Icarus 250 (2015) 262–267

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Meteorological insights from planetary heat flow measurements

Ralph D. Lorenz *

Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA

ARTICLE INFO

Article history:
Received 19 November 2012
Revised 26 October 2014
Accepted 21 November 2014
Available online 27 November 2014

Keywords:
Geophysics
Meteorology
Regoliths
Mars, interior

ABSTRACT

Planetary heat flow measurements are made with a series of high-precision temperature sensors deployed in a column of regolith to determine the geothermal gradient. Such sensors may, however, be susceptible to other influences, especially on worlds with atmospheres. First, pressure fluctuations at the surface may pump air in and out of pore space leading to observable, and otherwise unexpected, temperature fluctuations at depth. Such pumping is important in subsurface radon and methane transport on Earth: evidence of such pumping may inform understanding of methane or water vapor transport on Mars. Second, the subsurface profile contains a muted record of surface temperature history, and such measurements on other worlds may help constrain the extent to which Earth's Little Ice Age was directly solar-forced, versus volcanic-driven and/or amplified by climate feedbacks.

1. Introduction

Surface heat flow is one of the few direct observational constraints that can be applied to the thermal evolution of a planetary body. Early measurements of the temperature gradients in the Earth's crust (using deep mine shafts) were instrumental in the development of the understanding of the Earth's history (though for an interesting discussion on their misinterpretation, see England et al., 2007) and heat flow instrumentation was among the equipment installed on the lunar surface by the Apollo astronauts (e.g. Langseth et al., 1972). It is an even more challenging measurement to attempt within the resource limitations of an unmanned mission (e.g. Spohn et al., 2001) and careful account of lander perturbations must be taken into account (Grott, 2009; Keiffer, 2012). Recently, development has begun on an attempt to measure in-situ the geothermal heat flow at Mars, via deployment of a string of temperature sensors in the near-surface regolith by a self-hammering drill probe (HP^3 – Heat Flow and Physical Properties Package) on the NASA Discovery mission Insight (Spohn et al., 2012).

The estimation of heat flow from a vertical temperature gradient requires the assumption that thermal conduction is the only heat transport process, and that the thermal conductivity is adequately known (errors in its determination translate directly into errors in the recovered heat flow) via measurement of the diurnal and/or annual thermal wave, or by transient methods implemented underground with artificial heating. In this paper we note a couple of other influences on the subsurface temperature profile. First, shallow boreholes are susceptible to a number of confounding effects (e.g. Lovering and Goode, 1963) and care is required in averaging or modeling seasonal variations in surface temperature. A contribution to these effects may be the pumping of gas in and out of pore space in the regolith by changing surface pressure, which we term 'breathing'. In the presence of a temperature gradient this advection can perform heat transport that augments that due to conduction, and thus the conduction-only assumption may underestimate heat flow, by an amount that is not possible to determine in advance since it depends on meteorological variations and on poorly-known subsurface properties. Second, at intermediate depths of several to some tens of meters, there may remain a signal of century-millennium scale surface temperature changes which have propagated into the planetary interior, causing a perturbation to the gradient. Such a surface temperature change is detectable in terrestrial borehole records, due to the so-called Little Ice Age (LIA).

2. Breathing heat flow

2.1. A simple theory for breathing heat flow

Any near-surface regolith has porosity. Indeed, this porosity is essential to allow a practicable self-hammering drill ('mole') to burrow to a useful depth. Furthermore, the low thermal conductivity k (0.02–0.1 W/m/K, Grott et al., 2007) associated with porous regolith is essential for the geothermal heat flow to produce a measurable temperature increment (i.e. ~1 K) over reasonably achievable depths of a few meters – in more conductive solid rock the

* Fax: +1 443 778 8939.
E-mail address: Ralph.lorenz@jhuapl.edu

http://dx.doi.org/10.1016/j.icarus.2014.11.021
0019-1035/

small temperature differences would be susceptible to errors in the measurements themselves. Because of this porosity, the regolith contains atmospheric gas which has a non-zero conductivity (usually taken into account) and non-zero heat capacity (which is usually ignored). Pore diameters are typically sub-mm and so the gas rapidly attains thermal equilibrium with the adjacent regolith, and thus the column of pore gas has the same temperature gradient as the regolith itself. Let us assume for the moment that the porosity ϕ is uniform with depth, until some closure depth C, at which point it becomes zero (more realistically the porosity will decline smoothly with depth).

Now consider a step change ΔP in surface pressure, let's say a drop by a factor $\eta = \Delta P/P_o$. This has the effect of sucking out gas from the regolith column – assuming small temperature gradients and an ideal gas, a fraction η of the regolith gas will be withdrawn. This will manifest itself as the removal of the top ηC of the gas column, and the remaining $(1-\eta)C$ column must expand to fill the pore volume. Thus, on average a parcel of gas will be displaced by a distance $\sim\eta C/2$ upwards. It will then re-attain equilibrium with its (cooler) surrounding regolith, thus effecting an upward transport of heat. If the pressure is increased again, then free atmosphere is introduced into the column which is compressed, and the process can repeat e.g. after a time P. If the gas has a density ρ ($\sim$0.01 kg/m^3 for the martian lowlands) and a specific heat capacity c_p ($\sim$800 J/kg/K for CO_2), then it follows that this pumping process acts as the equivalent of an increment to the regolith thermal conductivity of $\sim\eta C\phi c_p\rho/2P$. Note that because this is an increment in effective conductivity, it becomes proportionately more important when conductivity of the regolith itself is low, i.e. when the temperature gradient increases (and can be measured more precisely) this new source of error becomes more important.

