MULTIPLE SCATTERING AND POLARIZATION OF THERMAL EMISSION FROM PARTICULATE PLANETARY SURFACES; B.G. Henderson*, B.M. Jakosky**, and C.E. Randall, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309-0392 (* also Department of APAS, ** also Department of Geological Sciences).

Introduction: Most of the thermal emission from planetary surfaces occurs in the mid-infrared region of the electromagnetic spectrum. When the surface is smooth on the scale of the wavelength (on the order of 10 μm), the emissivity and the polarization of the thermal emission are governed by the Fresnel relations for transmission of radiation through a smooth dielectric boundary. Real surfaces, however, are rough due to surface slopes, rocks, and particulates which make up the surface. These variables change the emission geometry and the scattering properties of the medium and in turn affect the directional and spectral properties and the polarization state of the emitted radiation.

The theory of emission spectroscopy of particulate media has been treated by a number of authors (1,2,3,4). However, no work that we know of has included polarization of the emitted radiation in the calculations. In this study, we model a planetary surface as a collection of spherical grains large relative to the scale of the wavelength of emission. Using a Monte Carlo ray tracing approach, we determine the effects that particulate roughness and scattering have on the emissivity (directional and spectral) and the polarization state of the emitted thermal radiation in the wavelength range 7-16 μm. The results are then applied to specific problems of planetary interest.

Model Description: We constructed a computer model of a planetary regolith composed of spherical grains large relative to the scale of the wavelength. Under this assumption, the geometrical optics approximation will apply and a ray tracing approach should be adequate. When a grain within the regolith emits photons along a particular trajectory, the grain’s emissivity (both directional and spectral), or equivalently, the beam’s intensity, will be determined by the Fresnel equations evaluated at the local emission angle for a given index of refraction (a function of wavelength). During a scattering event in which the photon beam collides with another grain, the reflectivity is calculated using Fresnel at the local incident angle, and the trajectory of the subsequent ray path is calculated assuming specular reflection. The scatterer is also emitting along the same trajectory, and the emitted contribution plus the scattered (reflected) contribution continue along the same ray path until the next scattering event. This process continues until the beam of photons bounces out of the regolith. Using a Monte Carlo technique, we obtained multiple ray paths within the regolith which emerged from the surface at a pre-selected emission angle (relative to the average surface). The averaged intensity of the beams along these ray paths determines the effective emissivity of the bulk surface at that particular emission angle. We repeated this procedure for emission angles between 0 and 90 degrees while varying the index of refraction to obtain the directional and spectral dependence of the emissivity of a particulate quartz regolith.

The geometrical optics approximation used in the model facilitates the calculation of polarization. At a given incidence (or emission) angle, the Fresnel relations give the values of reflectivity (or emissivity) for the polarization directions parallel and perpendicular to the local incident plane. From these values we obtain the amplitudes of the two components of the electric vector. These amplitudes plus the relative phase difference between the two components are the three parameters needed to define the Stokes vector, the complete characterization of the intensity and the polarization state of the radiation along a given ray path. We calculate the polarization of the emitted radiation as a function of emission angle (0°-90°) and wavelength (7-16 μm).

Results: The directional emissivity predicted by our model deviates significantly from Fresnel, especially at high emission angles. The deviation is a result of both particulate roughness and scattering. The direct, non-scattered component of the directional emissivity of a particulate surface looks more or less Lambertian, showing a flat response as a function of emission angle. The scattered contribution gives the signal an overall boost while adding curvature at oblique emission, resulting in a "limb-darkening" profile. The curvature is a result of there being fewer
"holes" visible into the subsurface at high emission angles, and therefore fewer available paths for scattered radiation to contribute to the signal. Our results show excellent agreement with the experimental studies of directional emissivity by Jakosky et al. (5).

The spectral emissivity predicted by our model shows an overall reduction in spectral contrast when compared to the emission spectrum from a smooth surface, as is well known from laboratory work done on powdered materials. By varying the degree of scattering allowed in the model, we show that scattering contributes most significantly in the reststrahlen bands. Emission spectra of the lunar surface obtained by Lucey (6) show a reduction in spectral contrast at extreme (> 85°) emission angles. Our model cannot reproduce this effect; our results actually show an increase in spectral contrast with increasing emission angle.

The polarization results show that, in general, roughness and scattering tend to depolarize the emitted radiation. At normal emission, the percent polarization approaches 0% (as required by symmetry), but increases with angle of emission. Furthermore, the percent polarization as a function of wavelength is correlated with the index of refraction, reaching a peak value near 7% at oblique emission when the extinction coefficient is a maximum. Past attempts (7,8) to characterize the nature of planetary surfaces using infrared polarimetry have modeled the emitting surface as a locally smooth plane. Since real surfaces are rough and usually particulate, use of our model would be a significant improvement for surface analyses incorporating infrared polarimetry.

Conclusions: Surface roughness and scattering within a particulate medium have a significant effect on the directional properties, spectral contrast, and polarization state of the thermal radiation emitted from planetary surfaces. Understanding these effects is important for interpreting data from past and future spacecraft missions. In addition, the magnitude of such effects might be used as an additional tool for learning more about the physical structure and composition of a planet's surface.