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The Late Asteroidal and Cometary Bombardment of Earth as Recorded in Water Deuterium to Protium Ratio

Nicolas Dauphas

Centre de Recherches Pétrographiques et Géochimiques, CNRS EP 2031, 15 rue Notre-Dame des Pauvres, B.P. 20, 54501 Vandœuvre-lès-Nancy Cedex, France
E-mail: dauphas@crpg.cnrs-nancy.fr

François Robert

Laboratoire de Minéralogie, CNRS URA 736, Muséum National d'Histoire Naturelle, 61 rue Buffon, 75005 Paris, France

and

Bernard Marty[1]

Centre de Recherches Pétrographiques et Géochimiques, CNRS EP 2031, 15 rue Notre-Dame des Pauvres, B.P. 20, 54501 Vandœuvre-lès-Nancy Cedex, France

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The deuterium to protium (D/H) ratio of the deep mantle may be a remnant of the hydrogen isotopic composition of Earth forming planetesimals, which later evolved as a result of the late accretion of asteroids and comets. If so, the mass of asteroids and comets incident on Earth since the time of its accretion is estimated to be 4×10^{20}–2×10^{22} kg. The combined use of water D/H ratios, the lunar cratering record, and terrestrial mantle siderophiles would favor a rather low mass fraction of comets among impacting bodies ($\lesssim$0.01). Asteroids, comets, and the early Earth contributed to 0–0.5, 0–0.1, and 0.5–0.9 of Earth's water inventory, respectively. A two stage model is advocated in which escape to space of terrestrial volatiles predated the late accretion of extraterrestrial gases. We wish to emphasize that our interpretations and conclusions might evolve in the future when additional data on asteroids, comets, and Earth's interior become available.

Key Words: **accretion; asteroids; atmospheres; evolution; comets; Earth.**

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1. INTRODUCTION

The surface density of lunar craters correlates with the age of the cratered surface, implying in turn that the Moon (and by extension Earth) endured a period of heavy bombardment by the remnants of planetary formation (Shoemaker and Hackman 1962). This late accretion of extraterrestrial matter is also recorded by highly siderophile elements (Ru, Rh, Pd, Re, Os, Ir, Pt, and Au) which are in chondritic proportion in Earth's mantle (Jagoutz *et al.* 1979) and are overabundant relative to that predicted in the case of equilibrium partitioning between the mantle and the core (Kimura *et al.* 1974). According to several heterogeneous accretion models, our planet received the bulk of its surface volatiles as a late accreting veneer. Conversely, the extreme ultraviolet radiation of the young evolving Sun (Zahnle and Walker 1982) could have driven a fractional loss of terrestrial volatiles. In the present contribution, an intermediate view is advocated in which escape to space of terrestrial volatiles predated the late accretion of extraterrestrial gases.

Mantle plumes sample a deep region of Earth (Bréger and Romanowicz 1998, Helmberger *et al.* 1998, Russel *et al.* 1998, Bijwaard and Spakman 1999, Goes *et al.* 1999, Ritsema *et al.* 1999), which offers the opportunity to study volatile elements trapped in our planet at the time of its accretion. The D/H ratio of the deep mantle (Deloule *et al.* 1991) may be a remnant of the hydrogen isotopic composition of Earth-forming planetesimals which later evolved to the present Earth value (Kyser and O'Neil 1984, Lécuyer *et al.* 1998) as a result of the late accretion of asteroids (Kerridge 1985) and comets (Balsiger *et al.* 1995, Eberhardt *et al.* 1995, Bockelée-Morvan *et al.* 1998, Meier *et al.* 1998). In consideration of water D/H ratios, the mass of asteroids and comets incident on Earth since the time of its accretion as well as the contributions of asteroids, comets, and early Earth to Earth's water inventory are estimated.

2. SETTING THE SCENE

The extraterrestrial flux to Earth ranges from a few micrometers up to several tens of kilometers. Melosh and Vickery (1989) and Vickery and Melosh (1990) constructed an analytical model of atmospheric erosion by impacts based on computer modeling.

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[1] Also at: École Nationale Supérieure de Géologie, rue du Doyen Marcel Roubault, B.P. 40, 54501 Vandœuvre-lès-Nancy Cedex, France.

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They suggested that vapor plumes created by high-speed impacts might eject part or the entire air mass above the plane tangent to the point of impact. Recent analytical and computational modeling of impact induced erosion led Newman *et al.* (1999) to conclude that impact events (at least those up to K/T) would not remove significant atmospheric gases. As a first approximation, we shall consider that Earth retained all incident volatiles.

