REVISITED MODELS OF MARS INTERNAL STRUCTURE AND THERMAL EVOLUTION. C. Sotin[1] and Ph. Lognonné[2], [1]Laboratoire de Planétologie et Géodynamique, Université de Nantes, 2 rue de la Houssinière, B.P. 92208, 44322 Nantes France, sotin@chimie.univ-nantes.fr, [2]Institut de Physique du Globe de Paris, Tour 14 2ème étage, 4 place Jussieu, 75252 Paris Cedex 5 France, lognonne@ipgp.jussieu.fr.

Introduction: This paper describes models of the internal structure and dynamics of Mars based on recent models describing thermal convection of an infinite Prandtl number fluid with strongly temperature dependent viscosity. Main differences compared to previous models include the definition of the lithosphere, an early thermal history which cannot be described by stationary scaling laws, high mantle temperature, and some predictions concerning the formation of hot plumes at the core-mantle boundary. The role of the Netlander mission to Mars to constrain the present internal structure and the thermal evolution of the planet is then described.

Description of the modeling : Recent 3D numerical models [1] describing the cooling from above of a hot fluid were carried out i) to make a comparison with laboratory experiments [2] and ii) to check that the cooling of a fluid can be described by scaling laws obtained for a volumetrically heated fluid [3,4].

Onset of convection The temperature profile inside Mars just after accretion may be different from an adiabatic temperature profile but this very simple hypothesis relies on the fact that the early and rapid formation of an iron-rich core implies the downwelling of dense hot iron-rich droplets which must have homogenized the temperature throughout the planet very quickly. The subsequent cooling of the planet is driven by the formation of cold thermal instabilities at the top thermal boundary layer. The present study shows that the time required for the first cold downwelling to form is related to the viscous temperature scale. Then, the time required for cooling rate to be equivalent to internal heating is proportional to the square of the conductive lid. This time may be on the order of 1 Gy.

Thermal evolution. Previous models of Mars thermal evolution [5,6] assume that Mars has always been a one-plate planet and that scaling laws based on thermal convection of an isoviscous fluid can be applied below the lithosphere. Recent work [1,2,3,7]on thermal convection for a fluid having a strongly temperature-dependent viscosity have shown that the conductive lid is not equivalent to the thermal lithosphere not only because the temperature at the interface between the conductive lid and the top thermal boundary layer is much larger than that of the thermal lithosphere but also because this temperature evolves with time. Thermal evolution models are based on the following equations: the temperature difference across the top thermal boundary layer is proportional to the viscous temperature scale, the thickness of the top thermal boundary layer is determined by the value of the thermal boundary layer Rayleigh number and the continuity of heat flux between the thermal boundary layer and the conductive lid. These equations allow us to determine the amount of volumetric heating, which is the sum of the radiogenic heating rate and the secular cooling. A fourth order Runge-Kutta method is employed to follow the evolution of mantle temperature with time. Finally, the stability of the lower thermal boundary layer at the core-mantle interface is assessed.

Results: The 1D internal structure of the planet can be described as it follows: A conductive lid at the top which includes the thermal lithosphere, a convective mantle with an unstable top thermal boundary layer and eventually a lower unstable thermal boundary layer at the core-mantle boundary, and an iron-rich core whose radius is a free parameter and which eventually differentiates into an inner solid core. Using the algorithm described above, we have investigated several parameters that may be important to consider: initial temperature of the mantle, radius of the core-mantle interface, and viscosity law of the mantle.

Initial temperature of the mantle. The initial temperature of the mantle must be larger than the melting temperature of iron alloys. Models run with different initial temperature end up with very similar temperatures: if the temperature is very high at the beginning, then the viscosity is law and the cooling rate is fast. If the initial temperature is smaller, the convection is less efficient and the cooling rate much smaller.

