Implantation of Earth's Atmospheric Ions Into the Nearside and Farside Lunar Soil: Implications to Geodynamo Evolution

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Abstract Earth's present dipolar magnetic field extends into the interplanetary space and interacts with the solar wind, forming a magnetosphere filled up with charged particles mostly originating from the Earth's atmosphere. In the elongated tail of the magnetosphere, the particles were observed to move either Earthward or tailward at different locations, even outside the Moon's orbit. We hypothesize that the lunar soil, on both the nearside and farside, should have been impacted by these particles during the geological history, and the impact was controlled by the size and morphology of the magnetosphere. We predict that the farside soil could also have the features similar to those in the nearside soil, e.g., 15N-enrichment. Furthermore, we may infer the evolution of the magnetosphere and atmosphere by examining the implanted particles in the lunar soil from both sides. This hypothesis could provide an alternative way to study the evolution of Earth's dynamo and atmosphere.

1. Introduction

A sustained active geodynamo and its dipolar magnetic field have been regarded as a crucial factor in maintaining the habitability of the Earth, as implied from comparison to the neighbor planets Mars and Venus (Lammer et al., 2008). It was speculated that the Martian dynamo ceased 4.0–4.1 Ga and did not thereafter restart (Lillis et al., 2013). The beginning of Earth's dynamo was previously dated back to ~3.45 Ga, while the latest results suggested that the strength of the magnetic field between 3.3 and 4.2 Ga varied between 1.0 and 0.12 times of recent equatorial field strengths (Tarduno et al., 2015), much earlier than the appearing time of life ever found at ~3.5 Ga (Schopf et al., 2002). However, the latest results have been questioned (e.g., Weiss et al., 2015), thus some independent evidences are still required for determining the beginning time of geodynamo. On the other hand, Wei et al. (2014) argued that the decrease of the geomagnetic intensity and the collapse of the dipolar configuration during the polarity reversals could have resulted in Mars-like atmospheric ion escape into the interplanetary space, and the accumulated oxygen loss might have caused the drop of the atmospheric oxygen level and eventually induced biological mass extinctions. To date, a consensus has been reached that Earth's magnetic field can provide key clues to understand the evolution of Earth system, and even provide implications for the history of other planets from a comparative perspective.

The present dipolar field interacts with the solar wind and forms a magnetosphere extending to 10 Earth radii (R_E, 1 R_E = 6371 km) on the dayside and at least thousands of R_E on the nightside (Macek, 1989). Such a configuration can help to maintain the habitability by preventing most of solar wind particles and cosmic ray from directly impacting on the biosphere, as well as reducing atmospheric ion escape because the Dungey cycle can bring the escaping ions back to the Earth (Moore & Horwitz, 2007). It should be noted that the effectiveness of protection of planetary magnetic field against atmospheric escape has been hotly debated for decades based on satellite observations on Earth alone or also with Mars and Venus (e.g., Blackman & Tarduno, 2018; Gunell et al., 2018; Seki et al., 2001; Slapak et al., 2017; Wei et al., 2012). This debate is likely to remain if researchers still only use in situ ion measurements from a single
satellite during recent years to calculate the total escape rate of a planet, while to infer its billion-year history. The newest theoretical study presented a new view on this issue that a weak dipolar magnetic field enhances atmospheric escape as well as a strong dipolar magnetic field reduces the escape (Egan et al., 2019). However, it is difficult to determine the size and morphology of early geomagnetic field from the paleomagnetic data alone. This is because the data points are very rare and their distribution is highly uneven in space and time (Biggin et al., 2009), and the sample locations today could not represent the original place where it was magnetized due to continuing tectonic process on the Earth. It still needs very long time and good fortune to build a database with a global coverage at a given geological time, and thus to conduct a reliable reconstruction of the global field (Donadini et al., 2010).

To constrain the evolution history of the geomagnetic dipole, an alternative solution may rely on the Moon, considering the modification of the geomagnetic field by the transport of volatiles from the Earth to the Moon. It has been believed that the Moon was tidally locked soon after its formation, and then receded from Earth with a distance increasing approximately from 10 to 60 \( R_E \) (Abe & Ooe, 2001). Before Earth had a strong and stable dipolar magnetic field, the atmospheric ions might continuously escape into the interplanetary space, similar to what we have seen at Mars and Venus (Lammer et al., 2008), due to direct solar wind interaction with the ionosphere (Figure 1a). Accordingly, to explain the observed abundance of nitrogen and its isotopic ratio in the lunar soil, besides considering the interplanetary dust and/or the carbonaceous chondrites (Mortimer et al., 2016), Ozima et al. (2005) proposed that most of the nitrogen and some of the other volatile elements in the nearside lunar soils may actually have come from the Earth’s atmosphere, which probably happened even before the dipolar field was formed. They further suggested that once corotation of the Earth-Moon system was established, almost no terrestrial components should be observed in the lunar soils on the farside (Ozima et al., 2008). We will address here that the farside lunar soil could have also received volatiles from the Earth, once it had a dipolar magnetic field and the strength was close to the present level. If a historical profile of those volatiles could be acquired from the lunar farside soil, it is possible to constrain the evolution history of Earth’s magnetic field and atmospheric composition.

