A planetary perspective on Earth’s space environment evolution

Yong Wei¹,²,³*, XinAn Yue¹,², ZhaoJin Rong¹,², YongXin Pan¹,², WeiXing Wan¹,², and RiXiang Zhu¹,²

¹Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China;
²College of Earth Sciences, University of Chinese Academy of Sciences, Beijing 100049, China;
³Institutions of Earth Science, Chinese Academy of Sciences, Beijing 100029, China

Abstract: The planet Earth is an integrated system, in which its multi-spheres are coupled, from the space to the inner core. Whether the space environment in short to long terms has been controlled by the earth’s interior process is contentious. In the past several decades, space weather and space climate have been extensively studied based on either observation data measured directly by man-made instruments or ancient data inferred indirectly from some historical medium of past thousands of years. The acquired knowledge greatly helps us to understand the dynamic processes in the space environment of modern Earth, which has a strong magnetic dipole and an oxygen-rich atmosphere. However, no data is available for ancient space weather and climate (>5 ka). Here, we propose to take the advantage of “space-diversity” to build a “generalized planetary space family”, to reconcile the ancient space environment evolution of planet Earth from modern observations of other planets in our solar system. Such a method could also in turn give us a valuable insight into other planets’ evolution.

Keywords: space environment evolution; space weather; generalized planetary space family; space diversity

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1. What is Space Environment Evolution?
The concept “space weather” was first proposed to describe some short-term variations, as early as the advent of the Space Era (Cade and Chan-Park, 2015). During recent thirty years, more and more attention was paid on the “space climate”, which describes the variations in the space with a longer time scale. With a little knowledge of meteorology, one could easily conceive the difference between space weather and space climate, though there is no clear boundary defined. Mursula et al. (2007) suggested that the boundary may be set as a few solar rotations, for which reasonable day-to-day forecasts of space weather can be made. The upper limit of time scale for space climate is millennium or even longer. It is nevertheless difficult to study space climate over such long time scale, because the available data was rare and indirect, with serious unevenness in the distribution versus space and time. How about the space environment with time scale longer than that of space climate? The history of Earth’s atmosphere could be back to billions of years ago when the Earth formed and had gravity to retain atmosphere. Moreover, the geodynamo generating global magnetic field was found to begin effectively working at 4.2 billion years ago (Tarduno et al., 2015). Since the atmosphere produces ionosphere under solar extreme ultraviolet (EUV) radiation and the geomagnetic field forms magnetosphere through interaction with solar wind, the ionosphere and the magnetosphere should have existed since then. By this means, the Earth should be regarded as an intact multi-sphere system from the core to magnetosphere, in which those spheres are coupled with each other via transportation and transformation of matter and energy, and the evolution of the Earth system should be regarded as co-evolution with those spheres. Therefore, the evolution of space environment must be considered in order to understand how the Earth system works in the past and even in the future.

We propose to name this research field as “space environment evolution”, rather than classify it into space climate, as a special regime of very long-term variation. Here are two considerations:

First, the atmosphere and geomagnetic field had exhibited many extraordinary changes unseen within recent thousands of years. For example, during geomagnetic polarity reversal (the last one in 780 ka B.P.) and excursion (the last one in 41 ka B.P.), the geomagnetic dipole collapsed and its magnitude of moment could decrease by 1 order or even more (Merrill and McFadden, 1999). In addition, the mixing ratios of atmospheric constituents had also changed over time (Kasting, 1993), and therefore should influence the property of the ionosphere at least through various photochemical and dynamical processes. We should also emphasize that, the solar luminosity, EUV radiation and solar wind, are also subject to evolution of a G-star after the young Sun arrived at the Zero-Age-Main-Sequence (ZAMS) ~ 4.6 billion years ago (Lammer et al., 2008). Therefore, new knowledge is desired to understand these space environment’s long-term variations.

Second, the traditional methods used for space weather and climate are not suitable for studying space environment evolution.
Those methods that the communities are familiar with highly rely on observational data made by either modern instruments or naked eyes, but for the deep past, it is hard to know what happened in the ionosphere and magnetosphere. Table 1 shows an overview of the available data related to space environment, from which one may find the bottleneck of research on very long-term variations in the near-Earth space. The fundamental parameters of ionosphere and magnetosphere, such as density, temperature, velocity of plasma, height of F2 Peak, position of magnetopause, strength of ring current, and so forth remain unknown.

