AN ANALYTIC MODEL FOR THE THERMAL CONDUCTIVITY OF PLANETARY REGOLITH: UNCEMENTED, NON-SPHERICAL PARTICULATES. Stephen E. Wood, Dept. of Earth and Space Sciences, Univ of Washington, Box 351310, Seattle, WA, 98195-1310, sewood@ess.washington.edu.

Introduction: Thermal conductivity is one of the most highly variable properties of planetary surfaces, with values ranging over more than three orders of magnitude from ~0.001 W/mK for dust on airless bodies to 2-5 W/mK for solid rock or ice. The effective thermal conductivity (k_{eff}) of porous, particulate material increases with the degree of intergranular cementation and is a function of atmospheric pressure when the pore size is comparable to the mean free path. It is the most variable component of thermal inertia (I=sqrt[$k\rho c$]) - the parameter that controls the surface temperature response to diurnal and seasonal insolation cycles; and below the depth of the seasonal thermal wave (a few meters), for a given interior heat flow Q, k_{eff} also determines the geothermal gradient ($dT/dz = Q/k$) and therefore the temperature profile at all depths where conductive heat transfer dominates. These effects also make it an important factor in determining the thermal stability and phase of volatiles or hydrated minerals in the regolith.

A new analytic model [1] is presented for estimating the effective thermal conductivity (k_{eff}) of porous planetary regolith as a function of the intrinsic thermal conductivities and physical properties of the material components (solid and gas), the porosity, particle size and shape, air pressure in the pore space, and temperature. A simplified version of the model for the case of regolith in vacuum is also presented. Model predictions of k_{eff} compare favorably ($\sigma < 20\%$) to previous laboratory measurements for a wide range of pressure/ temperature conditions and particle properties, including spherical glass beads [2,3], angular basalt and quartz powders [4,5] and Apollo lunar soil samples [6]. This model provides an easily implemented tool for quantitative analysis of planetary thermal inertia observations in terms of particle size, porosity, and composition. Matlab source code is available from the author.

Model Description: The model is based on the Maxwell-Eucken theoretical expressions for the upper and lower bounds for k_{eff} of heterogeneous, isotropic material. These equations provide tighter bounds than the parallel and series approximations often used to estimate k_{eff} for porous media [e.g. 7,8]. The effect of interparticle contact is modeled using an semiempirical parameter f_{sc} that represents the fractional continuity of the solid phase. An expression for this parameter is proposed with a functional dependence on the relative size and number of contacts between particles. The actual size of the contacts is estimated based on Hertzian mechanics of elastic deformation including the effects of cohesive surface forces [9]. An effective minimum contact radius is determined that also takes into account the heat transfer through the pore space in the immediate vicinity of the contact based on previous theoretical work [10], as well as lower limits due to plastic deformation.

Particle shape is quantified in terms of its sphericity and roundness. The effects of sphericity are explicitly included in calculations of the Maxwell-Eucken bounds, the effective pore size and, along with roundness, the average local radius of curvature at the contacts. The effect of radiative heat transfer is included, as well as the dependence of gas conductivity on temperature and Knudsen number from kinetic theory.

Previous Models: In the planetary literature, Mellon et al. [7,8] have described models for k_{eff} of loose particulates and icy regolith, but neither has been quantitatively compared to measured values to evaluate their accuracy. An empirical formula based on a log-linear fit to lab measurements for silica glass beads in CO_2 gas [2] has been used extensively for the past 15 years to interpret observations of Mars' surface thermal properties (e.g. relating thermal inertia to particle size). A finite-element numerical model for loose particulates on planetary surfaces has recently been developed and shown to match laboratory measurements of k_{eff} for glass beads in various gases over a wide range of pressures [11]. In comparison, the analytic model presented here is much less computationally intensive and has a greater range of applicability [1].

Results: This study has demonstrated that a model with a simple framework (a single parameter scaling between the Maxwell-Eucken limits) can successfully predict the effective thermal conductivity (k_{eff}) for a particulate medium such as planetary regolith as long as each component of the framework (kg, kr, ks, and the parameter fsc), and the primary quantities they depend on (pore size, contact size, particle shape, composition and coordination number) are determined carefully and accurately. In comparison to previous models that achieve accuracy through a more complex framework or greater dependence on empirical factors, this approach offers the advantage of being more easily extended to the wide variety of materials and conditions found on and beneath planetary surfaces. And it was shown that for the case of regolith in vacuum, the model equations can be simplified to the same functional form proposed and used in many previous studies (A + BT^3), but with an explicit dependence on measurable properties in each term.

Comparisons of the model with data for crushed crystalline silicates showed that the effects of non-spherical and angular particle shapes can be accounted for to first order, and that more angular particles can have a significantly lower k_{eff} on planets with negligible or thin atmospheres including Mars. Under these same conditions it was also shown that keff has a strong dependence on the intrinsic conductivity of the solid material (ks, and therefore the composition and temperature of the particles), contrary to claims in previous studies.

