LATE IMPACTS AND THE ORIGINS OF THE ATMOSPHERES ON VENUS, EARTH, AND MARS.

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Introduction. Diverse origins of terrestrial planet atmospheres are inferred from differences in the noble gas abundances and isotope ratios observed on Venus, Earth, and Mars [e.g., 1, 2]. Models for the origin of terrestrial atmospheres typically require an intricate sequence of events, including substantial loss and isotopic fractionation of solar nebula gases, outgassed mantle volatiles, and delivery of volatiles by late accreting planetesimals.

Impact events, large or small, may add or remove volatiles depending on the specific impact parameters. The Moon-forming giant impact is thought to be the last major collision on the growing Earth. Recently, Ćuk and Stewart [3] proposed that a giant impact onto a fast-spinning and nearly fully-grown Earth can explain the identical isotopic composition of the Moon and Earth.

Here we discuss the origin of Earth's early atmosphere in light of the high-spin model for Moon formation and new constraints from recent measurements of primordial noble gases in basalts from mid-ocean ridges and mantle plumes [4-6]. We propose that major differences in the noble gas signatures of terrestrial planetary atmospheres are a result of the different outcomes of late impact events on each planet.

Earth. The end stage of Earth's accretion included multiple giant impacts with sufficient energy to generate multiple magma oceans of varying depths. Because protoplanets formed in the presence of the solar nebula, the atmosphere and mantle of the growing Earth should include a nebular component. Chondritic meteorites contain a noble gas signature that is distinct from nebular, and accreting planetesimals should also add a chondritic component to the Earth.

Building upon previous work, Mukhopadhyay et al. [4] find that Earth's atmosphere cannot be derived from any combination of fractionation of a nebular-derived atmosphere followed by outgassing of deep or shallow mantle volatiles. The primordial Xe isotopic composition of the whole mantle is distinct from air, mantle Xe cannot be residual to atmospheric Xe, and the Ar/Xe ratio in Earth's mantle is near chondritic. If a nebular or outgassed atmosphere existed on the early Earth, it has largely been lost (>~70% with larger loss fractions favored).

Furthermore, more than one atmospheric loss event is inferred from the mantle ^{3}He/^{22}Ne ratio [6]. Plate tectonic processes are incapable of increasing this ratio of primordial isotopes in the mantle substantially, but the observed mantle ^{3}He/^{22}Ne is higher than solar by at least a factor of 6. The mantle ^{3}He/^{22}Ne ratio can be raised by a factor of 2 over the concurrent atmospheric value through degassing of a magma ocean as a result of the higher solubility of He over Ne in the magma ocean. Consequently, increasing the mantle's ^{3}He/^{22}Ne by a factor of 6 requires multiple magma ocean degassing and atmospheric loss events [6], one of which was likely associated with the Moon-forming impact.

However, previous calculations of impact-induced atmospheric erosion [7, 8] have found that it is difficult to completely remove the atmosphere from a body as large as Earth even under the giant impact conditions previously expected for Moon formation [9].

We reconcile the need for atmospheric loss inferred from the noble gas data with the dynamics of giant impacts by considering the new high-spin Moon formation hypothesis. We find that high-spin giant impact scenarios can remove most of the Earth's atmosphere.

During a giant impact, the atmosphere is lost by direct ejection near the impact point and loss induced by global ground motion from the impact shock wave [10]. Genda & Abe [7, 8] calculated the fraction of atmosphere that achieves escape velocity due to the air shock generated by the rapid upward motion of the ground or ocean. Using their scaling relations and our giant impact simulations, we estimate the atmospheric loss due to the canonical Moon-forming impact [9] and the new high-spin scenario [3] (see [11] for a more rigorous calculation).

For the canonical Moon-formation scenario (Mars-mass impactor at escape velocity and 45º impact angle [9]), only a few 10's % of the atmosphere would be lost, similar to the values found by Genda & Abe [7, 8]. During a giant impact onto a fast-spinning Earth, most of the atmosphere is lost. For example, 60-100% is lost depending on the mass of the ocean for the example in Fig. 1 of ref. [3] (half Mars-mass at 20 km/s and 30º onto a proto-Earth with 2.3-hr spin period).