2. Implantation of Earth’s Atmospheric Ions Into the Lunar Soil

2.1. Implantation in the Modern Magnetosphere

The Earth’s modern magnetosphere is defined as a region where the Earth’s intrinsic magnetic field dominates (Figure 2b). The Earth’s atmospheric ions continuously flow up into the magnetosphere along the magnetic field lines above the polar regions, and then enter the central tail if the magnetic field lines extend there. It has been estimated that ~10% (Seki et al., 2001) or ~90% (Slapak et al., 2017) of the upflowing ions can travel beyond the distant X-line and then escape into the interplanetary space, whereas the rest of them eventually return to the Earth. Here the distant X-line refers to a region at around 120 \( R_E \) far from the Earth where the stretched magnetic field lines from the northern and southern polar regions connect together. In fact, the upflowing ions can directly enter the central tail along magnetic field lines within the Earthside of distant X-line, including both sides of the lunar orbit. Such a magnetic reconnection process releases magnetic energy and accelerates ambient plasma to produce plasma flow (~100 km/s) both Earthward (blue arrow) and tailward (red arrow). The Earth’s atmospheric ions and solar wind ions embedded within the tailward flow finally escape into the interplanetary space, but the ions in the Earthward flow return back to the
Earth. The latter is the so-called “Dungey cycle.” The distant X-line always exists in the present magnetosphere, and a near X-line may occasionally exist during space weather event. The near X-line is a transient magnetic reconnection region producing Earthward and tailward plasma flows (~400 km/s). It is widely accepted that the near X-line is typically located at ~20–30 R_E from the Earth (Nagai et al., 1998), but sometimes may even reach ~12 R_E (Alexandrova et al., 2015).

The Moon enters the magnetosphere at 60 R_E and stays for 3–5 days during each orbit. In the classical picture of Figure 2b, the Earth’s atmospheric ions impact on the nearside soil with a speed of 400 km/s, and impact on the farside with a speed of 100 km/s. Therefore, it is expected to find Earth’s materials in both the nearside and farside soil. In the geological past, the farside soil could have also reserved Earth’s atmospheric ions, unless the Moon went far beyond the distant X-line due to the shrink of the magnetosphere or the distant X-line disappeared due to the collapse of dipolar configuration during geomagnetic polarity reversal (Wei et al., 2014).

### 2.2. Probability of Implantation in the Geological History

For simplification, we first examine the probability of Earth’s materials implanted into the nearside and farside soil from a theoretical perspective. The locations of the two X-lines (Figure 1b) depend on the dimension of the magnetosphere. The dimension of Earth’s magnetosphere has experienced secular variations during the long-term evolution of the geomagnetic dipole field intensity in the geological history. As a first order approximation, the size of a magnetosphere is usually described by R_M, the distance from the planetary center to the subsolar point of the magnetopause where the magnetosphere’s magnetic pressure balances the shocked solar wind. The satellite observations give a scaling relation R_M ∼ M_E^{1/3} (Spreiter et al., 1966), where M_E is the dipole moment (the solar wind dynamic pressure is missing here and R_M is known to always vary with the –1/6 power of the dynamic pressure). The distance between the X-line and the planetary center (d) can thus be estimated from the linear scaling law: d/d_0 = R_M/R_{M0} = (M_E/M_{E0})^{1/3}, where the subscript “0” denotes the present values. This linear scaling law has been proved to be excellent according to its application to other planetary magnetospheres (e.g., Vasyliūnas, 2004). For the present magnetosphere, the locations of the near X-line and distant X-line are assumed to be at 10–30 and 120 R_E, respectively. Using the scaling law, the variations of these X-line distances are calculated (Figure 2) based on the log-linear evolution of the dipole moment from a value of 3 × 10^{22} Am^2 at 2 Ga up to the present value of 8 × 10^{22} Am^2 (Macouin et al., 2004). The Moon-Earth distance during the evolution of the Moon (Abe & Ooe, 2001) is also shown in Figure 2 for comparison. After the formation, the Moon quickly went away from its original orbit and kept away from the near X-line. This implies that the 400 km/s Earthward fast plasma flow produced at the near X-line could ever impact the farside of the Moon during a very short time after formation of the Moon if Earth’s dynamo existed at that time, but these materials are impossible to be identified today considering the lunar magma ocean during that time. It is clear that the Moon has been staying between the near X-line and the distant X-line for the recent 4.2 billion years. Theoretically, the plasma embedded with the 100 km/s Earthward flow produced at the distant X-line (red curve) could have been implanted into the farside soil if the strength of geomagnetic field at 4.2 Ga was comparable to the present level.

