MARS THERMAL EVOLUTION: AIDED BY TIDAL DISSIPATION?

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Introduction: Early models of accretion of Mars [1] suggested long time scales and led to assumed cold post-accretion initial temperatures [2]. But later accretion models [3] gave much shorter time scales and led to the general acceptance of a hot Mars heated by the kinetic energy of impacting planetesimals. Evidence from isotopic studies also seems to require early melting; in particular, Hf-W systematics indicated that accretion, large-scale melting, and core segregation would be accomplished within 20 Myr [4].

But doubts about the adequacy of accretion to produce melting persisted. Adopting the model of runaway accretion, Ghosh et al [5] therefore investigated the contribution from radioactive heating from short-lived Al-26 (half-life 0.7 Myr) as an important source of energy. This requires, however, that the accretion process take no more than 1 Myr. Such short time-scales conflict with many dynamic models of accretion; some of which arrived at values of 100 to 1700 Myr [1]. More recent studies [3] have reduced these numbers, but there is still exists a wide gap.

But there is no good evidence that large amounts of Al-26 ever existed, or even if they did, that the accretion process was brief enough to incorporate sufficient Al-26 into Mars to add appreciable heat. For example, a recent finding of the absence of measurable Mg-26 in hibolite grains in the Murchison meteorite [6] suggests a corresponding absence of radioactive Al-26, as does other evidence. We may therefore consider the thermal evolution of Mars as a problem yet to be settled.

Energy from Accretion: The problem with deriving sufficient energy from accretion, even if it takes place rapidly, can be briefly stated. In the absence of rapid radioactive heating, melting of Mars would result only if more than 13% of the kinetic impact energy of accreting planetesimals were converted into heat. This can be shown by calculating the kinetic energy of a shell of thickness δr falling on a planetary core of radius r. When integrated, the total kinetic energy is proportional to the fifth power of the final radius of the planet. If distributed uniformly throughout the planet's volume, the energy per unit mass would vary as R^2; for Mars it would be eight times that required to produce melting of silicate rock, about 10^{10} erg per gram.

But with any reasonable time-scale of accretion, we can show that most of the impact energy will be radiated away, leading to the formation of a cold planet. For example, at a temperature of 1800K, the energy would be radiated away within about 1000 years. We therefore need to look also at other sources of energy to achieve melting and core segregation.

Contribution from paleo-radioactivity: Ghosh et al [5] have investigated a simple model for the thermal history of Mars, introducing Al-26 as an additional heat source. It assumes runaway accretion within 1 Myr but varies the onset of accretion between zero and 3 Myr with respect to CAI formation. If accretion starts at CAI formation, the planet melts completely. Increasing delays yield a surface temperature of 2500K but reduce the temperature in the interior of the planet --- with a delay of 2 Myr yielding an interior temperature of 1800K.

The crucial question is of course the amount of Al-26 and other short-lived radioactive nuclides present and incorporated into the accreting planet. For example, Marhas et al [6] found evidence for Be-10 but no evidence for Al-26 or Ca-41 in hibonite grains in the Murchison meteorite. Srinivasan et al [7] and Nyquist et al [8] reported evidence of Al-26 in a basaltic eucrite. But an angrite, another type of meteorite from a different parent body, shows barely detectable levels present when the angrite solidified [9]. Evidence from tungsten isotopes [10] suggests that accretion and core segregation spanned a mean interval of 11 Myr. We conclude that paleo-radioactivity contributed little to the heating of Mars.

Tidal dissipation: We therefore propose to investigate another source of energy, namely the dissipation of much of the initial energy of rotation by tidal friction within Mars. This is a plausible picture – as can be seen by comparing with the history of the Earth. Extrapolating the lunar orbit backward in time under the influence of tidal perturbations would have placed the Moon at about 2.5 Earth radii, with the Earth having a spin period of about 5 hours. (This picture holds for the capture theory of lunar origin and for most other theories as well.) If the Earth was cold at that time, then despinning it as the Moon receded would have released sufficient energy by internal tidal friction to melt the Earth within a few millennia [11].

An argument can be made [see, e.g., 12] that Mars should have a total angular momentum similar to that of the Earth-Moon system, but in fact exhibits an "angular-momentum deficiency". (The fact that the present spin periods of Earth and Mars are similar is purely a coincidence.) We therefore hypothesize that Mars captured a large body from a retrograde orbit near the end of its assembly. This would change the rotation period of Mars from an assumed initial value of ~3 hours to its present value of 24 hr-37 min. In the process, the kinetic energy of rotation of Mars would be dissipated by internal tidal friction --- more than adequate to melt the planet. (If we assume a somewhat longer initial spin period, then the energy created by friction can add to that of accretion and radioactivity.)

