LONG-TERM EVOLUTION OF MARS ECCENTRICITY AND OBLIQUITY. Laskar, J., ASD/IMCCE, CNRS UMR8028, Observatoire de Paris, UPMC, France (Laskar@imcce.fr).

Introduction: The insolation on Mars' surface depends on the position in space and orientation of the planet. Since the semi major axis is practically invariant, as was shown by Laplace in the XVIII th century, the important quantity that drives the total insolation received on the planet is the eccentricity of its orbit, while the obliquity (tilt of the equator over the orbit), and precession angle control the seasonal variations of the insolation at a given latitude. The present eccentricity of Mars is 0.0933 but has varied in a large amount in the past due to the chaotic evolution of its orbit [1, 2]. In the same way, the obliquity of the planets evolves chaotically with variations of large amplitude [2,3,4].

Mars paleoclimates: Since the first images of polar regions on Mars revealed alternating bright and dark layers, there has been speculation that their formation might be related to the planet's orbital climate forcing [5,6]. But uncertainties in the deposition timescale remained extremely large. Using MGS high-resolution images and high-resolution topography [7,8] and improved calculations of the orbital and rotational parameters of Mars, Laskar et al. [9] provided for the first time a direct correlation between ice-layer radiance as a function of depth and the insolation variations in summer at the Martian north pole, similar to what has been shown for palaeoclimate studies of the Earth. The best fit between the radiance profile and the insolation parameters provided an average deposition rate of 0.05 cm/yr. for the top 250m of deposits on the ice cap of the north pole of Mars. This accumulation rate led to think that the formation of the polar cap was recent, and was built in the recent 5 Myr. Nevertheless, these results were still very hypothetical and it was necessary to search for some independent confirmation. Starting a collaboration with the LMD in Paris, we could use their Martian GCM to investigate the long term evolution of the ice cycles on Mars [10] and calibrate the rate of ice formation and sublimation in the various reservoirs which led to a scenario that is consistent with the formation of the northern ice cap in the past 5 Myr [11] (Fig.1). Similar results have been obtained more recently [12,13]. This can be considered as encouraging, but one should still be attentive that these scenarios are still very hypothetical, and any additional information on the evolution of the North ice cap over the past 5 Myr should be welcome. The scenario that was derived in [9, 11] strongly depends on the large increase of the obliquity of Mars about 5 Myr ago (Fig.1) [2]. It is thus important to know how robust is this feature of the astronomical solution. More generally, as many of the present studies on Mars paleoclimates rely on the published solution La2004 [2], I will take the opportunity of this meeting to make an update on the status of these solutions since their publication in 2004.

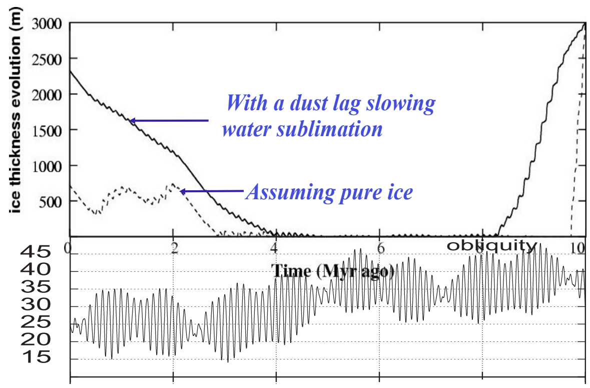

Fig.1 : Top : Evolution of the ice thickness in the north ice cap as a function of time for a model of pure ice and for a model with dust. Bottom : Variation of insolation [11].

Orbital motion and eccentricity: Due to the chaotic behavior of the orbital motion of the planets, the uncertainty on the solution is multiplied by 10 every 10 Myr [1]. This puts some strict limitations to the possibility of recovering the past evolution of the planet orbit over several tens of Myr. In La2004, it was estimated that the solution was valid over about 40 Myr. Since, we have conducted a very large effort in order to improve their interval of validity, motivated by the search for accurate solutions for the astronomical calibration of the Earth geological time scales [14]. In order to achieve this goal, we had to revise entirely the determination of the initial conditions for our model, and we constructed from scratch some high precision planetary ephemerides, similar to the JPL DE ephemerides, that are directly adjusted to all available planetary and lunar observations. The construction of this new ephemerides (INPOP) [15–17] allows us then to master the real precision of the model compared to observations. As we have removed time limitation in this model, we have also integrated it over 1 Myr and we use this long time integration as the starting point of the long-term ephemerides over several tens of Myr. Despite all these efforts, and a substantial improvement of the numerical scheme of the numerical integration, we have not been able to extend the solution to 65 Myr, as was aimed for a covering of the whole Cenozoic era, but only to about 50 Myr [14]. This unexpected limitation is due to the interaction of the planets with the asteroids, and in particular with Ceres and