Now we examine the probability in detail with paleomagnetic records. We used the most recently updated version of the PINT paleointensity database (Biggin & Paterson, 2014), which includes over 4,000 dipole moments between ~3.5 Ga and now. Figure 3 shows the records of dipole moment as a function of the Earth-Moon distance. The red, green, and white shaded regions separated by predicted X-lines correspond to Cases 1, 2, and 3 in Figure 1, respectively. It is shown that the Moon has been located between the distant X-line and the near X-line (Case 2) during the majority of the past several billion years. However, some very low dipole moment records distribute in the region for Case 3, indicating that the Moon could have ever been
located beyond the distant X-line due to the much lower dipole moments. For such a small magnetosphere, though still much larger than Mercury’s magnetosphere, Earth’s atmospheric ion cannot be implanted into the farside lunar soil. No paleomagnetic record supports occurrence of Case 1, which corresponds to a large dipole moment approaching that of Saturn and even of Jupiter.

We should emphasize that the locations of the near-Earth and distant X-lines used here are based on statistical results of satellite observations, which are only appropriate for the average status of a dynamic magnetosphere. In reality, the magnetosphere is much more dynamic, especially during severe space weather events. Even in the modern magnetosphere, the near X-line may be occasionally located near the Moon orbit or even beyond (e.g., Øieroset et al., 2001). Moreover, the latest observations suggest that the 400 km/s plasma flow appears within the lunar orbit for 2% of time, during which the probabilities of Earthward and tailward flows are nearly equal (Kiehas et al., 2018). This implies that the present farside soil has 1% of time to suffer the impact of Earth’s atmospheric ions with speeds of 400 and 100 km/s simultaneously. It can be imagined that the magnetosphere was also highly dynamic in the geological history, and thus the implantation of Earth’s atmospheric ions into the farside lunar soil might also have frequently happened even during the period of low dipole moment.

2.3. Testing Method of Hypothesis

The early Moon may have had a short-lived and episodic atmosphere due to magmatic degassing (Hui et al., 2018; Needham & Kring, 2017), which may interfere the interaction between the plasma particles and lunar soils. This atmosphere, however, must have been lost shortly after the main volcanism at 3.3–3.8 Ga on the Moon (Shearer et al., 2006). With limited interference of the lunar exosphere, the lunar soil grains could have recorded the implantation activities of plasma particles over the last several billion years. Recently, focusing on the lunar water source, more and more evidences from the isotopic analyses of Apollo regolith and the remote sensing data from lunar spacecraft supported that the solar wind interacts with the global lunar soil (Li & Milliken, 2017; Sunshine et al., 2009). These studies provide possible methods to test our hypothesis in the future.

Figure 3. Scatter plots (black circles) of long-term evolution (~3.5 Ga to now) of the geomagnetic dipole moment as a function of the Earth-Moon distance. The predicted distances of the distant X-line (red line) and the average near X-line (blue line) to the Earth are also plotted for comparison (same as Figure 2). The distant X-line and the near X-line separate three cases of transport of materials from the Earth to the moon, as illustrated in Figure 1b.
The Moon was tidally locked to Earth within the first few tens of million years after its formation. It is believed that the Earth’s atmospheric ion could not reach the lunar farside, and thus the soil should not have $^{15}$N-rich component similar to the nearside soil if part of the nitrogen indeed came from Earth (Füri & Marty, 2015; Ozima et al., 2005). However, this prediction only considered the dynamics of the Moon-Earth system, but not the dynamics of the plasma flow which has been discussed in our hypothesis. Our calculation suggests that the plasma flows containing the Earth’s atmospheric ions could have reached both the nearside and farside of the Moon. It has been suggested that early Earth’s atmosphere was in a regime that was controlled by a certain mixture of CO$_2$ and N$_2$, and the upper atmosphere/exosphere level could reach distances where nitrogen was lost by ion escape or thermal escape due to the heating of the higher EUV flux of the young Sun between the end of the Hadean and during the Archean (Lammer et al., 2018; Lichtenegger et al., 2010; Tian et al., 2008; Tian et al., 2008). Even today, N$^+$ still can be found in the atmospheric upflowing ions (Ilie & Liemohn, 2016). Therefore, our hypothesis could be tested by analyzing the nitrogen isotope in the farside soil.

