EPSC Abstracts
Vol. 11, EPSC2017-601-1, 2017
European Planetary Science Congress 2017

Paleo-Magnetospheres of Earth and Mars: Possible implications for their ancient atmospheres

M. Scherf (1), M. Khodachenko (1), I. Alexeev (2), E. Belenkaya (2), M. Blokhina (2), C. Johnstone (3), J.Tarduno (4), H. Lammer (1), L. Tu (3), M. Güdel (3)
(1) Space Research Institute, Austrian Academy of Sciences, Graz, Austria, (2) Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia, (3) Institute of Astrophysics, University of Vienna, Vienna, Austria, (4) Department of Earth and Environmental Sciences, University of Rochester, Rochester, NY 14627, USA
(manuel.scherf@oeaw.ac.at)

Abstract

We present simulations of the terrestrial and Martian paleo-magnetosphere for ~4.1-4.0 billion years (Gyr) ago, which were performed with adapted versions of the Paraboloid Magnetospheric Model (PMM) of the Skobeltsyn Institute for Nuclear Physics of the Moscow State University. For the Earth our simulations show that the paleo-magnetosphere was significantly smaller than today, with a standoff-distance r_s ranging from ~3.4 to ~8.2 R_e, depending on the chosen input parameters. Our simulations also show that the Martian paleo-magnetosphere should have been comparable in size to the terrestrial paleo-magnetosphere until its cessation ~4.0 Gyr ago. At Earth, a nitrogen-dominated atmosphere would not have survived the harsh conditions during the late Hadean eon, i.e. ~4.1 Gyr ago, whereas a CO2-dominated atmosphere could have survived. Further implications for the ancient atmospheres of Earth and Mars will be discussed.

1. Introduction

The intrinsic magnetic field of a terrestrial planet is considered to be an important factor for the evolution of terrestrial atmospheres. This is in particular relevant for early stages of the solar system, in which the solar wind [3] as well as the EUV flux [8] from the young Sun were significantly stronger than at present-day. We therefore will present simulations of the paleo-magnetospheres of ancient Earth and Mars, which were performed for ~4.1 billion years ago, i.e. the Earth's late Hadean eon and Mars' early Noachian. These simulations were performed with specifically adapted versions of the Paraboloid Magnetospheric Model (PMM) of the Skobeltsyn Institute of Nuclear Physics of the Moscow State University, which serves as ISO-standard for the Earth's magnetic field (see e.g. [2]).

One of the input parameters into our model is the ancient solar wind pressure. This is derived from a newly developed solar/stellar wind evolution model, which is strongly dependent on the initial rotation rate of the early Sun [3]. Another input parameter is the ancient magnetic dipole field. In case of Earth this is derived from measurements of the paleomagnetic field strength [3]. These data from zircons are varying between 0.12 and 1.0 of today's magnetic field strength. For Mars the ancient magnetic field is derived from the remanent magnetization in the Martian crust as measured by the Mars Global Surveyor MAG/ER experiment (see e.g. [1]). These data together with dynamo theory are indicating an ancient Martian dipole field strength in the range of 0.1 to 1.0 of the present-day terrestrial dipole field.

2. The terrestrial paleo-magnetosphere

Our simulations of the terrestrial paleo-magnetosphere with the adapted PMM show that for the most extreme case of a fast rotating Sun and a paleomagnetic field strength with 0.12 of today's value, the stand-off distance of the magnetopause r_s shrinks significantly down from today's 10-11 R_E to 3.43 R_E (i.e. 2.43 R_E above the Earth's surface, with R_E as the Earth's radius). Even for the least extreme case – i.e. the same magnetic field strength as that of today and a slow rotating Sun - r_s shrinks down to 8.23 R_E. Another outcome of the modelling is that polar cap as well as auroral oval were significantly bigger ~4.1 billion years ago than at present-day.

