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Oxygen escape from the Earth during geomagnetic reversals: Implications to mass extinction

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ABSTRACT

The evolution of life is affected by variations of atmospheric oxygen level and geomagnetic field intensity. Oxygen can escape into interplanetary space as ions after gaining momentum from solar wind, but Earth's strong dipole field reduces the momentum transfer efficiency and the ion outflow rate, except for the time of geomagnetic polarity reversals when the field is significantly weakened in strength and becomes Mars-like in morphology. The newest databases available for the Phanerozoic era illustrate that the reversal rate increased and the atmospheric oxygen level decreased when the marine diversity showed a gradual pattern of mass extinctions lasting millions of years. We propose that accumulated oxygen escape during an interval of increased reversal rate could have led to the catastrophic drop of oxygen level, which is known to be a cause of mass extinction. We simulated the oxygen ion escape rate for the Triassic–Jurassic event, using a modified Martian ion escape model with an input of quiet solar wind inferred from Sun-like stars. The results show that geomagnetic reversal could enhance the oxygen escape rate by 3–4 orders only if the magnetic field was extremely weak, even without consideration of space weather effects. This suggests that our hypothesis could be a possible explanation of a correlation between geomagnetic reversals and mass extinction. Therefore, if this causal relation indeed exists, it should be a "many-to-one" scenario rather the previously considered "one-to-one", and planetary magnetic field should be much more important than previously thought for planetary habitability.

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1. Introduction

In the past half a century, many efforts have been devoted to seeking the links between geomagnetic reversals and mass extinctions, but no consensus has been reached (Glassmeier and Vogt, 2010). An important test of any successful mechanism is to explain the patterns of mass extinctions. Fossil records reveal that a mass extinction has a gradual pattern persisting for millions of years, during which a stepwise pattern is manifested by a series of impulsive extinctions (Jin et al., 2000). These patterns suggest that the main cause should be continual environmental degradation. The drop of atmospheric O_2 level has been verified to be able to induce environmental degradation because reducing the supply of O_2 is lethal for most species (Huey and Ward, 2005). However, it is difficult to explain the O_2 level drops if only considering Earth-bounded geochemical processes (Berner, 2005). An alternative possibility is that the O_2 molecules are dissociated into oxygen atoms by solar radiation and subsequently ionized; these O^+ ions are further energized in the ionosphere by the solar wind forcing and can thus overcome the containment by the magnetosphere and gravity, finally escape into the interplanetary space. Since the magnetospheric containment is expected to be severely weakened when the dipole collapses during geomagnetic reversals, we hypothesize that geomagnetic reversals cause O_2 level drops, and the subsequent mass extinctions. To test this hypothesis, in this paper we will examine the newest databases and simulate O^+ escape during reversals.

Fig. 1A shows the newest reversal rate data during the Phanerozoic era (solid line, Ogg et al., 2008). Because of several data gaps

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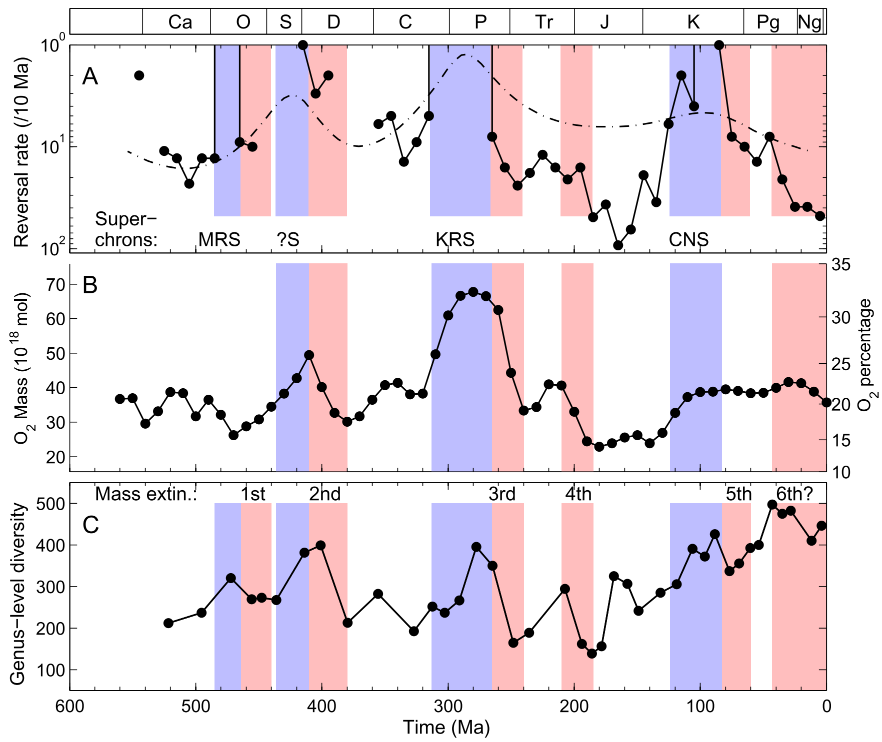