Despite the observation that ∼4% of meteorite falls are carbonaceous chondrites (Sears and Dodd 1988), there is strong evidence that the accretion tail consisted of organic rich matter. Indeed, carbon-rich asteroids (Gaffey *et al.* 1993) dominate the asteroid belt population (Gradie *et al.* 1989), most xenoliths in meteorite regolithic breccias resemble carbonaceous chondrites (Anders 1978, Wasson and Wetherill 1979, Lipschutz *et al.* 1989), the lunar regolith is known to contain 1–2% of carbonaceous debris (Keays *et al.* 1970), and micrometeorites which represent the major extraterrestrial flux to Earth share similarities with carbonaceous chondrites (Kurat *et al.* 1994, Engrand and Maurette 1998). On the whole, we shall assume that our planet owes its water to Earth forming planetesimals (early Earth) and a late accreting veneer (asteroids similar to CI–CM chondrites and comets). It is worthwhile to note that recent papers (Delsemme 1999, Pavlov *et al.* 1999) address the late addition of water to Earth in a manner different from that which we advocate.

3. WATER IN ASTEROIDS, COMETS, AND EARTH

Literature data are compiled in Table I. Kerridge (1985) measured water concentrations and D/H ratios in some carbonaceous chondrites. The mean water concentrations of CI and CM are 0.0032 ± 0.0003 and 0.0038 ± 0.0002 mol g^{-1}, respectively. The mean D/H ratios of CI and CM are $181 \pm 10 \times 10^{-6}$ and $159 \pm 10 \times 10^{-6}$, respectively. Water concentrations in cometary ice and dust are 0.041 ± 0.009 and 0.025 ± 0.005 mol g^{-1}, respectively (Delsemme 1988, Jessberger *et al.* 1988). The ratio dust/ice is poorly known but may vary in the range 0.5–1.3 (Delsemme 1988). Measurements of D/H ratios in Halley 1P/1982 U1 (Balsiger *et al.* 1995, Eberhardt *et al.* 1995), Hale–Bopp C/1995 O1 (Meier *et al.* 1998), and Hyakutake C/1996 B2 (Bockelée-Morvan *et al.* 1998) yielded consistent results centered around $311 \pm 13 \times 10^{-6}$. The early Earth D/H ratio is consistently higher than the lowest ratio measured so far in undifferentiated meteorites ($\gtrsim 128 \times 10^{-6}$, Kerridge 1985) and is necessarily lower than the inferred deep mantle ratio ($\lesssim 136 \times 10^{-6}$, Deloule *et al.* 1991). Lécuyer *et al.* (1998) estimated the amount and D/H ratio of water stored at Earth's surface (oceans, ice sheets, organic matter, metamorphic rocks, shales, sandstones, continental carbonates, evaporites, marine clays, and marine carbonates) to be ca. 9.4×10^{22} mol and 153×10^{-6}, respectively. Measurements of water concentrations in nominally anhydrous minerals led Bell and Rossman (1992) to propose that at most ca. 6.6×10^{22} mol of water could be accommodated in the whole mantle. The mean mantle D/H ratio is ca. 143×10^{-6} (Kyser and O'Neil 1984).

4. FORMAL REASONING

If we assume that Earth retained all incident volatiles and that the late accreting veneer consisted of asteroids similar to CI–CM carbonaceous chondrites and comets, then it is straightforward to draw up mass balance equations (Javoy 1997, 1998, Dauphas *et al.* 1998) for H and D between asteroids (A), comets (C), the early Earth (E), and the present Earth (P).

$$M[(1-\alpha)C_{\mathrm{A}} + \alpha C_{\mathrm{C}}] + M_{\oplus} C_{\mathrm{E}} = M_{\oplus} C_{\mathrm{P}}$$

$$M[(1-\alpha)C_{\mathrm{A}} R_{\mathrm{A}} + \alpha C_{\mathrm{C}} R_{\mathrm{C}}] + M_{\oplus} C_{\mathrm{E}} R_{\mathrm{E}} = M_{\oplus} C_{\mathrm{P}} R_{\mathrm{P}},$$

where M is the mass of asteroids similar to carbonaceous chondrites and comets incident on Earth since the time of its accretion, α is the mass fraction of comets among impacting bodies, C and R stand for concentration and isotopic ratio (respectively), and $M_{\oplus}$ denotes the mass of Earth. There are two mass-balance equations (H and D) in three unknowns (M, α, and C_{E}), so that one must fix a parameter to compute the remaining two (Figs. 1 and 2).