Table 1. An overview of historical data

|                      | Modern data | Ancient data | Sources          |
|----------------------|-------------|--------------|------------------|
| Upper atmosphere     | 60 years    | No           |                  |
| Ionosphere           | 90 years    | No           |                  |
| Magnetosphere        | 60 years    | No           |                  |
| Geomagnetic field    | 170 years   | 4.2 billion years | Rock; Sediment |
| Sunspot number       | 400 years   | 11,000 year  | Tree ring; Ice core |
| Solar wind           | 60 years    | 4.6 billion years | Solar analogs |

Yet it seems that the researchers still have chance to find some clues. For example, Tomkins et al. (2016) extracted fossil micro-meteorites from limestone sedimentary rock that had accumulated slowly 2.7 billion years ago before being preserved in Australia’s Pilbara region, and suggested that Archaean upper-atmosphere oxygen concentrations may have been close to those of the present-day Earth, though the Great Oxidation Event (GOE) had not started at that time (Lyons et al., 2014). This could give an important constraint to model the Archaean ionosphere with present knowledge. The authors personally believe this kind of surprising discovery will appear more in the near future because the technology grows faster and faster, but we cannot predict when and how it will appear. Before a wildly spreading media (like rocks) was found, it is not possible to reconstruct a global picture of ancient space environment as we have done with many ground- and space-based instruments. We may have an alternative way to go forward, i.e., to change our own view to look and think these questions. It might be the “planetary perspective”.

2. A Planetary Perspective on Space Environment Evolution

If we set the start point of exploration of planetary space environment at 1965, when Mariner 4 crossed the Martian bow shock (Smith et al., 1965), i.e., the first crossing of non-terrestrial bow shock by manmade instrument, then the exploration has persisted over half century. To date, the manmade spacecrafts have sampled all the planetary space environments in our solar system, even including Pluto, Moon, icy moons, asteroids, and comets. If only one word is allowed to describe what has been found, we have to make a new term “space-diversity”, in analogy to biodiversity. Some common features have been identified, but most show unique features. Our present Earth’s space environment added just one normal sample to this database, though it owns the unique habitability. Standing upon this star, one could expect that the space-diversity is also evolved during the past billions of years, i.e., the planetary space environment should be different from what we have seen today. We may treat the planetary space environment at a given geological time as an equivalent sample to the space-diversity database. We call it “generalized planetary space family” (GPSF).

To illustrate this notion more straightforwardly, Table 2 lists several samples of GPSF. The early Hadean Mars may resemble the present Earth in several aspects, e.g., a working dynamo in its core, a magnetosphere effectively prevent the solar wind from directly interacts with its ionosphere to weaken ion/water escape, and thus even the liquid water could flow on the surface. The Phanerozoic Earth during geomagnetic reversal is more interesting, its small magnetosphere may be comparable to present Mercury’s, while the pattern of ionospheric ion escape is more like present Mars due to absent of protection of a strong dipolar magnetosphere (Wei et al., 2014). When the Earth becomes very old after billions of years, the geodynamo inevitably ceased if there is no enough energy to drive flow in the outer core, an induced magnetosphere will be created and several mini-magnetospheres spread over strong geomagnetic anomalies, much like what we have seen on the southern hemisphere of present Mars.

The GPSF is an open system, and could be continuously enlarged as more research carried out. Considering an unknown physical picture in the space environment at a given planet on a given geological time to be explored, one could find one or several similar known pictures from other samples of GPSF, and extract the dominant physical processes to construct a possible solution. Next, the results add a new sample to the GPSF. One can also expect that, as the number of samples grows, the research on space environment evolution will become easier, and then the number of samples grows faster.

Table 2. Selected samples of space environment of generalized planetary space family

| Atmosphere | Ionosphere | Magnetosphere |
|------------|------------|---------------|
| Present Mercury | No | No | Yes, weak |
| Present Venus | Yes, thick, CO2 | Yes | No |
| Present Earth | Yes, N2, O2 | Yes | Yes |
| Present Mars | Yes, thin, CO2 | Yes | No, mini-magnetosphere |
| Present Jupiter | Yes | Yes | Yes, very strong |
| Early Hadean Mars | Yes, CO2 | Yes | Yes |
| Early Hadean Earth | Yes, CO2 | Yes | No |
| Proterozoic Earth | Yes, N2 | Yes | Yes |
| Phanerozoic Earth during geomagnetic reversal | Yes, N2, O2 | Yes | Yes, weak |

Now, one may realize the advantage of planetary perspective on research of space environment evolution. The traditional method extensively applied in space weather and space climate is from

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3. The Path to Probe Space Environment Evolution

To study the space environment evolution, one should utilize the modern data as much as possible to constrain the hypothesized physical pictures. In other words, the researchers in space physics and the related fields could always take advantage of their knowledge and skills to extend their research to space environment evolution. To know an ancient space environment at a given time, one has to reconstruct many key parameters to describe the physical processes in that space environment. By this means, contributions from various research topics are required. Below are two examples to show how to make the expected contributions.

