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Paleo Mars energetic particle precipitation

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ABSTRACT

A young Mars may well have possessed a global dipolar magnetic field that provided protection for the planet's atmosphere from the space weather environment. Against this background, we study in the present paper the effect of various dipole magnetic fields on particle precipitation (range 10 keV–4.5 MeV) on the upper Martian atmosphere as the magnetosphere gradually declined to become an induced magnetosphere. We utilized a hybrid plasma model to provide, in a self-consistent fashion, simulations (that included ion-kinetic effects) of the interaction between the Martian obstacle (magnetized or otherwise) and the solar wind. Besides the intrinsic dipole, with field strengths of ~100 nT and below, we assume modern solar and atmospheric parameters to examine the effect of the single variable, that is the dipole strength. We thereby investigated the precipitation of solar energetic particles on the upper atmosphere of the planet in circumstances characterized by the evolution of a diminishing Martian dynamo that initially generated an ideal dipolar field. It is demonstrated that an assumed Martian dipole would have provided, in the energy range investigated, significant shielding against proton impingement and that the interaction between the solar wind and the assumed Martian magnetic dipole would have been responsible for generating the shielding effect identified.

1. Introduction

The processes of atmospheric evolution and erosion at Mars are of great interest, particularly with respect to their association with the present Martian water content. A likely cause of the current, tenuous Martian atmosphere is atmospheric escape into space (processes involved include thermal and hydrodynamic escape as well as non-thermal ion pickup, all affected by the space weather conditions provided by the Sun). Young Mars, on the other hand, may well have possessed a global, intrinsic magnetic field that provided protection against the erosion produced by the solar wind and energetic particles. In continuation of our previous studies (such as Kallio et al., 2010, 2012), we estimate in the present paper the effects of the interaction between the solar wind and an assumed Martian dipole field on the Martian energetic particle environment.

Sufficiently strong Solar Energetic Particle (SEP) events have been suggested to increase: particle escape from the planet, the total electron content of the Martian ionosphere, and energy deposition into the top layers of the atmosphere (Sheel et al., 2012; Leblanc et al., 2002; Haider et al., 2002). Ulusen et al. (2012) have instead observed, although inconclusively, high-altitude decreases and low-altitude increases of Martian ionospheric electron density possibly associated with SEP events, whereas Frahm et al. (2013) in a case study observed Martian ionospheric expansion during an SEP event. Additionally, the Mars Express MARSIS instrument experienced blackouts possibly connected to SEP events (Withers, 2011). Lately, the effect of precipitating energetic particles on the Martian atmosphere and surface radiation environment has been modeled by e.g. Norman et al. (2014) and Gronoff et al. (2015), to determine the dose and ionization rates inside the Martian atmosphere, thereby predicting significant dose rates to accompany large SEP events.

NASA's MAVEN mission is currently spearheading research into the evolution of the Martian atmosphere, utilizing an energetic particle detector dedicated to monitoring SEP and pick-up ion effects in the Martian upper atmosphere (Jakosky et al., 2015). It was estimated by Sheel et al. (2012) using contemporary values for atmospheric composition and taking into account the continuous slowing down approximation, that most of the energy deposition by energetic protons in the atmosphere above 50 km–100 km is caused by protons with energies below 10 MeV (i.e. close to the stopping altitude of those particles) (see Sheel et al., 2012, Fig. 2). The same lowest-energy SEPs are also the most susceptible to deflection by magnetic fields due to their low magnetic rigidity. In consequence, the induced magnetosphere of Mars has been shown to affect protons of these energies, producing for instance

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magnetic shadowing, although the effect tends to fade as proton energy increases into the 10 MeV range (McKenna-Lawlor et al., 2012).

Inclusion of a magnetic dipole at Mars, even a relatively weak one, has been shown using hybrid modeling to drastically modify the surrounding plasma environment (Kallio et al., 2008), possibly thereby affecting the precipitation of energetic protons. In the present work we study the effect of different weak global dipoles on the energetic particle environment and especially on the associated levels of energetic particle precipitation on the exobase. We aim to determine the atmospheric protection afforded to a young Mars by its assumed magnetic dipole with respect to solar energetic particle irradiation.

In this regard, we employ an ideal dipole approximation, which may, however, only produce a simplistic view of the ancient Martian magnetosphere, since the cessation of the Martian dynamo might have been a complex process, involving for instance subcritical dynamo processes (Wang et al., 2013) or perhaps giant impacts that shut down the dynamo (Roberts et al., 2009). Alternatively, a hemispherical dynamo configuration has been proposed by Stanley et al. (2008). Again, certain dynamics of magnetic pole reversals have been inferred from the remnant crustal magnetization (e.g. Arkani-Hamed and Boutin, 2004). The effects of these kinds of complex, varied magnetic environs are, however, outside the scope of this paper.