Vesta, despite their mass is only 1/6000 and 1/22000 of the Earth mass, respectively. In fact, due to close encounters of these two celestial bodies, their motion is highly chaotic [18], contrarily to what was previously assumed, and this strong chaos induces an irreducible uncertainty on the planets orbits after 60 Myr. Indeed, after this span of time, the cost to extend the solution is no longer a factor of 10 improvement for each 10 Myr, but a factor of 10 for each 50 kyr, reflecting the rapid chaos among the asteroids. It becomes thus hopeless to obtain a precise orbital solution for Mars beyond 60 Myr, and the newly published solution for the Earth La2010 [14] is about the best that can be achieved for the inner planets, with a time validity of more than 50 Myr. In the case of the Earth, gaining 10 Myr beyond 40 Myr is of high importance for the derivation of precise geological time scales, but in the case of Mars, where accurate data are still lacking, the recent results can be considered as a confirmation of the validity of the La2004 solution over 40 Myr, while the statistical treatment that was exposed in [2] can still be used for longer periods of time.

Chaotic evolution of the obliquity: Because of the planetary perturbations, spin axis of Mars evolves chaotically [3,4] with large amplitude in the obliquity that can range from 0 to 60 degrees and more [2, 3]. The chaotic behavior of the obliquity is not only the result of a coupling with the orbital motion of the orbit which is itself chaotic, but is due to the perturbation of the spin axis by the multiple periodic components of the secular evolution of its orbital plane.

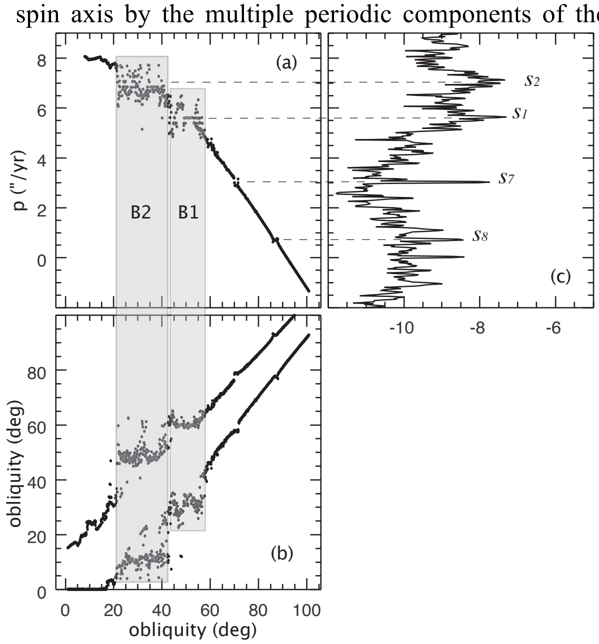

Fig.2 : a) The chotic zone for the obliquity is separated into two boxes that corespond to resonances with the proper modes s1 (Mercury) and s2 (Venus) of the motion of the orbital plane. b) Min and max values of the obliquity over 56 Myr, starting with a given obliquity (from [2])

This chaotic behavior is even stronger than the orbital chaos, and due to the uncertainty of the initial conditions and parameters for Mars, it is difficult to predict precisely the long-term evolution of the obliquity. In La2004, the time of validity was estimated to be of 10 to 20 Myr, depending on the uncertainty on the parameters. As the increase of obliquity at 5 Myr in the past is important, it is useful to see how much these estimates vary with the improved knowledge on these parameters from [19].

Parameter	Value	
Obliquity ε (degrees)	25.189417	(35)
	25.189398	(11)
Node ψ (degrees)	35.43777-	(140)
	35.437667	(11)
Precession rate $d\psi/dt$ (mas/year)	-7576	(35)
	-7568	(21)
Rotation rate ω (degrees/day)	350.89198521-	(80)
	350.891985286	(27)

Table 1 : Initial conditions from [20] in black, and in color from [19]. The uncertainty given in brackets is expressed in the units of the latest digit.

The most important parameter is the initial precession rate *p*. The new uncertainty interval for *p* is very close to the interval that was considered in figure 8a of [2] in the optimistic option. One can thus conclude that this option is relevant and that the interval of validity of the obliquity is close to 20 Myr, which comfort the large increase of obliquity at 5 Myr.

