A hybrid origin for the Martian atmosphere

K. Pahlevan, L. Schaefer, D. Porcelli

Supplementary Information

The Supplementary Information includes:

- Enhancement of Nebular Capture
- Energetics, Mechanisms, and Extent of Mixing
- Fractionation via Hydrodynamic Escape
- Magnitude of Impact Erosion
- Supplementary Tables S-1 and S-2
- Data Availability Statement
- Supplementary Information References

Enhancement of Nebular Capture

Pure nebular captured atmospheres

The structure of a planetary atmosphere in hydrostatic equilibrium and thermal steady state with a gas disk is related to the planetary luminosity and the temperature (T_H) and density (ρ_H) of the gas disk in which it is embedded (Hayashi *et al.*, 1979). For nebular conditions at the radial distance of Mars, we adopt $T_H = 200\ K$ and $\rho_H = 5 \cdot 10^{-10} g\ cm^{-3}$ (Hayashi, 1981). We take the outer boundary of the atmosphere where the hydrostatic structure continuously connects to the solar nebula as the Hill radius, $R_H [\equiv a \cdot (M_p/3M_*)^{1/3}]$, with a the semi-major axis of the planetary orbit, M_p the planetary mass, and M_* the stellar mass. R_H for Mars is ≈320 planetary radii. We note that different model assumptions are possible (e.g., outer boundary at $R_H/4$) (Chambers, 2017) but that choice of outer boundary condition has only a minor effect on calculated densities lower in the atmosphere where most of the mass resides (Piso and Youdin, 2014).

The mass of the nebular-captured atmosphere is calculated using the minimum of the Hill radius and the Bondi radius $R_B [\equiv G M_p \bar{\mu}/k_B T_H]$ (Ikoma and Genda, 2006) with G the universal gravitational constant, $\bar{\mu}$ the mean molecular weight of the atmosphere (=2.4 amu for a H_2-He-rich nebular gas), and k_B Boltzmann's constant. For nebular capture onto Mars, the Bondi radius is smaller than the Hill radius by about an order of magnitude. Hence, even though the Hill sphere is the outer boundary where hydrostatic equilibrium with the solar nebula is assumed, captured atmospheric masses are calculated by considering only the mass inside the Bondi radius.

To calculate vertical temperature and density structure, we consider compositionally uniform two-layer atmospheres in which the lower layer is convective and the upper layer is radiative. At the bottom of the atmosphere, we consider heat input via gravitational energy release due to planetesimal accretion:

$$L_{in} = \frac{G M_p \dot{M}_p}{R_p} \quad \text{(Eq. S-1)}$$

with M_p and R_p the planetary mass and radius, and $\dot{M}_p$ the mass accretion rate, which we take to be 0.01-1 Mars mass/Myr. ^{26}Al heating may also be relevant for early Mars but can be modelled using this range of accretion rates. In quasi-steady state, this heat input is balanced by radiative heat losses at the radiative-convective boundary of the surrounding atmosphere (Ginzburg *et al.*, 2016):

$$L_{out} = \frac{64\pi\sigma_{SB}T_{rcb}^4 R_B'}{3\kappa_{rcb}\rho_{rcb}} \quad \text{(Eq. S-2)}$$

with σ_{SB} the Stefan-Boltzmann constant, T_{rcb} the temperature at the radiative-convective boundary, which is the same as the nebular temperature to within a factor of order unity (Piso and Youdin, 2014), κ_{rcb} and ρ_{rcb} the opacity and density at the radiative-convective boundary, and R_B' the modified Bondi radius:

$$R_B' = \frac{\gamma-1}{\gamma}\frac{GM_p\bar{\mu}}{k_B T_H} \quad \text{(Eq. S-3)}$$

with γ the adiabatic index, for which we adopt a value appropriate for diatomic molecules (7/5) (Kittel and Kroemer, 1998). For our analysis, we make the approximation that $T_{rcb} = T_H$. To solve for the atmospheric structure, a prescription for the upper atmospheric opacity near the radiative-convective boundary is needed. We assume atmospheric opacity is dominated by dust with a size-distribution like that of the interstellar medium (Bell and Lin, 1994):

$$\kappa = 2 \cdot \left(\frac{T}{100\ K}\right)^2\ cm^2 g^{-1} \quad \text{(Eq. S-4)}$$

With these equations, it is possible to solve for the density at the radiative-convective boundary (ρ_{rcb}) as a function of the planetesimal accretion rate ($\dot{M}_p$), which is one of the parameters that determines the total mass of captured gas. For conditions typical of the radiative-convective boundary (ρ_{rcb}~$10^{-8} g\ cm^{-3}$,T_{rcb}~$200\ K$, P_{rcb}~$0.2\ millibars$), the opacity is dominated by the dust, with molecular lines and collision-induced absorption of H_2 contributing several orders of magnitude lower opacity, as evident in e.g., Figure 1 of (Lee *et al.*, 2014). Although opacity in deeper layers can be dominated by pressure-broadened gas absorption, the entropy of the adiabat is determined by conditions in the upper atmosphere where dust opacity dominates. In addition, we solve for the radial distance of the radiative-convective boundary (R_{rcb}). Approximating the radiative layer above the radiative-convective boundary as an isothermal layer in hydrostatic equilibrium to the Hill sphere, we obtain:

$$\frac{R_{rcb}}{R_B} = [\ln\left(\frac{\rho_{rcb}}{\rho_H}\right) + \frac{R_B}{R_H}]^{-1} \quad \text{(Eq. S-5)}$$