And based on previous theoretical work by Batchelor and O'Brien (1977), this model predicts that the contribution of conduction through the solid particles contacts is linearly proportional to the contact radius, rather than the area of the contact as might be expected, for the range of conditions relevant to planetary regolith in our solar system (ks=(kg + kr) > 3.

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References: [1] Wood, S. E. (2013) *Icarus, in press*. [2] Presley, M.A. and P.R. Christensen (1997) *JGR, 102*, 6551-6566. [3] Huetter E.S. et al. (2008) *JGR, 113*, E12004. [4] Fountain, J. A., and E. A. West (1970), J. Geophys. Res., 75, 4063. [5] Presley, M. A., and P. R. Christensen (2010), JGR, 115, E07003. [6] Cremers, C. J., and R. C. Birkebak (1971), Proc. 2nd Lunar Sci. Conf., Vol 3., pp 2311. [7] Mellon, M.T. et al (1997) *JGR 102*, 19357-69. [8] Mellon, M.T. et al. (2008) The Martian Surface, ed. J. Bell III, Cambridge Univ. Press, pp. 399-427. [9] Batchelor, G. K. and R. W. O'Brien (1977), Proc. Royal Soc. London A, 355, 313. [10] Johnson, K. L., K. Kendall, and A. D. Roberts (1971), Proc. Royal Soc. London A, 324, 301-313. [11] Piqueux, S. and P.R. Christensen (2009a) *JGR, 114*, E09005. [12] Maxwell, J.C. (1892) *A Treatise on Electricity and Magnetism*, Vol. 1, Clarendon Press, Oxford. [13] Hashin, Z. and S. Shtrikman (1962) *J. Appl. Phys., 33*, 3125-3131.

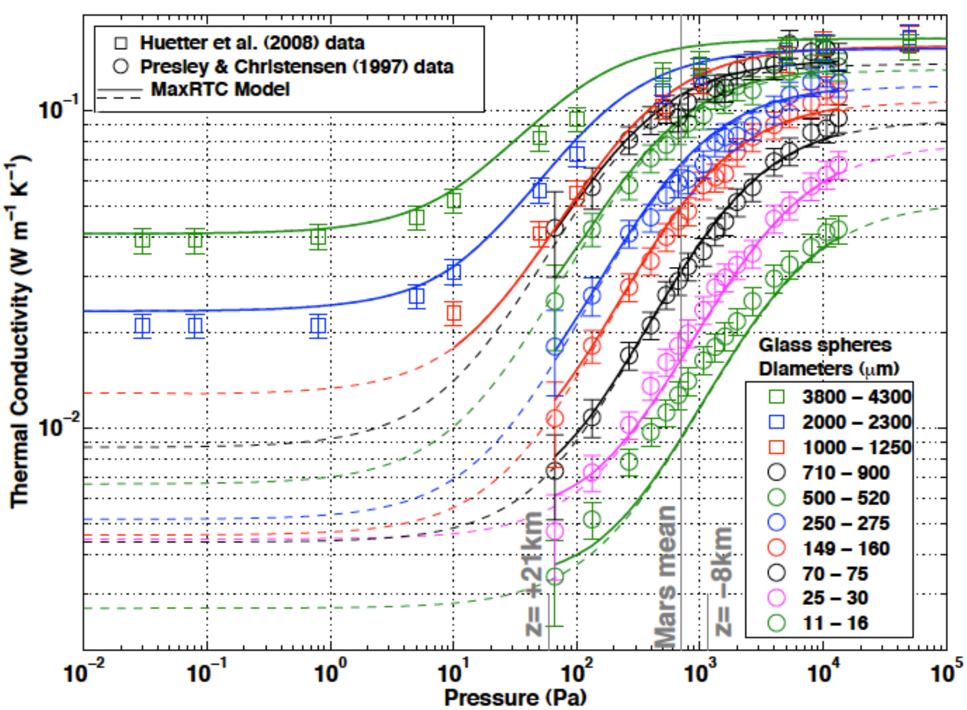

Figure 1: Comparison of the MaxRTC analytic model predictions (solid and dashed lines) to laboratory measurements (symbols with error bars) of the effective thermal conductivity of soda-lime glass beads as a function of particle size and pore gas pressure. Squares indicate data obtained in N_2 gas at 300-315 K *Huetter et al.* (2008) and circles are data obtained in CO_2 gas at 300-375 K *Presley and Christensen* (1997b). Both studies used a line heat source which heated the samples more at lower conductivities. The dashed lines indicate extrapolations of the model fits to lower and higher pressures but for a constant temperature of 300K. The parameter values used for the model fits are given in Table 3 and Table 4, for the cases with fixed values (Y_{sc} = 0.09 and f_{pore} = 0.46). The vertical gray lines indicate Mars' global average surface pressure and the values at the extremes of surface elevation.