A FERROELECTRIC MODEL FOR THE LOW EMISSIVITY HIGHLANDS ON VENUS;

Michael K. Shepard, Raymond E. Arvidson, Robert A. Brackett, and Bruce Fegley Jr., McDonnell Center for the Space Sciences, Washington University, St. Louis, MO, 63130

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 believed to exist on Venus. Ferroelectric minerals possess extremely high dielectric constants (10^5) in a small range of temperatures and therefore require only minor (<<1%) abundances to explain the observed emissivities. The ferroelectric model simply explains: (1) the observed trends in emissivity with altitude, (2) the sharp transition back to normal emissivities at the highest elevations, (3) the variations in the critical elevation observed from region to region, and (4) emissivity polarization properties.

An interesting feature 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 of planetary radius [1]. Because the temperature and pressure are functions only of altitude, one mechanism proposed for this observation is that pyrite (FeS_2) becomes thermodynamically stable at higher elevations [2,3] where, when incorporated in a rock matrix, it acts as a 'loaded dielectric' and raises the effective dielectric permittivity of the surface. One difficulty with this model is that the measured dielectric permittivity of pyrite is only ~10 [4] whereas the value at high altitudes on Venus is ~65. In addition, experimental studies show that pyrite rapidly decomposes under the entire range of venusian surface conditions [5]. An alternate proposal is that perovskite ($CaTiO_3$) is found only at high elevations on Venus where its destruction by reactions involving CO_2 and SO_2 is kinetically inhibited [6]. Perovskite has a dielectric constant of 170 at microwave frequencies and may be able to explain the observed low emissivities; however, a significant amount of perovskite is probably required. Additionally, the rates of perovskite destruction by CO_2 and SO_2 are currently unknown.

Textural changes have also been invoked to explain the low emissivities, including decimeter-scale voids interior to the surface which would mimic high dielectric permittivities via multiple scattering [1] or scattering from a matrix of igneous rocks in low loss soils [7]. However, no mechanisms have been proposed to explain why these textural changes occur with elevation. In part, textural changes (and the resulting volume scattering) have been proposed to explain the correlation between venusian topography and observed depolarized to polarized (LL/LR) backscatter ratios [7]. However, studies of terrestrial surfaces demonstrate that surface roughness can explain this correlation [8]. Furthermore, scattering theory implies that an increasing surface dielectric constant (with altitude) will also increase LL/LR ratios, independent of roughness [8].

Ferroelectric minerals are a subset of the piezoelectric minerals with permanent polarizations that can be reversed upon the application of an electric field, analogous to the behavior of ferromagnetic minerals. Also like ferromagnetic minerals, this behavior disappears above a certain critical temperature which is referred to as the Curie or transition temperature. The term ferroelectric is misleading in that these minerals are not metallic and the presence of iron is not common [9]. Below the Curie temperature, the dielectric permittivity of a ferroelectric is typically 10^2 - 10^3. At the Curie temperature, however, the dielectric permittivity sharply (often discontinuously) increases to values as high as 10^5 and then decays inversely proportional to the temperature. This behavior can be expressed with the Curie-Weiss equation:

$$\varepsilon_S = \frac{C}{T - T_C} \quad \text{for } T > T_C \tag{1}$$

where ε_s is the dielectric permittivity of the ferroelectric, C is the Curie constant which is a function of the composition of the material, T is the temperature, and T_c is the Curie temperature [10]. Minerals which display ferroelectric behavior include many of the perovskites (although not pure $CaTiO_3$) and pyrochlores [11]. These minerals are of interest because perovskites and pyrochlores occur naturally in alkaline basalts and carbonatites, both of which have been proposed to exist on Venus [6,12].

