Seasonal Variations of Soil Thermal Conductivity at the InSight Landing Site.

M. Grott[1], S. Piqueux[2], T. Spohn[1,3], J. Knollenberg[1], C. Krause[4], T.L. Hudson[2], F. Forget[5], L. Lange[5], N. Müller[1], M. Golombek[2], S. Nagihara[6], P. Morgan[7], J.P. Murphy[8], M. Siegler[9,10], M. White[10], S.D. King[8], D. Banfield[11], S.E. Smrekar[2], W.B. Banerd[2], [1]German Aerospace Center (DLR) (Matthias.grott@dlr.de), Berlin, Germany, [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA, [3]International Space Science Institute (ISSI), Bern, Switzerland, [4]German Aerospace Center (DLR), Cologne, Germany, [5]Laboratoire de Meteorologie Dynamique (LMD/IPSL/CNRS), Sorbonne Universite, Paris, France, [6]Department of Geosciences, Texas Tech University, Lubbock, USA, [7]Colorado Geological Survey, Colorado School of Mines, Golden, USA, [8]Virginia Polytechnic Institute and State University, Blacksburg, USA, [9]Planetary Science Institute, Tucson, AZ, USA, [10]Southern Methodist University, Dallas, USA, [11]Cornell University, Ithaca, New York, USA.

Introduction: Thermal conductivity is a fundamental parameter that governs heat transport in planetary soils. For atmospheric pressures of a few mbar like those typically encountered on Mars a strong dependence of soil thermal conductivity on atmospheric pressure is expected for unconsolidated soil with grain sizes between a few tens of µm and a few mm [1, 2]. In contrast, conduction through the gas phase becomes less important when the soil is cemented or indurated [3].

To study the relative importance of different heat transport mechanisms in the martian soil, measurements at different atmospheric pressures are needed. In this way, the contributions of grain-to-grain conduction as well as conduction through the pore filling gas can be separated. Here we report on the first in-situ long term monitoring of soil thermal conductivity on Mars as obtained by the Heat Flow and Physical Properties Package (HP^3) on the InSight mission [4].

Data Acquisition: Following deployment onto the martian surface, a total of seven thermal conductivity measurement with a fully buried mole were performed. The first of these, on Sol 680, was not used, however, because it was followed by mole hammering. The six measurements on Sols 798, 827, 874, 1070, 1160, and 1204, corresponding to solar longitudes L_s of 8.0, 22.0, 44.2, 135.3, 184.0 and 210.0 were obtained in an identical configuration [5] and we focus on these measurements.

Thermal conductivity measurements were conducted monitoring background temperature for two consecutive Sols before each measurement was started. Then, a defined amount of heating power was applied to the mole for 24 hours, thus using the mole as a modified line heat source. The observed heating curve, i.e., the observed temperature rise as a function of time, was then corrected for the average background temperature drift and inverted for thermal conductivity using a finite element model [4].

Background corrected heating curves for all six measurements considered here are shown in Fig. 1. All measurements follow a similar trend, showing the classical log-linear regime at intermediate heating times between 2 and 10 hours before axial heat flow causes a deviation from the log-linear trend at later times. Inspection of the different slopes indicates that thermal conductivity changes in between measurements.

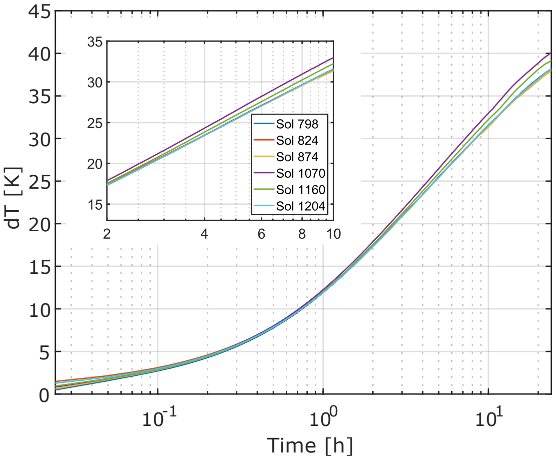

Figure 1: Temperature rise as a function of heating time for the six measurements performed in the final mole configuration. The inset shows the log-linear regime of the heating curve. The difference in slope between measurements is evident.

