered the thermodynamic stability of the perovskites or pyrochlores. While somewhat exotic from a terrestrial standpoint, ferroelectric minerals may be common under the rather unusual venusian conditions.

Certainly the types of rocks in which they occur are strong candidates for the venusian surface. Experimental thermodynamic work and additional chemical constraints on the venusian surface are therefore required to conclusively test this model.

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