Conclusion: We conclude that neither accretional heating nor paleo-radioactivity may be sufficient to heat Mars to melting point. Tidal dissipation of part of its initial kinetic energy of rotation can supply the necessary energy. The hypothesis of a Mars-Moon might also provide the key to account for the existence of Phobos and Deimos; but it is difficult to explain their present orbits [12]. Previous attempts have assumed that they were captured asteroids or that they formed contemporaneously with the formation of Mars; but these attempts have not been able to derive the near-equatorial orbits of the Martian moons [13].

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Parameters for Earth and Mars (all in CGS units)

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	Earth	Mars
Mass M	5.98×10^{27}	6.4×10^{26}
Radius R	6.37×10^{8}	3.4×10^{8}
Density ρ	5.52	3.95
Moment of Inertia/MR^2	0.33	0.36
Escape velocity	11.2×10^{5}	5.0×10^{5}
Kin Engy of accretion	2.27×10^{39}	5.0×10^{37}
KE/M	3.7×10^{11}	7.9×10^{10}

The **Kinetic Energy** contributed by a shell of thickness δr is

$\delta KE = (4\pi r^2\ \delta r\ \rho)\ G\rho\ 4/3\ \pi r^3/r = 16/3\ \pi^2 G \rho^2\ r^4 \delta r$

[We assume zero planetocentric velocity. This leads only to a slight underestimate for δKE]

Integrating between r=0 to r=R, gives the total energy of accretion as the kinetic energy of the impacting planetesimals as

Total KE = $k\rho^2 R^5$ where $k = 16/15\ \pi^2\ G = 7.1 \times 10^{-7}$

Thus, total KE of accretion is 2.27×10^{39} for Earth and 5.02×10^{37} for Mars.

The important quantity is energy per unit mass, $KE/M = 4/5\ \pi G\rho\ R^2$ For Earth, $KE/M = 3.7\times 10^{11}$ erg/gm; for Mars, $KE/M = 7.9 \times 10^{10}$ erg/gm.

Since silicate melting requires about 10^{10} erg/gm, at least 13 percent of the kinetic energy of accretion must be converted into heat. But the kinetic energy of impact is only partly converted into internal heating. There are losses.

From a molten surface the **radiation loss** is $4\pi\sigma T^4$ erg/cm^2-sec. With T = 1800K and for 1Myr (= 3.1×10^{13} sec), the radiation loss is 2.5×10^{40} erg for Earth and 0.7×10^{40} erg for Mars, which vastly exceeds the impact energy. In creating an impact crater, some fragments will escape the Mars gravity field but most of the energy is likely lost by radiation from the hot crater and from the gas cloud.

We can easily calculate the initial **angular momentum** J_M and KE_{rot} of Mars under the assumption of an initial spin period of 5 hours, i.e., an angular velocity Ω of 3.5×10^{-4}/sec.

Initial $J_M = 0.36MR^2\ \Omega = 9.2\times10^{39}$; present $J_M = 1.9\times10^{39}$ The corresponding $KE_{rot} = ½(0.36MR^2)\Omega^2 = 1.6\times10^{36}$ erg, and $KE_{rot}/M = 2.5\times10^{9}$ erg/gm. [An initial spin period of 2.5 hours would yield a value for KE_{rot}/M of 10^{10} erg/gm, sufficient to melt Mars – without any additional heating from accretion.].

To investigate what it would take to despin Mars, we perform an illustrative calculation on capture of a Mars-Moon (MM) of mass *m* from an inclined retrograde parabolic orbit. From such an orbit it would quickly change inclination and then spiral into Mars and disappear. Its orbital angular momentum is given by L_{MM} = mvr, where $v = (2GM/r)^{½}$ Therefore $L_{MM} = (2GMr)^{½}$ m. If we assume $m = 3.5\times10^{25}$ gm (about 5% of Mars mass) and r~2R_M, then $L_{MM} = 8.3\times10^{39}$

Comparison with (Initial J_M) above suggests that this capture could despin Mars and change its period of rotation from 5 hours to its present value.

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I thank L. Nyquist for useful comments and LPI for its hospitality.