LATE IMPACTS AND THE ORIGINS OF THE ATMOSPHERES ON THE TERRESTRIAL PLANETS: THE IMPORTANCE OF VENUS. S. Mukhopadhyay and S. T. Stewart, Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, MA 02138 (sujoy@eps.harvard.edu)

Introduction. The 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.

Here we discuss the origin of the atmospheres on the terrestrial planets in light of new ideas about lunar origin [3,4], general models on atmospheric loss associated with giant impacts [5], and constraints from recent high-precision noble gas measurements in basalts from mid-ocean ridges and mantle plumes [6-8]. We propose that major differences in noble gas signatures of the terrestrial atmospheres are a result of planetary size, the stochastic nature of giant impacts and different outcomes of late impact events on each planet.

Earth. In combination with previous work, we find that noble gases in the 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. We find that 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 chondritic. While Ne in the mantle retains a nebular component [6], the present-day atmosphere does not. Thus, 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 [8]. Plate tectonic process are incapable of increasing this ratio of primordial isotopes in the mantle substantially [8], 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 via 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 [8], one of which was likely the Moon-forming impact.

As protoplanets formed in the presence of the solar nebula, the atmosphere and mantle of the growing Earth should include a nebular component, which explains the solar Ne component of the solid Earth. The end stage of Earth's accretion included multiple giant impacts with sufficient energy to generate multiple magma oceans of varying depths. Outgassing of a magma ocean would transfer most of the noble gases to the atmosphere, particularly the heavy noble gases (Ar, Kr and Xe) that are less soluble in magmas compared to He and Ne. A subsequent giant impact (or many small impacts) could have ejected a significant fraction of the outgassed noble gases from the atmosphere. Such a sequence of multiple impact events would have depleted the global noble gas inventory and preferentially removed the heavy noble gases.

During the giant impact phase of Earth's accretion, chondritic noble gases, which are distinct from nebular gases, should also have been added through the delivery of chondritic planetesimals. However, since Earth's atmosphere and mantle cannot be related through outgassing and hydrodynamic fractionation, most of the chondritic noble gases delivered prior to the last equilibration between the Earth's surface and mantle must have been lost. Thus, the present inventory of noble gases was largely delivered after Moon formation.

Previous calculations of impact-induced atmospheric erosion [9,10] have found that it difficult to completely remove the atmosphere from a body as large as Earth even under the giant impact conditions previously expected for Moon formation [11]. New giant impact-driven atmospheric loss calculations, however, find that the high-angular momentum models for lunar origin lead to substantial atmospheric loss [5].

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 [12]. If water were present as a condensed ocean, it would be removed in much smaller proportions compared to the atmospheric gases [5,8,10]. In this manner, giant impacts preferentially remove N_2 and noble gases compared to water, which may explain the higher than chondritic H/N ratio of the bulk silicate Earth.

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, noble gases in Earth's early atmosphere were generated by outgassing late-accreting chondritic planetesimals.

Venus. The isotopic compositions of noble gases on Venus are poorly determined. While present-day

Venus is depleted in water compared to Earth, Venus's atmosphere has about 20 times higher abundance of ^{20}Ne, 70 times higher ^{36}Ar abundance and a ^{20}Ne/^{22}Ne ratio closer to the solar value, although this ratio is poorly determined [13]. While the water depletion on Venus is likely related to a runaway greenhouse and photodissociation of water in the atmosphere, we suggest that the high primordial noble gas abundance on Venus implies that the planet has 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 stochastic absence of a late giant impact with substantial atmospheric erosion. Most accretionary giant impacts will generate magma oceans but remove little of the atmosphere [5,9,10]. We predict that Venus' atmosphere should include both a nebular component and a chondritic component derived from late-accreting planetesimals, with the heavier noble gases having more of a chondritic flavor.

Thus, major differences between Venus' and Earth's atmospheres at the end of accretion (and their correlated effects on the subsequent 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 constraint on the origin of the martian atmosphere is the Kr isotopes measured in SNCs: the Kr isotopic ratios are identical to solar [1]. If Mars accreted in a couple million years [14], it's 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 mantle 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 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 [15,16]. Thus, the volatile component of late-impacting planetesimals was not accreted to Mars, preserving the original nebular atmospheric signature.

Conclusions: The Importance of Venus. Precise noble gas measurements on Earth [4-6] and the high angular momentum Moon-formation scenario [3] shed new light on the origin of Earth's early atmosphere. We conclude that 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 noble gases were dominantly derived from late-accreting planetesimals. In contrast, Venus did not suffer substantial atmospheric loss by a late giant impact and retains a higher abundance of both nebular and chondritic noble gases compared to Earth. Fast-accreting Mars has a noble gas signature inherited from the solar nebula, and its low mass led to gravitational escape of the volatile components of late planetesimals due to vaporization upon impact. We propose that a common set of processes operated on the terrestrial planets and their subsequent evolutionary divergence are simply explained by planetary size and the stochastic nature of giant impacts. A critical test of our hypothesis could be obtained by deploying mass spectrometers in the atmosphere of Venus to precisely measure the isotopic composition of noble gases, carbon and nitrogen. We predict Ne isotopic ratios to be closer to solar values, primordial Ar isotopic ratios to be intermediate between solar and chondritic, and Kr ratios to be closer to the chondritic value. The measurement of noble gases in Venus' atmosphere will not only provide important constraints on impacts and volatile loss during Venus' accretion (VEXAG goal 1A), but also provide critical clues to the processes that control the origin and composition of the early atmosphere on all terrestrial planets.

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