Data Analysis: Heating curves were inverted for thermal conductivity using a finite element model [4, 6]. We use a Monte-Carlo approach to find admissible thermal conductivities that fit the observations by requiring the root mean square deviation between the modeled and observed temperatures to be smaller than 0.17 K, a threshold corresponding to the observed day-to-day temperature variations and other sources of uncertainty (see [4] for details). Two sets of Monte-Carlo simulations were run assuming soil densities of 1007 and 1211 kg m^{-3}. These correspond to the densities determined from the Sol 680 experiment, where the latter includes an additional thermal inertia constraint derived from HP^3 radiometer measurements [4]. For each measurement, 20,000 Monte-Carlo simulations were run and thermal conductivity k and contact conductance H were treated as free parameters. They were varied assuming uniform probability distributions and span the range of $0.034 < k < 0.042$ W m^{-1} K^{-1} and $3 < H < 250$ W m^{-2} K^{-1}, respectively.

Results: Results of the simulations are shown in Figure 2, where inverted soil thermal conductivities for the case including the additional thermal inertia constraint are shown as a function of martian season. Measurements cover about 60% of a martian year and 85% of the pressures encountered. A clear correlation of thermal conductivity and atmospheric pressure as a function of solar longitude is evident.

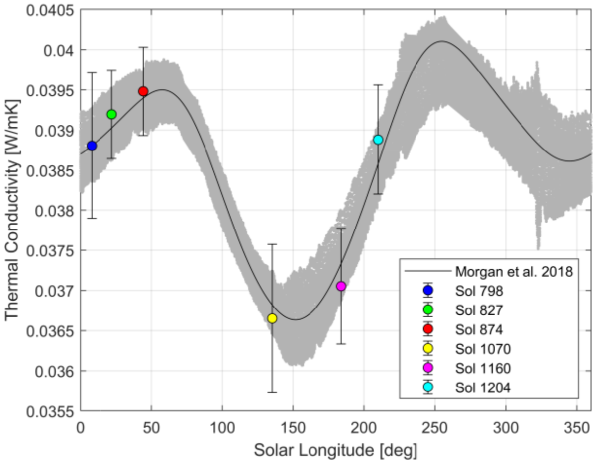

Figure 2: Thermal conductivity as a function of martian season assuming a soil density of 1211 kg m^{-3}. Results of the six measurements are shown along with a model of thermal conductivity as a function of average diurnal atmospheric pressure (solid line, [7]). The gray shaded area shows the expected fluctuations of thermal conductivity due to diurnal pressure fluctuations as measured by the auxiliary Payload Sensor Suite (APSS) [8, 9] according to the model.

For comparison, a prediction of thermal conductivity as a function of atmospheric pressure based on the observed pressure at the landing site [9] and the model of [7] is also shown. In Figure 2, the solid line corresponds to the expected thermal conductivity at the average diurnal pressures while the gray-shaded area shows conductivities predicted including diurnal pressure fluctuations. Overall, the model fits the measured thermal conductivities very well, although a slightly larger than predicted pressure dependence of thermal conductivity is indicated.

Inverted soil thermal conductivities are insensitive to the chosen soil density and thermal conductivities for the two sets of simulations using densities of 1007 and 1211 kg m^{-3} are indistinguishable within their respective error bars. In addition, it is worth noting that a linear analysis using analytical models already reproduces the trends reported here. This is consistent with the log-linear trends observed in Figure 1. However, thermal conductivities are slightly overestimated in the analytical inversion as axial heat flow cannot be accounted for in the classical line heat source approach [10].

Conclusions: We have conducted the first in-situ long-term monitoring of martian soil thermal conductivity using the HP^3 mole as a modified line heat source. We find that soil thermal conductivity at the InSight landing site correlates with atmospheric pressure and follows the trend predicted by laboratory experiments [1] and models [7] for unconsolidated soil in which a significant fraction of heat transport occurs through pore-filling gas.

Both the rather low absolute value of thermal conductivity of around 0.038 W m^{-1} K^{-1} as well as the observed strong pressure dependence of 6.5% mbar^{-1} indicate that the soil probed by the HP^3 experiment is unconsolidated. Cementation or induration would significantly increase grain-to-grain contacts and thus increase the absolute conductivity by a large factor while at the same time removing its pressure dependence [3].

The thermal conductivities that are derived clearly indicate that soil cementation or induration should be minimal. However, this is difficult to reconcile with the analysis of images that show steep sided pits with pebbles in a finer matrix as well as cohesion estimates using the arm [11, 12] and penetration data gathered by the HP^3 mole [5]. These data strongly suggest a duricrust to be present and significant cohesion seems to be required to be compatible with the observations. This discrepancy may be at least partially resolved when considering the process of probe emplacement [5], which significantly disrupted the duricrust. Furthermore, part of the mole is in contact with loose material that has been scraped and tamped down into the hole generated by the mole hammering. It therefore seems likely that the thermal properties determined here are more representative of the unconsolidated soil layers above and below the undisturbed duricrust and our results show for the first time that the martian atmosphere directly interacts with the uppermost soil layers.

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