Fig. 1. Temporal evolution of reversal rate, O_2 level and marine diversity over the Phanerozoic era. (A) Geomagnetic reversal rate. The solid line is total reversals within a 10-Myr bin from the new database (Ogg et al., 2008). The dashed line is the relative reversal rate to represent the trend of reversal rate from an older database (McElhinny, 1971). The blue blocks show the superchrons. KRS: Kiaman Reversed Superchron (267–313 Ma). CNS: Cretaceous Normal Superchron (83–125 Ma). MRS: Mayero Reversed Superchron (463–481 Ma). (B) Modeled percentage and amount of atmospheric O_2 over time (Berner, 2009). (C) Number of marine genera (Alroy, 2010). The red blocks show the gradual pattern of 5 well-known mass extinctions, and the 6th mass extinction has not been confirmed. The blue blocks show the superchrons. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in this database, the relative reversal rate from an older database (dashed line, McElhinny, 1971) is also plotted to show the trend of reversal rate for a reference. The reversal rate, atmospheric O_2 level (Fig. 1B) (Berner, 2009) and Marine diversity (Fig. 1C) (Alroy, 2010) show a strong correlation in support of our hypothesis. During the 2nd, 3rd and 4th mass extinctions identified by the diversity drops (red), the reversal rates increased and the O_2 level decreased. On the contrary, when the reversal rate remained at zero or very low, namely during the superchrons (blue) (Merrill and Mcfadden, 1999), the diversity increased, and the O_2 level also increased for 3 out of 4 superchrons. However, during 1st and 5th mass extinction, the reversal rate also increased despite that the O_2 level just remained at low level or had no discernable change. These features suggest that some mass extinctions might be explained by our hypothesis: increasing geomagnetic reversals continually enhance oxygen escape, and this cumulative effect could cause a significant drop of O_2 level over a few millions years. As a result, the global hypoxia might gradually kill numerous species.

2. Explanation and simulation

Planetary ion escape is universal in our solar system throughout its history (Lammer, 2008; Lundin et al., 2007 and Moore and Horwitz, 2007). Many spacecraft observations and theories have revealed that ion escape from terrestrial planets is mainly driven by solar wind dynamic pressure, but the efficiency of this process highly depends on the intensity and morphology of the planetary intrinsic magnetic field (Lundin et al., 2007 and Moore and Horwitz, 2007). Earth's present dipole field interacts with solar wind and forms an intrinsic magnetosphere, and its outer boundary, the magnetopause usually extends to 10 R_E (Earth's radius) at the subsolar point (Fig. 2B). An Earth-like intrinsic magnetic field can effectively prevent the planetary ionosphere from directly interacting with solar wind and thus constrains ion escape (Moore and Horwitz, 2007 and Seki et al., 2001). Mars and Venus have no global intrinsic field, thus their ionospheres directly interact with solar wind and form induced magnetospheres. However, an induced magnetosphere is much smaller in size; for example, Martian magnetopause only extends to 1.2 R_M (Mars' radius) at the subsolar point (Dubinin et al., 2006). Direct comparison of spacecraft observations has illustrated that a Mars-like ion escape is much more efficient in removing planetary O^+ ions (Wei et al., 2012). No doubt, Earth will also have a Mars-like ion escape (Lundin et al., 2007) when Earth's dynamo is substantially weakened (Fig. 2C). Collapse of the dipole during its polarity reversal (Merrill and Mcfadden, 1999) reduces the size of the magnetosphere, thus also causes a transition from the Earth-like ion escape to the Mars-like.

To quantitatively estimate the O^+ escape rate during reversals, we first make an estimate of the evolution of solar wind dynamic pressure (P_{SW}) over Phanerozoic era. Studies of solar analogs suggest that the stellar wind dynamic pressure can be represented as a function of the star's age or X-ray flux (Wood et al., 2002). By using this method the solar wind pressure 600 million years ago (Ma) was 1.3–1.5 times larger than its present value P_{SW0}. Details are given in supplementary material, see Appendix A. If we use X-ray flux, we consider a Sun-like star, 18 Scopii (HD 146233), which is identical to the Sun but ~300 million years (Myr) or more younger than the Sun (Wright et al., 2004). The stellar wind dynamic pressure of 18 Scopii may represent the upper limit of the Phanerozoic P_{SW} because its age overlaps the early Phanerozoic era. This method gives an upper limit of P_{SW} as 3–3.7 times larger than P_{SW0}. Details are given in supplementary material, see Appendix A. The averaged P_{SW0} over one solar cycle is observed as 2–8 nPa, without consideration of space weather effects (Richardson and Wang, 1999). Therefore, the P_{SW} over Phanerozoic era was about 3–30 nPa.

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