3. The Martian paleo-magnetosphere

For Mars our simulations are showing that ~4.0 Gyr ago the most extreme case of a fast rotating Sun and a paleomagnetic field strength of 0.1 of the present-day terrestrial value, leads to a Martian magnetopause standoff-distance r_s of ~5.5 R_M (i.e. ~2.9 R_E). Assuming a strong dipole field (i.e. 1.0 of present-day terrestrial field) and a slow rotating Sun – our least extreme case – would lead to a standoff-distance of r_s~16 R_M (i.e. ~8.5 R_E). Auroral oval and polar cap were slightly smaller than for the Earth ~4.1 Gyr ago.

4. Implications for the ancient atmospheres of Earth and Mars

These results also have implications for the early ancient atmospheres of Earth and Mars. For ~4.1 Gyr, according to [8], the EUV flux of the ancient Sun ranged from ~15 to ~150 times the present day value, depending whether the Sun was a slow or a fast rotator. According to [7], the exobase of a nitrogen-dominated atmosphere would then already have been extended above r_s in all of our simulations even for a slow rotating Sun. In such a scenario the terrestrial atmosphere would have been gone in less than ~5 Myr via ion-pickup escape [5]. A CO_2-dominated atmosphere on the other hand would stay below r_s for much higher EUV fluxes [4], preventing it from atmospheric erosion. An atmosphere with 96% CO_2 would not start to hydrodynamically expand until ~32 EUV, indicating that ~4.1 Gyr ago the terrestrial atmosphere should have been CO_2-dominated. Compared to the ion-pickup escape the ion outflow rates via the polar caps were negligible. At Mars a CO_2-rich atmosphere should also have been protected by the magnetic field from rapid atmospheric erosion until the cessation of the Martian dipole field ~4.0 Gyr ago.

5. Summary and Conclusions

The viability of the PMM as ISO standard for the Earth's magnetosphere has been demonstrated. The adapted PMM should do the same for the paleo-magnetospheres of Earth and Mars depending on how adequate the input parameters can be chosen. However, there are uncertainties on these parameters, since it is not known, whether the Sun was a slow rotator. Additionally, measurements by [6], indicate a highly variable terrestrial paleomagnetic dipole field. Likewise, the field strength of ancient Mars is not known exactly. Both factors lead to significantly different magnetosphere sizes. Therefore our results show a broad range of potential values for r_s ranging from ~3.4 R_e for the most extreme case to ~8.2 R_e for the least extreme case for Earth and from ~6.4-17.2 R_m in the case of Mars. It can be concluded that for the Earth, due to the enhanced EUV flux ~4.1-4.0, the exobase of a nitrogen dominated atmosphere would most probably have been above r_s, leading to an enhanced erosion, whereas a CO_2-dominated atmosphere would have been prevented from atmospheric erosion at least for a slow to moderate rotating Sun. For Mars a CO2-dominated atmosphere should also have been preventend from atmospheric erosion pontentially providing habitable conditions prior to ~4.0 Gyr ago. Finally, our results favour the idea that the young Sun must have been a slow to moderate rotator. The solar wind and EUV flux from a fast rotating Sun would have been so intense, that most probably the ancient atmospheres of Mars and Earth would not have survived.

Acknowledgements

The authors acknowledge the support of the FWF NFN project S11601-N16 “Pathways to Habitability: From Disks to Activ Stars, Planets and Life”, in particular the related subproject S11606-N16 “Magnetospheric electrodynamics of exoplanets”. This publication is supported by the Austrian Science Fund (FWF) and the US NSF (EAR1015269 to JAT).

References

[1] Acuña, M.H. et al., Science, 284, 790-793, 1999.

[2] Alexeev, I. I. et al., J. Geophys. Res., 101, 7737-7748, 1996.

[3] Johnstone, C.P. et al., Astron. Astrophys., 577, id.A27 2015.

[4] Kulikov, Yu.N. et al., Planet Space Sci., 54, 1425-1444, 2006.

[5] Lichtenegger, H. et al., Icarus, 210, 1-7, 2010.

[6] Tarduno, J. A. et al., Science, 349, 521-524, 2015.

[7] Tian, F. et al., J. Geophys. Res., 113, E05008, 2008.

[8] Tu et al., Astron. Astrophys. 577-580, 2015.