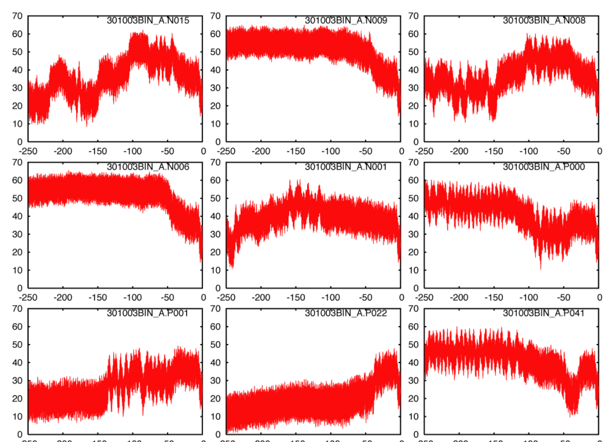

Fig.3 : Selected examples of the possible evolution of Mars obliquity over the past 250 Myr (adapted from Laskar et al, 2004).

Long-term evolution of the obliquity: Beyond, 20 Myr, various behavior can happen, as was illustrated by the figure 11 of [2], (see Fig. 3). In these examples, the obliquity can stay for a long time at very high values, or stay at low values, or oscillate between low and high values. As these are selected examples, natural

questions arise as what are the most probable outcomes, as one may hope to ultimately find some way to constraint the possible solutions from the observation of detailed geological features on Mars' surface.
In la2004 [2], 1001 solutions were computed, as the ones in Fig.3, and many more could be computed now without difficulty, but this lead to huge amount of data that is not easy to analyze. One thus needs to condense this information in order to retain only the most relevant features. In figure 4, the nominal solution La2004 of the obliquity is plotted together with its averaged over every interval of 1 Myr. This average is in fact a condensed view of the solution, with a much simpler behavior. Qualitatively, the full solution can be retrieved by adding an oscillation of about ±10 degrees on this average.

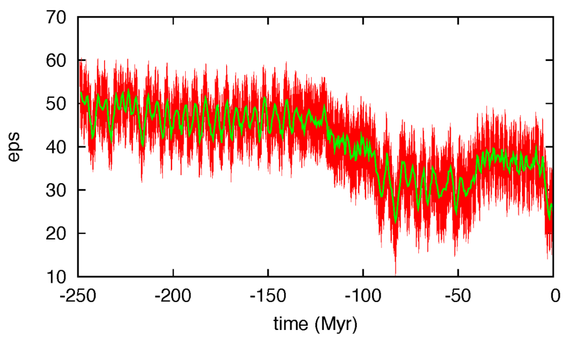

Fig. 4 : Nominal solution of the obliquity from [2], and its average over slices of 1 Myr.

With this simplified view, it is possible to plot all 1001, solutions together, although we have reduced here the plot to the first 50 Myr, as it becomes very confused beyond that point (Fig. 5).

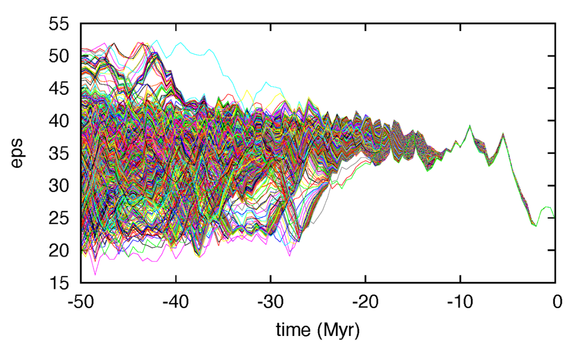

Fig.5 : All 1001 averaged solutions from [2] are plotted over 50 Myr in the past .

At was already said above, it is even more clear from Fig. 5 that the obliquity solution is valid over about 20 Myr, as all solutions plotted here can be considered as compatible with the present knowledge of the parameters of the System, as their parameters nearly covers the interval of uncertainty of the precession speed (Tab. 1). It is thus clear from this plot that there was an increase of the obliquity at about 5 Myr that led to a status of high obliquity that lasted for more than 10 Myr. Beyond 20 Myr, the situation is more confused, and in order to better understand the obliquity behavior, the histogram of the average obliquity over each 1 Myr interval is plotted in Fig. 6

