THERMODYNAMICS WITH A PINCH OF SALT : MARTIAN LANDSCAPE ENERGETICS

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Introduction: A purely energetic approach sheds instructive light on the history of Mars. The vigor of the past Martian hydrological cycle can be estimated from vertical convective heat fluxes, and the corresponding transport of salts into the Northern lowlands can be calculated. The conversion of incident sunlight into advective motions (and specifically, into mechanical work) allows an estimation of surface modification by winds. The expression of geothermal heat flow as tectonics and volcanism can similarly be estimated and shows good agreement with photogeologic studies. The ratios of the energies associated with these processes and with impact cratering can be compared with the corresponding ratios for other planets and with the observed geological character of Mars.

Convection and the Hydrological Cycle: On a global-average, annual-average basis, Mars receives about 150 Wm^{-2} of sunlight. The thin atmosphere offers little greenhouse warming ($\Delta T\sim 2K$, $\tau\sim 0.1$) and simple parameterizations (Lorenz and McKay, submitted) yield average vertical convective fluxes of around 5 Wm^{-2}. The martian atmosphere is therefore much less efficient an engine than Earth, where the thicker atmosphere ($\tau\sim 4$) transports almost 30% of the incident 340 Wm^{-2} as convection. (The caution must be expressed, although I ignore it here, that taking large-scale averages is somewhat misleading, and will lead to an underestimate of the total vigor. Surface measurements show typical heat fluxes peaking at ~20 Wm^{-2} in the early afternoon)

Nonetheless, 5 Wm^{-2} can be converted, if transported upwards a few km in an approximately dry adiabatic atmosphere, to mechanical work with an efficiency of ~10%, yielding 0.5 Wm^{-2} about 1/20 of Earth's output. This flux is, however, enough to drive dust devils and the formation of occasional clouds. (Note that some models may overpredict the magnitude of the fluxes in the hydrological cycle by using terrestrial insolation levels and/or a 1 bar atmosphere [1,2].)

Dividing the heat flux by the latent heat of water yields an annual potential rainfall of 5 cm per year, similarly 1/20 of Earth's, less than many deserts. Dynamically, the amount of water vapor observed in the atmosphere is too small to favour precipitation, and precipitation would be frozen in any case, but the energetics argument is ultimately more robust than these considerations.

If the Clifford and Parker paradigm of Martian paleohydrology is correct, then water accumulated preferentially at the south pole as snow, eventually to melt at the base of the thickening ice cap to flow as groundwater to the northern lowlands. There it would arrive as catastrophic outbursts to form ephemeral ice-covered oceans which slowly sublimed back into the atmosphere to complete the cycle. This process lacks a mechanism by which salts transported northwards and downwards as solutes can be recycled back into the crust,as occurs on Earth by tectonic subduction and sea-salt aerosols, and thus salts should accumulate in the north [3]. Some features have been observed in MOC imagery which resemble salt domes on Earth [4].

In this paradigm, the limiting factor for the water flux is not the evaporation of water to be transported south (atmospheric convective heat flux divided by latent heat of evaporation) but rather the basal melt (geothermal heat flux divided by the latent heat of fusion). Taking the geothermal heat flux at 30 mWm^{-2} yields an annual melt rate of only 3mm/yr.

Taking ~1% salinity (less than terrestrial oceans, higher than typical groundwater) yields 30g/m^2/yr : this salt transport can be lowered by a further factor of 10 in that the basal melt only captures geothermal heat from a fraction of the planet's surface, yielding 3 g/m^2/yr. With this transport rate, salt deposits might form at about 1 micron thickness per year, or 1 km/Gyr. Thus the formation of widespread massive salt deposits requires either the Clifford/Parker hydrology to prevail for a significant fraction of Mars' history, or geothermal heat flow to have been much higher and/or concentrated at the polar cap where atmospheric water accumulates. Note, however, that localized salt deposits, perhaps in the negative gravity signatures 'outflowing' from Vallis Marineris, could be formed rather more easily.

This is of course a simplistic 'steady-state' analysis. Substantial groundwater melt could form as annual-average temperatures change down to ~1km depths during the 120,000yr obliquity cycle – in this case (which essentially taps a fraction of the 3-4 order of magnitude higher energy flux from the sun to drive melting) the available melt energies are higher, and salt transport would be greatly enhanced.