The penetration or implantation depth into the lunar soil grain depends on the energy of the incident ion, the angle of incidence, and the composition of the target surface, which is typically about 20 nm for a 400 km/s proton (Farrell et al., 2017). For the two kinds of flow speed discussed in this paper, 400 and 100 km/s, the implantation depths of the same ion species with 16 times of energy difference are significantly different and thus it is possible to distinguish them in laboratory. The implanted outmost layer of a single soil grain can be used to derive the isotope compositions of implanted plasma particles, while the exposure ages could be determined with the interior part of this grain (Ozima et al., 2008). Therefore, the comprehensive isotopic analyses of soil grains from the lunar farside will provide the decisive evidence on whether the Earth’s atmospheric ions could reach the farside of the Moon.

The uncertainties mainly come from the lunar dynamo and volcanism before ~3.5 Ga. It is suggested that the lunar dynamo field persisted from at least 4.25 to 3.56 billion years ago (Ga), with an intensity reaching that of the present Earth (Weiss & Tikoo, 2014). For this case, the Earth's atmospheric ions would mainly implant into the lunar magnetic polar region, similar to the way that the solar wind particles enter Earth’s atmosphere via the cusp tunnel. However, the positions of the magnetic pole remain unknown. The short-lived and episodic atmosphere due to magmatic degassing might also have prevented the Earth's atmospheric ions from implanting into the lunar soil. For example, the maximum atmospheric pressure at the lunar surface at ~3.5 Ga could have reached ~1 kPa, or ~1.5 times higher than Martian current atmospheric surface pressure, and might have taken ~70 million years to fully dissipate (Needham & Kring, 2017). In analogy to the fact that the solar wind ions cannot reach to Martian surface, we do not expect that the Earth’s atmospheric ions could have implanted into lunar soil for this case.

3. Summary and Predications

We have proposed a hypothesis that Earth's atmospheric ions have been implanting into both farside and nearside lunar soil since Earth began to have a dipolar magnetosphere. The lunar soil could have almost continuously preserved discernable Earth's atmospheric ions after the main mare volcanism and significant declination of lunar magnetic field, i.e., from 3.5 Ga to present. The main points we have hypothesized can be summarized as follows:

1. The nearside soil has been impacted by ~400 km/s atmospheric ions for most of the past 3.5 billion years.
2. The farside soil has been impacted by ~100 km/s atmospheric ions for most of the past 3.5 billion years.
3. Presently, the farside soil is impacted by ~400 km/s atmospheric ions for 1% of time, but this probability has been changing due to the variation of Earth’s dipole moment in the geological past.
4. The farside soil was not impacted by atmospheric ions during the periods of geomagnetic polarity reversal and very low dipole moment.
5. Before 3.5 Ga, the atmospheric ions could have intermittently implanted into the lunar soil near the lunar magnetic pole.

We predict that Earth’s volatile will be also detected in the farside lunar soil, if they can be discovered in the nearside soil. We also propose that the global configuration of ancient Earth's magnetic field, which is difficult to be reconstructed from paleomagnetic records, however, can be inferred from the information...
inferred from both the nearside and farside lunar soil. If this method could be proved to be feasible, it is possible to infer the dynamo evolution of Jupiter, Saturn, Neptune, and Uranus who have no paleomagnetic records on its gas surface from their rocky moons. Then we could understand not only the diversity of planetary dynamo in our solar system, but also their evolution history. Although it is extremely challenging to locate the beginning time of Earth’s dynamo, the possibility still exists if we could acquire samples near the ancient lunar magnetic pole.

Inferring early atmospheric composition is a very complicated issue. The escaping ions from present Earth (pressure: ~1 bar, O2: ~21%; N2: ~78%) are mainly H+, He+, O+, and a little N+. (Ilie & Liemohn, 2016). However, the satellite observations (Dubinin et al., 2011) show that H+, He+, O+, and/or O2+ are still dominating in escaping ions on both Venus (pressure: ~93 bar, CO2: ~97%) and Mars (pressure: ~0.006 bar, CO2: ~95%). This implies that we may only infer whether N2 was one of the major species in Earth’s early atmosphere or not, even if it was probably a mixture of CO2 and N2 (Lammer et al., 2018).

Looking forward to the future, the sample-return missions may be more important than what we have thought for exploring the evolution history of the solar system and its planets. China has announced lunar missions for returning sample from the nearside and south pole (Li et al., 2019), as well as has been discussing the possibility of sample-return or in situ study on the farside lunar soil. Besides, the announced sample-return missions on Mars and asteroid (Wei et al., 2018) could also be helpful for testing our hypothesis.

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