A NEW ASTRONOMICAL SOLUTION FOR THE LONG TERM EVOLUTION OF THE INSOLATION QUANTITIES OF MARS. J. Laskar, M. Gastineau, F. Joutel, B. Levrard, P. Robutel, *Astronomie et Systèmes Dynamiques, IMCCE-CNRS UMR8028, 77 Av. Denfert-Rochereau, 75014 Paris, France*, A. Correia, *Observatoire de Genève, 51 chemin des Maillettes, 1290 Sauverny, Switzerland, Centro de Astronomia e Astrofísica da Universidade de Lisboa, Tapada da Ajuda, 1349-018 Lisboa, Portugal*.

Introduction

As the obliquity of Mars is strongly chaotic[2, 5], it is not possible to give a solution for its evolution over more than a few million of years. Using the most recent data for the rotational state of Mars, and a new numerical integration of the Solar System, we provide here a precise solution for the evolution of Mars spin over 10 to 20 Myr. Over 250 Myr, we present a statistical study of its possible evolution, when considering the uncertainties in the present rotational state. Over much longer time span, reaching 5 Gyr, the chaotic diffusion prevails, and we have performed an extensive statistical analysis of the orbital and rotational evolution of Mars, relying on Laskar's secular solution of the Solar System, based on more than 600 orbital and 200 000 obliquity solutions over 5 Gyr. The density function of the eccentricity and obliquity are explicited with simple analytical formulas. We found an averaged eccentricity of Mars over 5 Gyr of $\bar{e} = 0.0690$ with standard deviation $\sigma_e = 0.0299$, while the averaged value of the obliquity is $\bar{\varepsilon} = 37.62^\circ$ with a standard deviation of $\sigma_\varepsilon = 13.82^\circ$, and a maximal value of 82.035°. We find that the probability for Mars obliquity to have reached more than 60° in the past 1 Gyr is 63.0%, and 89.3% in 3 Gyr. Over 4 Gyr, the position of Mars axis is given by a uniform distribution on a spherical cap limited by the obliquity $\varepsilon_{\tilde{m}} = 58.62^\circ$, with the addition of a random noise allowing a slow diffusion beyond $\varepsilon_{\tilde{m}}$. We can also define a standard model of Mars insolation parameters over 4 Gyr with the most probable values for the eccentricity $e_s = 0.067$ and $\varepsilon_s = 45.60^\circ$ for the obliquity.

Data available on the WEB

Together with the main paper that describes these new solutions [4], we have provided the most useful data on a WEB site for possible use by the Martian climate community at the address : **http://www.imcce.fr/Equipes/ASD/mars.html** .

The nominal solution La2004

The nominal solution for the eccentricity, obliquity, and longitude of the perihelion from the moving equinox is provided from -20 to +10 Ma together with FORTRAN routines that allows the computation of insolation quantities for any date within the time period of the data files (-20 to +10 Ma), following the lines of [3]. The solution La2004 is the up to date insolation solution with initial conditions from [6] $k_2 = 0.149; Q = 92$; initial precession rate : $p = -7.597$ arcsec/year. The stability of this solution has been tested with respect to the uncertainty of the parameters and initial conditions. The initial precession frequency is the most critical parameter, but it appears that within the published uncertainty of this parameter, the solution remains practically unchanged over 10 Myr. The large increase of the obliquity at about 5 Myr is thus robust and can be used as a constraint for martian paleoclimate studies.

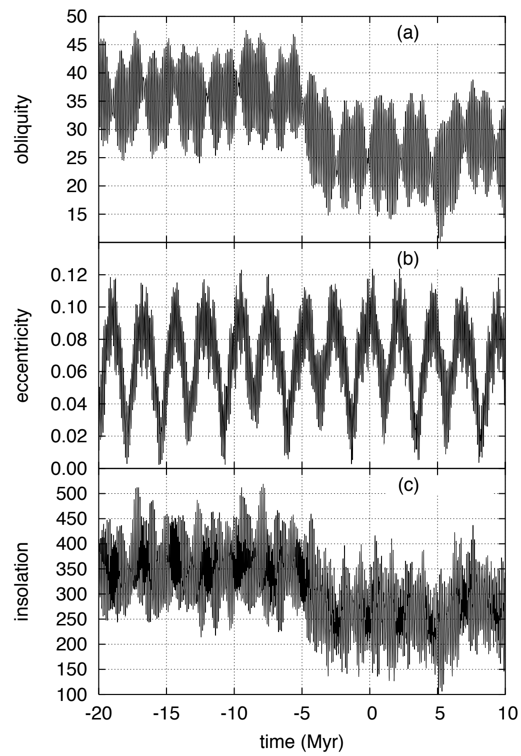

Figure 1: Obliquity (in degrees) (a), eccentricity (b), and insolation (c) (in w/m^2) at the north pole surface at the summer solstice ($L_S = 90^\circ$) for the solution La2004 from -20 Myr to $+10$ Myr.