We employed a global 3-D hybrid model to derive energetic proton fluxes for a gradual SEP event at the exobase for injected proton energies in the range 10 keV to 4.5 MeV, adopting five different dipole strengths, namely 0 nT, 10 nT, 25 nT, 50 nT and 100 nT, providing in each case the field magnitude at the magnetic equator for the chosen exobase radial distance of 3600 km (i.e. at an approximate altitude of 200 km). This definition of dipole strength is used throughout the present paper, and also these values are used as labels for the self-consistent simulation cases. We disregard Martian crustal magnetic anomalies (described in e.g. Acuña and Connerney, 1999) in this study due to their localized nature and the high spatial resolution required to model these regions. Additionally, the formation of the local crustal magnetism may have been connected to the cessation of the Martian dynamo, posing questions on how and when they should be included – and in which form – that we do not presume to address here. To introduce the intrinsic dipole effects on the plasma environment, we describe and compare the results with previous intrinsic dipole modeling made in a slightly different part of the input parameter space by Kallio et al. (2008) in Section 3.1.

We employed modern parameters for the solar wind models and Martian atmosphere, as, despite recent developments in stellar wind evolution models, the parameters are as yet rather poorly constrained. Widely varying models for stellar wind velocity and density have been presented for different solar histories and model parameters, such as the rotation rate of the young Sun and choice of solar wind temperature scaling (Johnstone et al., 2015). Solar rotation and XEUV models by Tu et al. (2015) tend to converge for different solar histories at around 1 Ga, corresponding roughly to the early Hesperian period, coincidental with some estimates on the dynamo cessation event (Hood et al., 2010). Assuming the 1 Gy old Sun had approximately twice its present the rotation rate as given in Tu et al. (2015) and Johnstone et al. (2015) would yield, depending on the model, a solar wind velocity having modern-day values or approximately twice higher, and a solar wind density a factor of a few times greater than is the case today.

The Martian exobase altitude is dependent on atmospheric composition and density and solar activity, in particular on solar extreme ultraviolet emissions, which have been studied by e.g. Kulikov et al. (2007), who also provided an estimate for the Martian exobase altitude of 210 km (modern-day value). Martian atmospheric density also has spatial variability (see e.g. Forget et al., 2009). We have approximately adopted herein the value provided by Kulikov et al. (2007), disregarding spatial variations. Looking at modern variability, the early Hesperian XEUV emission may have intermittently had XEUV fluxes that were on a par with modern measurements, as Tu et al. (2015) estimate the XEUV emissions to have been about an order of magnitude larger at 1 Gy. Jakosky et al. (1994) give a corresponding 6 EUV estimate for the Martian exobase altitude of 310 km, which we regard as a minor correction.

Previously, a zero-age main sequence solar wind interaction with an unmagnetized body (late dynamo onset) was envisaged. Mars was investigated with respect to ion loss by Terada et al. (2009), who provided estimates of significant atmospheric erosion in the first 150 Ma. We approach the early Mars case from a direction opposite to that of Terada et al. (2009), taking rather a small dipole and a 'pre-depleted' atmosphere. This choice also allows us to concentrate on the singular effect of the varying dipole field with respect to well-known modern, instead of poorly-known ancient, conditions.

In Section 3.2, we present SEP precipitation results for the self-consistent cases, for two classes of SEP velocity distributions, and discuss the effect of the modified plasma environment described in Section 3.1. To distinguish the shielding effect of the solar wind-Mars interaction from that of a pure dipole, the modeled precipitation fluxes from our self-consistent model are compared with test particle simulations in "ideal", non-interacting cases, where the environment is described only by static, prescribed magnetic fields: (a) *Undisturbed*, in which there is no planetary interaction whatsoever ($\vec{B} = \vec{B}_{IMF} = (-4, 4, 0)$nT), to serve as a baseline value, (b) *Pure dipole*, in which the magnetic field is that of a pure dipole ($\vec{B}(\vec{r}) = \vec{B}_{dipole}(\vec{r})$), and (c) *Dipole+IMF* in which the magnetic field is the superposition of a dipole field and the IMF ($\vec{B}(\vec{r}) = \vec{B}_{dipole}(\vec{r}) + (-4, 4, 0)$nT). In these ideal cases, the intrinsic dipole moment is chosen to be equal to the self-consistent 50 nT case, and particles are collected and removed from the test particle simulation at the exobase.

2. Model description

2.1. The hybrid model

We employed the HYB hybrid plasma model, which treats ions as kinetic particles, with electrons providing a massless, charge-neutralizing fluid. Ions are propagated by the Lorentz force, yielding updated ion currents and densities when accumulated on a Cartesian, hierarchically refined grid. Ion currents and magnetic field – including the Hall term – are used in conjunction with the charge-neutralizing electron fluid assumption to provide the electron velocity field. Electron fluid velocity and magnetic field data are then employed to calculate the electric field, giving the change rate of magnetic flux via Faraday's law. Updating the magnetic field then completes an iteration, allowing for the next Lorentz force propagation of ions. An in-depth description of the model can be found in e.g. Kallio and Janhunen (2003). Also, the previously developed SEP package is described in Kallio et al. (2012).

The model does not presuppose any ion velocity distributions, and includes automatically finite ion gyroradius effects in a natural form. Finite gyroradius effects have been shown to modify the plasma environments of induced magnetospheres, producing for example a magnetic North–South asymmetry (Kallio and Janhunen, 2002). Energetic ion populations are easily included in an ion-