Tectonics and Seismicity: Tectonics is driven by that part of the geothermal heat flow that passes through the mantle. Heat generated by radionucleides in the crust (contributing around 60% of the heat flow on Earth) does not participate. The work done in deforming the Earth's crust by continental drift (and, in fact, the energy released by earthquakes) corresponds fairly well [5] to this mantle heat flow multiplied by a Carnot efficiency $\Delta T/T$. Since the temperature drop across the mantle is significant compared to the hot-end temperature, the efficiency is in fact quite high: ~10-30% or more.

Estimates of Martian seismicity (e.g. Golombek, [6]) have been made by studying the slip on faults detected from orbital imagery, and suggest an annual seismic moment release of 10^{17}-10^{19} N-m/yr. A Newton-meter is of course, 1 Joule. We may compare the seismicity estimate with the heat flow and likely efficiency of the planet's internal heat engine.

Taking a global average heat flow of 30 mWm^{-2} gives an annual crustal heat flow of some $1.3x10^{20}$ J. Realistically, as for Earth, only a fraction of this will be derived from the mantle, and a modest conversion efficiency must be applied. Crudely taking these factors as about 30% each, as for Earth, we obtain a work output of the mantle engine of 10^{19} J/yr – very consistent with Golombek's upper (and favored) estimate.

The total seismicity is therefore about a factor 10 or more lower than Earth. However, seismicity – as many other self-organized critical processes - is expressed as a 1/f power law of events, and the event frequency for any given sized event will therefore depend on the spectral bandwidth over which the total power is expended – if the internal structure is such as to inhibit the largest events, the frequency of smaller events may be correspondingly increased.

Mechanical Work from Horizontal Atmospheric Heat Transport: The large-scale motions in the Martian atmosphere transport a remarkable ~25 Wm^{-2} of heat – not via sensible heat transport, the atmosphere is too thin to hold much heat – but by the latent heat transport associated with the annual CO_2 frost cycle. (Were the atmosphere thick enough to make this unneccesary or impossible, sensible heat transport would take over : climate systems regardless of working fluid or dynamical regime appear to select a state of maximum dissipation or maximum entropy production [7]) Transported across a substantial temperature difference (~50K) this yields a fairly high Carnot efficiency (~20%) and thus a work output of some 5 Wm^{-2}. Unlike the Earth, where the horizontal heat transport performs much less work than the vertical heat transport, the opposite is the case on Mars, as evidenced by the general absence of clouds. Widespread aeolian activity bears witness to the capacity of the Martian atmospheric heat engine to modify the surface.

Landscape Energetics: We can express these processes, and impact cratering (assuming approximately the same rate as for Earth, crudely handwaving the effects of atmospheric shielding, impact flux and impact energy as mutually compensating) as rates of mechanical work per unit area, as previously considered for Titan [8]. For Earth, vertical and horizontal atmospheric working, tectonics and impacts exert specific work fluxes of ~10, 2, 0.015 and 10^{-6} Wm^{-2} respectively. For Mars, the corresponding quantities are ~1, 5, 0.005 and 10^{-6} Wm^{-2} .

Qualitatively these numbers support the picture of Mars as a comparatively windswept but hydrologically-inactive planet, not without volcanotectonic expression but substantially preserving its crater record. Comparing these numbers with those for the Earth and the observed character of both worlds, we might expect the erosive processes on Mars to be weaker than the energetic arguments suggest. This discrepancy (if indeed it is one – I have not attempted a quantitative metric of planetary morphological character) is presumably related to the mechanical coupling between surface and atmosphere, which on Mars is poorer owing to the low atmospheric density. The absence of a working fluid with three-phase stability such as water on Earth is another 'kinetic' barrier. While these mechanistic difficulties may indeed be real obstacles to predicting the modifications to the landscape, one may point out that the energetic approach gives robust upper limits on processes. By defining the power supplied to the forge, if not the weight of the hammer, a useful understanding of how Mars is shaped – and how those processes may have changed through time – can be gained with little effort.

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