2.2. Application to Mars

The gas properties of the Mars atmosphere are reasonably known, the regolith values less so. Surface porosity values of at least 0.1–0.2 appear reasonable in the absence of sintering (which requires high temperatures) or precipitation of soluble minerals by percolating rainfall or hydrothermal fluids. The closure depth is most uncertain, but ample evidence exists at Mars of thick sedimentary sequences and a possible megaregolith, so values up to a few km are plausible. Clifford (1981) suggests an exponentially-declining porosity with a surface porosity of 20% and a final closure at 20 km, but with 50% of the pore volume within 2 km of the surface. Hanna and Philips (2004) suggest 0.16 at the surface and 0.04 at 10 km. For gross estimation purposes, we adopt ϕ = 0.15 and C = 4 km (see Table 1).

There are in fact several features of the martian climate which cause periodic surface pressure variations. First is the dramatic annual pressure cycle (e.g. Hess et al., 1980), wherein 20–30% of the atmospheric mass is cycled into the seasonal polar frost caps. Here $\eta\sim0.3$, $P\sim1$ martian year ($P\sim$ 7E7s). Second, there are strong thermal tides which produce a significant (0.2–0.3 mbar) pressure variation on diurnal and semidiurnal timescales (e.g. Schofield et al., 1997), thus $\eta\sim0.05$ with $P\sim$ 4.3E4 or $P\sim$ 8.6E4s. Finally, we can consider the passage of a dust devil: this is a stochastic, rather than periodic, event. The pressure drops in dust devils appear to follow a power law (Lorenz, 2012), with larger events being much less frequent. Events with an amplitude of >0.05 mbar appear to occur on average once per day during the Pathfinder mission (Murphy and Nelli, 2002), with the largest event observed being $\sim$0.3 mbar: for the typical daily event we can assume $\eta\sim0.0007$, P = 8.6E4 (for calculating the frequency of pressure 'pumps' P is the interval between dust devils, 1 day: for calculating the diffusion depth discussed in the next section, the appropriate timescale is the duration of the pressure drop, perhaps $\sim$100 s).

2.3. Qualifications to the simple theory

The principal debatable assumption in this linear theory is that a uniform column of gas all the way to the closure depth is instantaneously pumped by the surface pressure forcing. If regolith is uniform without macroporosity, diffusion through the pores will limit the flow response.

Some interesting experiments are reported by Fanale et al. (1982) who applied pressure changes to a tank of soil at Mars conditions, and found that the effective diffusion coefficient ($D\sim1$–2.5×10^{-2} cm^2/s) was so low that the pressure changes propagated only slowly into the soil column (e.g. their Fig. 2 has only $\sim$30% of the applied 2 mb pressure change recovered at 49 cm depth after 12 h). However, these experiments were made with exceptionally fine-grained material (Kaolin clay, used typically as a paper finisher – chosen as 'a convenient compromise between our everchanging ideas of possible regolith mineralogy and the availability of materials to fill our tank'). Fanale et al. (1982) do not report the grain size but by definition clays are <2 μm, and in kaolinite $\sim$0.3 μm is common (e.g. Mackinnon et al., 1993). They also use clay mixed with crushed basalt: in earlier experiments (Fanale and Cannon, 1971) they crushed basalt in a ball mill, and obtained adsorption areas of $\sim$6 m^2/g, which is typical for $\sim$1 μm particles.

Table 1
Regolith and atmospheric parameters with resultant conduction increment and error.

Body	Phenomenon	ΔP (mbar)	η	P (s)	L (m)[a]	$K_{eff(C)}$[b] (W/m/K)	Error[c] (C) (%)	Error[d] (L) (%)
Mars[A]	Annual CO_2 cycle	2	0.3	6E7	170	1.1E−5	0.05	0.002
	Diurnal tide	0.2	0.03	8.6E4	7	8.0E−4	4	0.01
	Semidiurnal tide	0.3	0.04	4.3E4	4.5	2.4E−3	12	0.01
	Dust devils	0.03	.004	1.6E4[e]		6.4E−4	3	
				100[f]	0.2			<0.001
Venus[B]	Putative diurnal	10	1E−5	1E7		3.2E−5	0.004	
Titan[C]	Diurnal tide	0.1	.001	1.4E6		2.62E−5	0.02	
Earth[D]	Baroclinic waves	10	.01	5E6				
	Diurnal cycle	1	.001	8.6E4				

[A] Mars: ϕ = 0.15, C = 4 km, P_o = 7 mbar, k = 0.02 W/m/K.
[B] Venus: ϕ = 0.15, C = 500 m, P_o = 90 bar, k = 0.5 W/m/K.
[C] Titan: ϕ = 0.2, C = 1 km, P_o = 1.6 bar, k = 0.1 W/m/K Tokano and Neubauer (2002).
[D] Earth (reference): P_o = 1.0 bar.
[a] The depth to which a pressure disturbance is felt $(DP)_{0.5}$, with D = 5E−4 m^2/s.
[b] Effective conductivity of gas transport if pressure disturbance affects entire column C.
[c] Relative error in recovered heat flow given gas transport (b).
[d] Relative error in recovered heat flow if disturbance is limited to column of L (a).
[e] Interval between dust devil events.
[f] Duration of dust devil event.