We propose that Earth's high spin state was achieved by a giant impact prior to Moon formation. A giant impact event that increased Earth's angular momentum to near its spin stability limit would also generate a magma ocean and eject most of its atmosphere. The Earth may have been spun up by its penultimate giant impact or a previous giant impact [e.g., 12]. Thus, one or more magma oceans prior to Moon formation likely led to efficient outgassing of the mantle. Then, any remaining outgassed component in Earth's atmosphere would have been removed during the terminal giant impact that formed the Moon. Hence, the sequence of giant impacts near the end of Earth's formation led to near complete removal of nebular-derived and mantle-outgassed components in the atmosphere.

Atmospheric removal by giant impacts may also lead to separation of the water budget from the other volatiles. The time between giant impacts is expected to exceed the cooling time for a magma ocean [13]. If water were present as a condensed ocean, it would be removed in much smaller proportions compared to the atmospheric gases [8]. In this manner, giant impacts preferentially remove CO_2 and noble gases compared to water, which may explain the higher than chondritic H/C ratio of the bulk silicate Earth [14].

Our calculations suggest that the Earth's atmosphere after the formation of the Moon could have been dominated by water with significant depletion of other volatiles. Subsequently, planetesimals were delivered to Earth during late accretion with sufficient impact velocities to substantially vaporize the planetesimal. Thus, Earth's early atmosphere was generated by outgassing late-accreting chondritic planetesimals [4].

Venus. Compared to Earth, Venus's atmosphere has about 20 times higher abundance of Ne and a $^{20}Ne/^{22}Ne$ ratio closer to the solar value [15]. Therefore, Venus must have lost a smaller fraction of the volatiles that were accreted during the main stages of planet formation.

We propose that the abundance of noble gases on Venus reflects the absence of a late giant impact with substantial atmospheric erosion. Typical accretionary giant impacts onto a slowly spinning proto-Venus will generate magma oceans but remove little of the atmosphere [7, 8]. Hence, Venus's atmosphere should include both a nebular component and a chondritic component derived from late-accreting planetesimals.

As less than half of giant impacts are expected to substantially increase or decrease a planet's spin period [12], the different spin states near the end of Venus's and Earth's formation (and their correlated effects on the evolution of the atmospheres) may simply reflect the stochastic nature of the giant impact stage.

Mars. The present atmosphere of Mars is significantly fractionated in the lighter noble gases due to long term atmospheric escape [1]. The strongest constraints on the origin of the martian atmosphere are the Kr isotopes measured in SNCs: the Kr isotopic ratios are identical to solar [1]. If Mars accreted in a couple million years [16], its entire growth occurred in the presence of the solar nebula. Thus, one would expect a primary nebular signature for its noble gases followed by fractionation processes. However, late planetesimals were accreted to all the terrestrial planets (as inferred from the abundance of highly siderophile elements). These planetesimals are expected to have also delivered volatiles with a chondritic signature.

We propose that the puzzling lack of a chondritic Kr component in the martian atmosphere is due to incomplete accretion of late-impacting planetesimals. Upon impact-induced vaporization, the vaporized projectile (or at least its volatile components) achieved escape velocity from Mars.

Toward the end of terrestrial planet formation, the mean velocity of late-accreting planetesimals is expected to be high (typically 1 to 3 times the escape velocity from the largest bodies [17-19]) because of dynamical stirring by the fully grown planets. Simulations of high-velocity impacts find that most of the vaporized projectile mass should be accreted to Earth and Venus but lost from Mars [20, 21]. In this manner, the volatile components of late-impacting planetesimals may not be accreted to Mars.

Conclusions. Noble gas measurements on Earth [4-6] and the high-spin Moon-formation scenario [3] shed new light on the origin of Earth's early atmosphere. Most of the mantle was degassed and most of the outgassed volatiles were lost during the final sequence of giant impacts onto Earth. Earth's early atmosphere was dominated by late-accreting planetesimals. Venus did not suffer substantial atmospheric loss by a late giant impact and retains a higher abundance of nebular noble gases compared to Earth. The fast-accreting Mars has a solar noble gas signature inherited from the nebula, and its low mass led to gravitational escape of the volatile components of late planetesimals due to vaporization upon impact.

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