5. THE LATE BOMBARDMENT AND THE ORIGIN OF WATER ON EARTH

Results of the calculations are displayed in Figs. 1 and 2. The mass of asteroids and comets incident on Earth since the time of its accretion (Fig. 1) is estimated to be 4×10^{20}–2×10^{22} kg, which compares well with independent calculations based on the

TABLE I
Literature Data

	Asteroids	Comets	Early Earth	Present Earth
H_2O (10^{-3} mol g^{-1})	3.2 ± 0.3–3.8 ± 0.2	32 ± 5–36 ± 6	—	0.016–0.027
D/H (10^{-6})	159 ± 10–181 ± 10	311 ± 13	128–136	149–153

Note. $x - y$ and $x \pm y$ uncertainties were simulated as uniform and gaussian random variables (respectively) in Monte-Carlo error propagations (Anderson 1976). Some uncertainties are correlated (see text). References: Asteroids—Kerridge (1985). Comets—Delsemme (1988), Jessberger *et al.* (1988), Balsiger *et al.* (1995), Eberhardt *et al.* (1995), Bockelée-Morvan *et al.* (1998), Meier *et al.* (1998). Early Earth—Kerridge (1985), Deloule *et al.* (1991). Present Earth—Kyser and O'Neil (1984), Bell and Rossman (1992), Lécuyer *et al.* (1998).

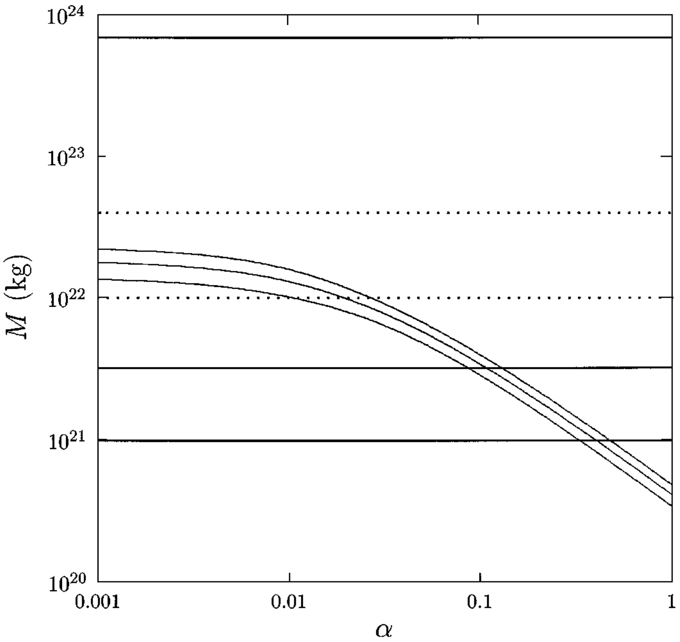

FIG. 1. Mass of asteroids and comets incident on Earth since the time of its accretion (M) as a function of the mass fraction of comets among impacting bodies (α). Light curves are based on water deuterium to protium ratios (uncertainties are depicted as 1σ and were propagated by means of Monte-Carlo simulations; Anderson 1976), heavy lines are derived from the lunar impact record (9.9×10^{20}, 3.2×10^{21}, and 6.9×10^{23} kg; Chyba 1990), and dotted lines are based on terrestrial mantle siderophiles (1×10^{22}–4×10^{22} kg; Chyba 1991).

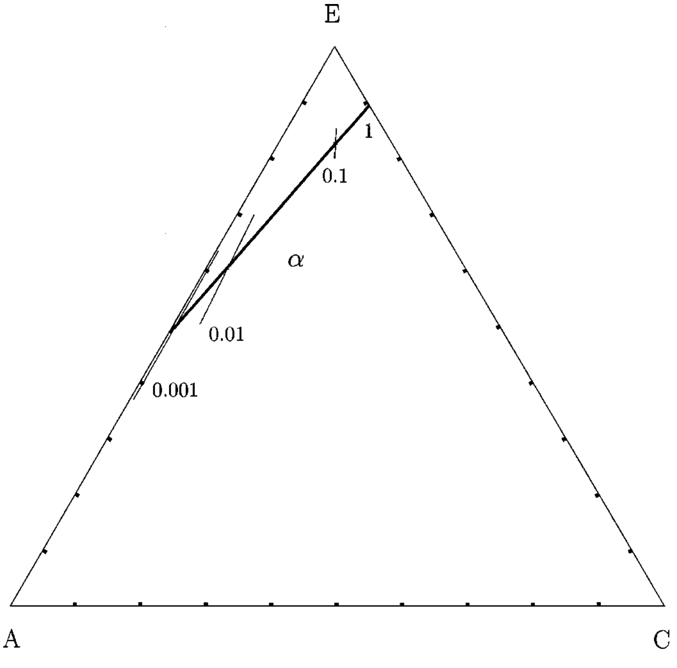

FIG. 2. Contributions of asteroids, comets, and the early Earth (ACE) to Earth's water inventory as a function of the mass fraction of comets among impacting bodies (α). Under the closure condition $x + y + z = 1$, x, y, and z are conveniently represented in an equilateral triangle. Uncertainties are depicted as 1σ and were propagated by means of Monte-Carlo simulations (Anderson 1976).