3.1 The Earth’s Ionosphere During Holocene

Up to date, no historical media was found that could be used to record ancient ionosphere and thermosphere. As stated in Table 1, the modern measurements regarding ionosphere could be back to 90 years ago, which was made by the ionosonde first began in UK. In China, the oldest ionosonde located in Wuhan is almost 70 years old. The instrument for ionospheric observation has changed for many generations, from manual radar at the beginning in 1947 to the modern Digisonde Portable Sounder 4D (DPS4D). As an example, Figure 1 shows the comparison between NCAR-TIEGCM (National Center for Atmospheric Research-Thermosphere Ionosphere Electrodynamic General Circulation Model) simulation and realistic ionosonde observation over Wuhan around March equinox afternoon (LT=15.6) during the interval of 1947-2017. The observations are the monthly mean value of the quiet (daily Ap<18) days around DOY (Day number of Year) = 90. Since there was no ionogram record before 1957, all the used ionospheric peak height ($h_mF_2$) in this study was calculated from the ratio of the maximum usable frequency at a distance of 3000 km (M3000) parameter to ensure the consistency of the data. The model was driven by the realistic CO$_2$ level and $F_{10.7}$ index during geomagnetic quiet conditions based on IGRF (International Geomagnetic Reference Field) geomagnetic field (Thébault et al., 2015). The CO$_2$ level during 1958-2017 came from Mauna Loa Observatory (Keeling et al., 1995). During 1947-1957, its value was extrapolated from Mauna Loa observations. Generally, the variations are dominated by the solar activity level. Both the simulation and observation show pretty similar solar cycle variations with time. In addition, both the simulation and observation also show long term trend variation independent of solar activity, which is a hot topic recently in the community (Laštovička et al., 2006; Yue et al., 2008; Wang et al., 2017). The model overestimates the $h_mF_2$ especially over solar minimum (e.g.: ~1953, ~2008). There are some relatively larger deviations between simulation and observation, which might be due to uneven data distribution when calculating monthly mean value. Overall, it demonstrates that the model driven by the realistic drivers could reproduce ionosonde observations well at least for space environment evolution study.

However, in terms of space environment evolution study, even 70 years long is still far less than needed. Fortunately, the main drivers of Earth’s ionosphere/thermosphere, including geomagnetic field, solar activity, solar wind velocity, CO$_2$ level, and etc., could be traced back to even billion years through such as fossil as stated in Table 1. Given the known atmospheric composition and main chemistry and physics mechanisms, we can derive the ancient ionosphere and thermosphere via theoretical simulation. According to the reviews by Schunk and Sojka (1996) and Qian et al. (2011), the modern computer models actually are very accurate in representing the ionospheric and thermospheric variabilities in time scales from minutes to longer term trend larger than solar cycles.

As a first step of constructing ancient ionosphere-thermosphere database via simulation, we have done a preliminary study for the recent 12000 years. The reasons we chose past 12000 years here include: (1) Ready-made geomagnetic field model is available back to 10000 years B.C.; (2) The reconstructed sunspot number (SSN) begins around ~10000 years B.C.; (3) The atmospheric composition and physics keep similar during ~12000 years; (4) The computation cost for 12000 years’ simulation is acceptable by a general desktop. Specifically, we used the CALS10k (Continuous models based on Archeomagnetic and Lake Sediment data of the past 10 kyrs) model, which was developed based on almost all the available archeomagnetic and lake sediment data using spherical harmonic method by Korte et al. (2011), to represent the realistic geomagnetic field. This model has a time resolution of ~100 years. The reconstructed SSN based on dendrochronological dated radiocarbon concentrations by Solanki et al. (2004) was used to represent the solar activity. Note that this SSN number is actually the
average value during 10 years interval. Then the NCAR-TIEGCM was driven by these realistic geomagnetic field and solar activity. The NCAR-TIEGCM is a self-consistent model of photochemistry, dynamics, and electrodynamics for ionosphere and thermosphere. It is an open source model and has been widely used by the community (Roble and Dickinson, 1989). March equinox is selected to do the simulation. Based on several control runs, the geomagnetic field and solar activity effect on the long term variations of ionosphere and thermosphere was evaluated for both global average and specific location. Regarding the geomagnetic field effect, global average variations of electron density profile, neutral temperature, ion temperature, and integrated Joule heating could be up to 1%, 6 K, 15 K, and 5%, respectively. The equatorial ionization anomaly (EIA) morphology also changes significantly. In specific location, the geomagnetic field effect could be much larger than the global average condition. The 70 years long Ionosonde observations over Wuhan of China was also used to evaluate the simulation results as shown in Figure 1.