Solutions over 250 Myr

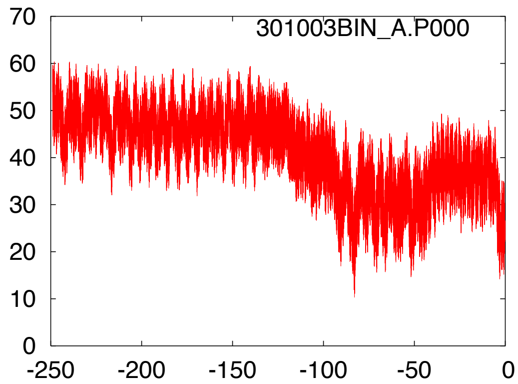

Figure 2: Nominal solution for Mars obliquity over 250 Myr. $p = p_0$

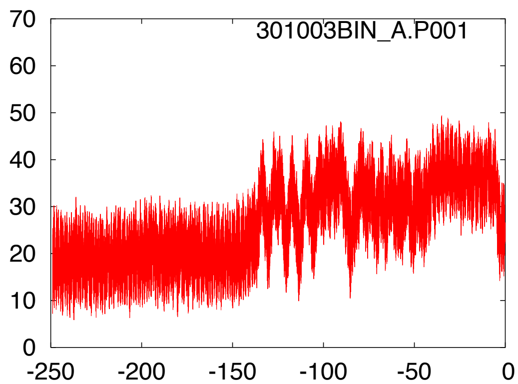

Figure 3: Solution for Mars obliquity over 250 Myr with $p = p_0 + \delta p/1000$

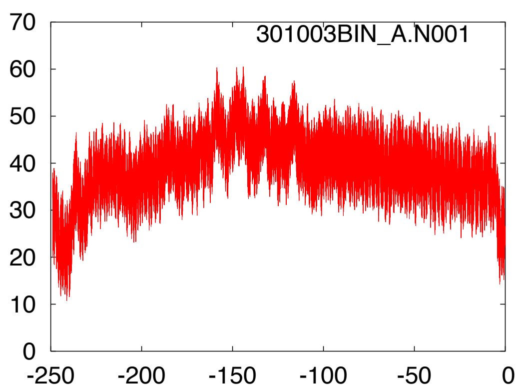

Figure 4: Solution for Mars obliquity over 250 Myr with $p = p_0 - \delta p/1000$

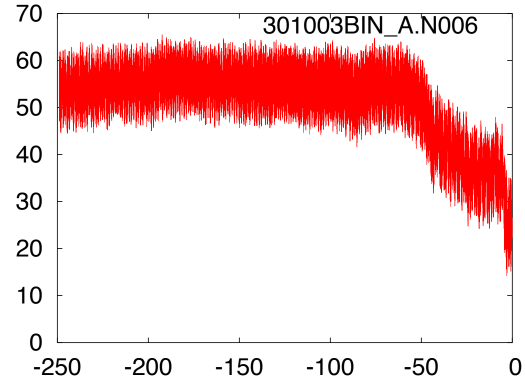

Figure 5: Solution for Mars obliquity over 250 Myr with $p = p_0 - 6\delta p/1000$

Several solutions are also provided over 250 Myr as an indication of the variability of the obliquity solution over long time intervals. They can be used with the program "insola" in order to generate climatic data for a given period (high obliquity regime for example). They correspond to very small change $x\delta p/1000$ of the initial precession frequency p_0, where δp is the assumed error on the determination of the present precession rate [1, 6] $p_0 = -7.576$ arcsec/year and $\delta p = 0.035$ arcsec/year.

REFERENCES

[1] Folkner, W.M., Yoder, C.F., Yuan, D.N., Standish, E.M., and Preston, R.A., Interior structure and seasonal mass redistribution of Mars from radio tracking of Mars Pathfinder, *Science*, **278**, (1749-1751) (1997)

[2] Laskar, J., Robutel, P., The chaotic obliquity of the planets, *Nature*, **361**, (608-612) (1993)

[3] Laskar, J., Joutel, F., Boudin, F., Orbital, precessional, and insolation quantities for the Earth from -20 Myr to $+10$ Myr, *Astron. Astrophys.*, **270**, (522-533) (1993)

[4] Laskar, J., Gastineau, M., Joutel, F., Robutel, P., Levrard, B., Correia, A.,: 2003, Long term evolution and chaotic diffusion of the insolation quantities of Mars. *preprint : http://hal.ccsd.cnrs.fr/view/ccsd-00000860/*

[5] Touma, J. and J. Wisdom, The chaotic obliquity of Mars, *Science*, **259**, (1294–1297) (1993)

[6] Yoder, C.F., Konopliv, A.S., Yuan, D.N., Standish, E.M., and Folkner, W.M., Fluid core size of Mars from detection of the solar tide, *Science*, **300**, (299-303) (2003)