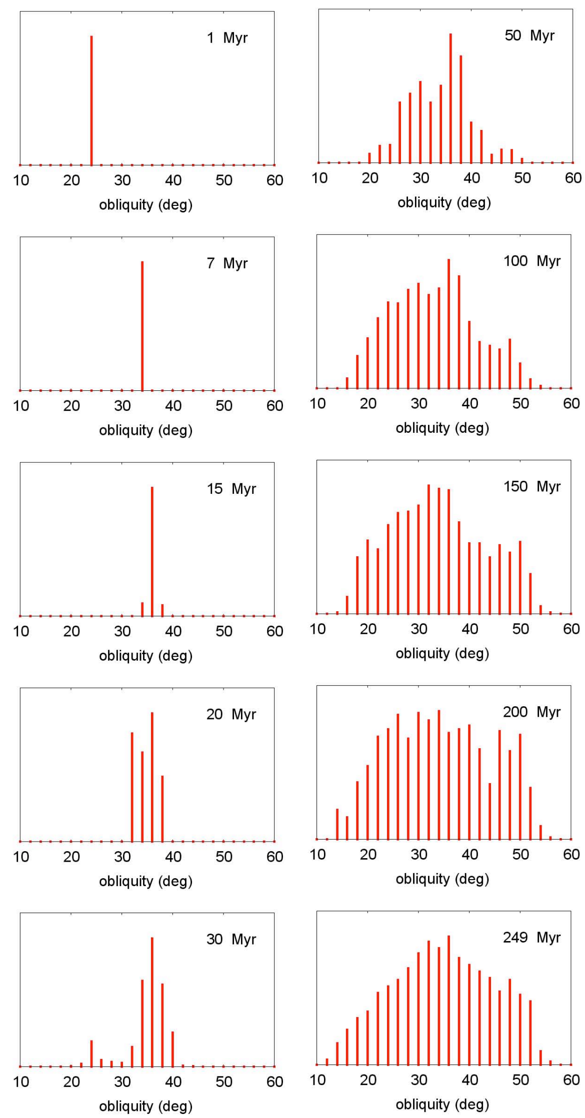

Fig. 6 : Histogram of the averaged obliquity over various 1 Myr time intervals. The solutions are the 1001 obliquity solutions displayed in Fig. 5.

As can be expected, over the first few Myr, all solutions give the same value for the obliquity, and the histogram is a single peak. As time goes on, the distribution of the values spreads, but it can be seen that over the first 50 Myr, high obliquity is the dominant feature. For those who are interested to explore further these solutions, all the averaged data, as well as some small animations that may help to select the proper files, including the histograms of figure 6 will be made available for download on the webpage of the author : http://www.imcce.fr/~laskar.

Conclusions: Nearly ten years after the release of the La2004 orbital and rotational solution for Mars [2], it is interesting to see the status of the assertions that were made in this paper. Quite luckily, most of the outcomes of this paper are still valid. The orbital solution has been improved, but without any major change, compared to the La2004 solution, which can still be used for Mars, although an update might be desirable in the near future, in order to be consistent with the solutions that are used for the understanding of Earth paleoclimate data [14].

For the obliquity the situation is different, as the uncertainty on the precession rate has been reduced [19], but the new interval of uncertainty fits well in the previous one, and the interval of validity of the obliquity can thus be extended to nearly 20 Myr, following the optimistic option of [2]. More important, the increase of the obliquity at about 5 Myr in the past is confirmed and should be considered as the largest feature in the astronomical solution that could be confirmed by geological observations. Although there are already some indications that there was an increase of the obliquity in the past [21], it should be important to comfort these findings and search for additional geological evidence of the increase of the obliquity at 5 Myr in the past.

In the same way, since the publication of a first estimate of the time scale for the formation of the North ice cap [9], several additional studies (e.g. [12,13]) converge towards a formation of the Northern Ice cap in the past 5 Myr. Nevertheless, this agreement should not be considered as a definite result and one should still search for independent confirmation of the formation history of the ice caps and its relation with the astronomical forcing.

References: [1] Laskar, J. (1989), *Nature, 338,* 237–238. [2] Laskar, J. et al. (2004) *Icarus, 32,* A74. [3] Laskar, J. and Robutel, P. (1993) *Nature, 361,* 608–612. [4] Sussman, G.J. and Wisdom, J. (1993) *Science, 257,* 56–62. [5] Murray, B.C. et al. (1972) Icarus, 17, 328–345. [6] Toon, O.B. et al. (1980), Icarus, 44,552–607. [7] Malin, M.C. & Edgett, K.S. (2001), JGR, 106, 23429. [8] Smith, D.E., et al. (2001), JGR, 106, 23689. [9] Laskar et al. (2002), Nature, 419, 375–377. [10] Levrard, B. et al. (2004) Nature, 431, 1072–1075. [11] Levrard, B. et al. (2007) JGR Planets, 112, E06012. [12] Greve, R. et al. (2010), PSS, 58, 931–940. [13] Holt, J.W. et al., (2012), LPSC, 43, Abs.2879. [14] Laskar et al. (2011) A&A, 532, A89. [15] Fienga et al. (2008) A&A, 477, 315–327. [16] Fienga et al. (2009) A&A 507,1675–1686. [17] Fienga et al. (2011) Cel. Mech. Dyn. Astron. 111, 363–385. [18] Laskar et al. (2011) A&A, 532, L4. [19] Konopliv et al. (2006) Icarus, 182, 23–50. [20] Folkner et al. (1997) Science, 278, 1749–1751. [21] Forget et al. (2006) Science, 311, 368–371.