As an example, Figure 2 shows the daily/global mean ionospheric electron density profiles (EDP) during -10000 to 2000 years simulated by the NCAR-TIEGCM model driven by the realistic geomagnetic field model and SSN with 10 years’ time interval. We can see clearly variations of EDP during the whole time period due to both geomagnetic field and solar activity variations. This database could be used to specify ancient climatological ionospheric electron density if needed. As a further example, we plotted the global mean neutral flux in the top boundary in Figure 3, which was calculated by multiplying the neutral density with the vertical wind in the top boundary. In this plot, the realistic geomagnetic field and constant solar activity driven NCAR-TIEGCM simulation was used. We can see that the top boundary neutral flux could vary by 2 times during 12000 years due to the variation of geomagnetic field. During the recent years, the flux keeps relatively low value. Although the calculated neutral flux here is not exactly the atmosphere escaping, it does manifest that the atmosphere could strike and or expand due to the geomagnetic field variation. Those simulated density, velocity, and temperature of iono-

Figure 2. Global daily mean electron density profiles during the past ~12000 years simulated by NCAR-TIEGCM based on the CALS10k geomagnetic field model and solar activity reconstructed from dendrochronological dated radiocarbon concentration. The Y-axis is pressure level, P and P0 is the pressure and reference pressure, respectively.

Figure 3. Daily global mean neutral vertical flux in the top boundary simulated by NCAR-TIEGCM during the past ~12000 years based on the CALS10k geomagnetic field model and constant solar activity index. Different colors represent different universal times.

3.2 The Earth’s Magnetospheric Ion Escapes During Geomagnetic Reversal
Space environment evolution requires viewing the space environment in the Earth’s multi-sphere system and considering how the space environment affects and is affected by the system during the evolution. Therefore, the space environment should be treated as an open system with input from interplanetary space and lower atmosphere as well as output to interplanetary space. The outgassing processes and geochemical processes could change the neutral and charged particles in space, while the irreversible escape of particles into the interplanetary space might change the whole system. For example, the hydrogen escape was suggested as an important cause for GOE (Catling et al., 2001).

The oxygen ion is the major species in the topside ionosphere at Earth, Mars and Venus, and those acquired adequate kinetic energies from solar wind interaction may escape to interplanetary space (Lundin et al., 2007). Based on the in-situ observations, it is found that oxygen ion escape may be reduced by planetary intrinsic dipolar magnetic field (Wei et al., 2012a) and lower solar wind dynamic pressure (Wei et al., 2012b). Currently, the Earth’s intrinsic magnetic field could reduce oxygen ion escape, and thus prevent the atmosphere from being changed much by solar wind interaction with the magnetosphere. However, the intrinsic dipole field collapsed during its polarity reversal, which frequently occurred in the geological past. With planetary perspective, Wei et al. (2014) modified a model of Martian oxygen ion escape to calculate the Earth’s oxygen ion escape rate during geomagnetic reversal, and found that the accumulated ion escape may explain the observed drop of atmospheric oxygen level around Triassic-Jurassic boundary. This work also links geomagnetic reversals and mass extinctions through oxygen ion escape.

4. Holding Planetary Magnetic Field: A Prospect
Planetary magnetic field should be regarded as one of the most important geophysical factors in the research of space environment evolution. It links all spheres in a planetary system, provid-
ing a background field to govern the motion of charged particles, taking part in various physical processes in planetary space, even directly change the manner of energy transport through magnetic reconnection. Fifty-year research has highlighted the importance of intrinsic magnetic field on the planetary space and planetary evolution. As shown in Table 1, the paleomagnetic field is the only geophysical parameter covering almost the whole history of planet Earth, though there is serious unevenness of data in spatial and temporal distribution. Furthermore, the difference of planetary magnetic field is an important part of space-diversity. Therefore, holding on the magnetic field could help to solve many problems in research on space environment evolution, and deepen our understanding on how the planet system works and evolves.

The variations of geomagnetic field originated from the geodynamic process. Therefore, paleomagnetic data can be used to infer the working state of the Earth's core (e.g., Biggin et al., 2015), and this implies that space environment evolution is closely associated with the core evolution. In other words, the knowledge of space environment evolution can provide useful clues to monitor the evolution of the Earth's interior. Likewise, it might hold for other terrestrial planets.

Once considering space environment evolution to explore the Earth multi-sphere system, the system must be regarded as an open system. The materials not only recycle among atmosphere, ocean, lithosphere and mantle, but also exchange with solar wind. Such an exchange is subject to modification by the Earth's magnetic field, which is controlled by those complicated processes in the Earth's interior. Ultimately, knowledge of space environment evolution will shed new lights on evolution of Earth and other planets.

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