We have developed a model utilizing ferroelectric minerals which can be directly compared to venusian observations of the distribution of emissivity with altitude. Several assumptions are made in the model: (1) ferroelectric minerals are ubiquitous (though this is not required), (2) ferroelectric minerals are present only in small concentrations (i.e. 0.1% - 1%), and (3) the Fresnel equations can be used to relate the surface dielectric constant to observed emissivities. We utilize the Polder - van Santen dielectric mixing model to calculate the effective dielectric constant of a basalt matrix (ε = 3-6) with small concentrations of ferroelectric inclusions (ε given by eq. 1) [13]. We find that concentrations of only 0.06-0.2% by volume are required to give an effective dielectric constant of 65, where the range represents tabular and acicular endmember mineral forms, respectively. Figure (1) shows model predictions (line) for emissivity as a function of temperature (and therefore altitude) plotted with Magellan emissivity (horizontal polarization) and elevation observations (small dots) over Ovda Regio. The scatter about the curve is due to uncertainties in altimetry measurements over rough topography, variations in ferroelectric abundance and T_c (caused by solid-solution compositional variations), and averaging over the large emissivity and altimetry footprints. Figure 1 also shows emissivity data (larger dots) over an area of Ovda Regio for which high resolution elevation data were obtained from a digital elevation model (DEM). The DEM was made using stereophotogrammetric analysis of Cycle 1 and 3 Magellan F-MIDR's (F05S098;1 and F05S099;301) [14]. The additional data points on Figure 1 show a sharp demarcation from low emissivity to normal emissivity in a narrow altitude range about 6056 km. This observation is consistent with the ferroelectric model in that the temperature at this elevation corresponds to the Curie temperature of the ferroelectric mineral. Regional variations in the critical elevation are caused by variations in the Curie temperature, which is known to vary with the solid-solution composition of the ferroelectric mineral [11].

The ferroelectric model can also explain the observed emissivity polarization properties. Figure 2 shows vertically polarized emissivity (EV) observations (small dots) from 6 orbits at longitudes of 93-98° and latitudes of 20° to -20°. EH data (coincident with EV data but not shown for clarity) were fit with the ferroelectric model (dashed-line). The EH model curve was then used to calculate expected EV behavior, assuming perfectly smooth surfaces and Fresnel reflection. The predicted EV model curve (solid-line) is quite close to the EV observations. If the surface was "perfectly rough" (i.e., Lambertian), EV observations would be identical to EH observations [15]. Thus, the proximity of the smooth surface EV model curve to the observations indicates that the ferroelectric model is viable and that emission is only weakly controlled by roughness.

To summarize, several observational features of the highlands are simply explained by a ferroelectric mineral model: (1) the observed trends of emissivity with elevation are due only to the change in temperature and not compositional or textural changes; (2) the sharp return to normal emissivity at the highest elevations observed in some regions (e.g, Maat, Sif, Ozza Mons; Ovda Regio) occurs where local temperature equals T_c and the ferroelectric behavior switches off; (3) regional variations in the critical altitude are due to slight compositional changes in the ferroelectric solid-solution phase which changes T_c; and (4) observations of horizontally and vertically polarized emissivity are consistent with a temperature (and therefore elevation) dependent surface dielectric constant and low to moderate surface roughness. Acknowledgements. We thank J. Alexopoulos and R. Phillips for providing the DEM.

Figure 1

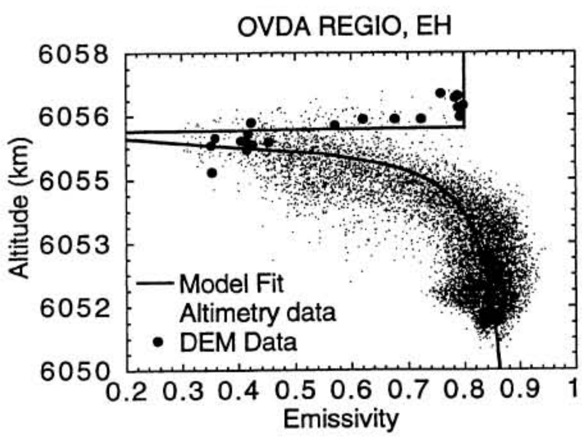
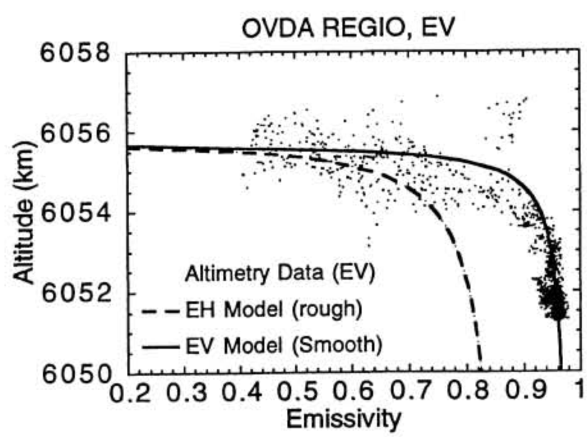


Figure 2



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