Radius of the core-mantle interface. Gravity measurements linked to orbital characteristics of the planet provide the moment of inertia of Mars. This information strongly supports the presence of an iron-rich core. However, both the radius and the state of the core (liquid or solid) cannot be determined with this information [6]. Different values of the core radius, consistent with the total mass of the planet, have been investigated in the range 1500 km to 2100 km. This parameter does not significantly modify thermal evolution models. Recent data from MGS on the crust remnant magnetic field support the idea that Mars had an internal magnetic field at the time of formation of the crust. This information implies that part of the core must have been liquid at that time.

Mantle viscosity. The nominal model uses an Earth-like viscous law assuming a viscosity equal to 10^{21} Pa.s for a mantle temperature equal to 1350°C. Viscosity is assumed to be Newtonian and different values of activation energy have been used to investigate how the viscous law controls both the mantle temperature and the cooling rate of the planet.

Thickness of the thermal lithosphere. As said before, the thermal lithosphere (T = 800°C) is not equivalent to the conductive lid. It increases at the beginning of the evolution (just after accretion) until the first cold plume takes place. Then it decreases during a period that cannot be described by steady-state scaling law [1]. The lithosphere thinning may be important because it occurred during the heavy meteoritic bombardment which created fractures through which deep partial melt could have migrated to the surface.

Temperature of the mantle. First numerical models show that the temperature of the mantle remains much larger than the melting temperature of peridotites if chondritic radiogenic heating rate is assumed. A large partial melt zone would still be present within Mars at the present time. On the other hand, if one assumes that radiogenic elements have been segregated into the crust early enough in Mars's history, the mantle temperature would be smaller than the solidus.

Cooling of the core. The cooling rate of the core can be assessed from the temperature evolution of the mantle. This is done by integrating the adiabatic temperature gradient at each time step assuming that convection in the liquid core is much faster than that in the mantle. When the temperature at the center of the planet becomes smaller than the liquidus of the iron-alloy, then the temperature profile in the outer liquid core is controlled by the temperature at the inner-core/outer core boundary which depends on the amount of light element present in the core. Recent laboratory data on the melting of iron alloys are incorporated into this study in order to investigate the cooling rate of the core. It is shown that in most of the models, the core remains liquid.

Hot plumes. The presence of volcanoes (Elysium, Olympus Mons, Tharsis area) strongly suggest that the lower thermal boundary layer at the core-mantle interface has been unstable during Mars thermal history. Although, it is known that thermal convection of a fluid heated from within is driven by downwellings [8,9], hot upwelling can appear if the temperature difference across the lower thermal boundary layer is large enough. In our models, this case occurs when a solid inner core forms at the center of the planet. Additional models are being conducted to investigate the range of parameters that lead to the formation of hot plumes at the core-mantle boundary.

Preliminary conclusions. New models of thermal convection for a fluid with a strongly temperature dependent viscosity provide different models of the cooling rate of Mars. One major question remains the possibility of plate tectonics [10] that would allow for a much faster cooling of the planet. The possibility for plate tectonics has been envisaged for interpreting the magnetic data of the MGS orbiter. But scaling laws in that case are not available at present time.

Expected constraints from the Netlander mission : The Netlander mission should provide the most important constraints on the internal structure of the planet. This CNES-lead mission is scheduled to be launched in 2005 in piggyback of the Mars Sample Return mission. It will deploy four stations at the surface of Mars. Each station will carry seismometers that will provide information on the seismicity of the planet and accurate information on the radius of the core-mantle boundary and the state of the core. This mission will provide the most valuable data to understand the internal structure of the planet in the same way seismic data acquired at the beginning of this century were able to tell us the 1D internal structure of the Earth. This paper describes the additional geophysical and geochemical instruments that will provide important information on the subsurface, the near surface atmosphere and the local mineralogy.

Conclusions : Recent advances in thermal convection modeling have changed our view of the efficiency of heat transfer for a one-plate planet. It appears that Mars could be still very hot inside and that convective motions may not be visible at the surface due to a thick conductive lid. Data from the Netlander missions will be very important to understand Mars's thermal history which cannot be separated to the overall history of the planet (differentiation, formation of the atmosphere, internal magnetic field) and in particular to the conditions required for life to exist.

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