lunar impact record (9.9×10^{20}, 3.2×10^{21}, and 6.9×10^{23} kg; Chyba 1990) and terrestrial mantle siderophiles (1×10^{22}–4×10^{22} kg; Chyba 1991). As discussed previously, there is strong evidence that the late accreting veneer consisted of organic rich matter. In such a case, the combined use of water D/H ratios, the lunar impact record, and terrestrial mantle siderophiles would favor a rather low mass fraction of comets among impacting bodies ($\lesssim$0.01). Asteroids, comets, and early Earth contributed to 0–0.5, 0–0.1, and 0.5–0.9 of Earth's water inventory, respectively (Fig. 2).

6. THE CASE OF RARE GASES

The concentrations and isotopic compositions of rare gases ranging in mass from neon to xenon integrate all events the terrestrial atmosphere suffered, which makes these elements very important when addressing the origin of Earth's volatiles. We shall focus our discussion on neon and xenon because these elements play a peculiar role in geochemistry. Indeed, the near solar (Benkert *et al.* 1993) neon isotopic composition of the mantle (Honda *et al.* 1991) is different from that of the atmosphere (Ozima and Podosek 1983), and the xenon isotopic composition of air (Ozima and Podosek 1983) is fractionated by 0.03 per amu (atomic mass unit) relative to solar and meteoritic xenon (Pepin and Phinney, unpublished preprint, 1978).

Mazor *et al.* (1970) measured rare gas concentrations in some carbonaceous chondrites. The mean ^{20}Ne concentrations of CI and CM are $1.6 \pm 0.2 \times 10^{-11}$ and $2.5 \pm 0.9 \times 10^{-11}$ mol g^{-1}, respectively. The mean ^{130}Xe concentrations of CI and CM are $5.0 \pm 0.7 \times 10^{-14}$ and $3.0 \pm 0.5 \times 10^{-14}$ mol g^{-1}, respectively. Cometary rare gas isotopic compositions and concentrations are not known (Krasnopolsky *et al.* 1997) but by laboratory experiments aimed at reproducing the poorly known conditions that prevailed when water ice formed (Bar-Nun and Owen 1998). The present-day atmosphere contains 2.91×10^{15} mol of ^{20}Ne and 6.26×10^{11} mol of ^{130}Xe (Ozima and Podosek 1983).

If the late accreting veneer consisted of asteroids similar to carbonaceous chondrites only ($\alpha = 0$), then the amount of ^{20}Ne brought to Earth (ca. 4×10^{14} mol) would have been much lower than the global ^{20}Ne inventory at the surface of our planet (2.91×10^{15} mol). It implies that the gross isotopic disequilibrium of neon isotopes between the mantle and the atmosphere would not result from such late addition of carbonaceous material. Consequently, such an isotopic disequilibrium would have to predate these impacting events, a possibility in agreement with models calling for isotopic fractionation of neon isotopes during early atmospheric escape to space (Hunten *et al.* 1987, Zahnle *et al.* 1990, Pepin 1991, Ozima and Zahnle 1993, Tolstikhin and Marty 1998). The isotopic composition of xenon sets another important constraint on processes and sources having contributed atmospheric rare gases. Indeed, the 0.03 per amu mass fractionation observed in the present-day atmosphere relative to the Sun or meteorites cannot be the result of the contribution of a meteoritic or a solar component. The origin of such a fractionation is unclear, but could result as well as from escape of a primitive atmosphere (Hunten *et al.* 1987, Sasaki and Nakazawa 1988, Pepin 1991, Tolstikhin and Marty 1998). The amount of ^{130}Xe contributed by impacting bodies is ca. 8×10^{11} mol, roughly similar to that present in the atmosphere (6.26×10^{11} mol). Although the contrast is less evident than for neon, it still allows the possibility that xenon isotope fractionation predated the extraterrestrial contribution considered in this model. If the late veneer comprised comets ($\alpha > 0$), then one cannot discuss further the origin of terrestrial rare gases.

7. CONCLUSIONS

Based on water deuterium to protium ratios, the mass of asteroids and comets incident on Earth since the time of its accretion is estimated to be 4×10^{20}–2×10^{22} kg. The mass fraction of comets among impacting bodies might have been lower than $\sim$0.01. Asteroids, comets, and early Earth contributed to 0–0.5, 0–0.1, and 0.5–0.9 of Earth's water inventory, respectively. A two-stage model is advocated in which escape to space of terrestrial volatiles predated the late accretion of extraterrestrial gases. We wish to emphasize that our interpretations and conclusions might evolve in the future when additional data on asteroids, comets, and Earth's interior become available.

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