With these parameters, we solve for the radius of the radiative-convective boundary (R_{rcb}) as a function of the density at that location (ρ_{rcb}). Because atmospheric mass in the radiative layer is negligible due to the exponentially decreasing density in that region (Piso and Youdin, 2014), the total mass of the nebular captured atmosphere can be expressed by integrating the density structure of the lower adiabatic convective layer (Ginzburg *et al.*, 2016):

$$M_H = \left(\frac{5\pi^2}{4}\right) R_{rcb}^3\rho_{rcb}\left(\frac{R_B'}{R_{rcb}}\right)^{\frac{1}{\gamma-1}} \quad \text{(Eq. S-6)}$$

Fully-mixed hybrid atmospheres

A fully-mixed hybrid atmosphere is one in which the outgassed components (e.g., CO_2) and the nebular captured gases are present in uniform proportions throughout the Hill sphere. A fully-mixed state describes the maximum enhancement of the nebular captured gaseous inventory and is therefore a useful and easily calculable end-member state. Identical expressions for the incoming luminosity (L_{in}), outgoing luminosity (L_{out}), and modified Bondi sphere (R_B') (Eq. S-1, S-2, and S-3) can be used. An important difference is that the mean molecular weight within the Hill sphere is no longer equal to that of the surrounding nebular environment but is given by the proportion of outgassed and nebular captured components:

$$\bar{\mu} = x_H\mu_H + (1-x_H)\mu_{CO2} \quad \text{(Eq. S-7)}$$

where x_H represents the mole fraction of gas species that derive from the nebular component, with μ_H and μ_{CO2} equal 2.4 and 44 amu, respectively. Two other adjustments to the capture model must be made to accommodate uniform mixing with an outgassed heavy gas component. First, the opacity law we have adopted (Eq. S-4) is appropriate to dust-dominated opacity, which may be the case for the nebular captured component but not the outgassed component, which is thought to be exsolved from a magma ocean and is assumed to be dust-free. Accordingly, we assume that the opacity of the mixture is dominated by the opacity of dust in the nebular component, and adopt an expression for a lower opacity relative to a pure nebular atmosphere:

$$\kappa = 2 \cdot \left(\frac{T}{100\ K}\right)^2 \cdot x_H \cdot \left(\frac{\mu_H}{\bar{\mu}}\right)\ cm^2 g^{-1} \quad \text{(Eq. S-8)}$$

The procedure for calculating fully-mixed hybrid atmosphere solutions is to take the mole fraction of the nebular component (x_H) as an independent variable and select a value, which in practice is in the range 0.5-1. With the composition of the hybrid mixture specified, Equations S-1 to S-3, S-7, and S-8 can be used to solve for the density at the radiative-convective boundary (ρ_{rcb}). As with the pure nebular case, the mass of the atmosphere is dominated by the mass in the convective layer. Accordingly, the radius of the radiative-convective boundary must be specified to calculate captured gas masses. A fully-mixed hybrid atmosphere is distinct from the pure nebular atmosphere because it hosts a compositional boundary at the Hill radius between the hybrid mixture and the nebular-composition gas. Hence, a relationship between the conditions across the compositional boundary must be specified. Hydrostatic equilibrium and thermal steady-state requires that pressure and temperature be continuous across the compositional boundary. For ideal gases, these requirements translate to a relationship between the density of the hybrid atmosphere approaching the Hill sphere (ρ_{out}) and that of the external nebula (ρ_H):

$$\rho_{out} = \rho_H \cdot \frac{\mu_H}{\bar{\mu}} \quad \text{(Eq. S-9)}$$

The radius of the radiative-convective boundary (R_{rcb}) can then be expressed by an equation analogous to Eq. S-5:

$$\frac{R_{rcb}}{R_B} = \left[\ln\left(\frac{\rho_{rcb}}{\rho_{out}}\right) + \frac{R_B}{R_H}\right]^{-1} \quad \text{(Eq. S-10)}$$

Because the mass in the low density radiative layer is expected to be negligible (Piso and Youdin, 2014), the mass of both the nebular captured gas and the outgassed inventory can be expressed by integrating the density structure across the dense adiabatic convective layer (Ginzburg *et al.*, 2016) and multiplying by the mass fraction deriving from the nebular and outgassed components, respectively:

$$M_H = x_H \cdot \left(\frac{\mu_H}{\bar{\mu}}\right) \cdot \left(\frac{5\pi^2}{4}\right) R_{rcb}^3 \rho_{rcb} \left(\frac{R_B'}{R_{rcb}}\right)^{\frac{1}{\gamma-1}} \quad \text{(Eq. S-11)}$$

$$M_{CO2} = (1 - x_H) \cdot \left(\frac{\mu_{CO2}}{\bar{\mu}}\right) \cdot \left(\frac{5\pi^2}{4}\right) R_{rcb}^3 \rho_{rcb} \left(\frac{R_B'}{R_{rcb}}\right)^{\frac{1}{\gamma-1}} \quad \text{(Eq. S-12)}$$

Energetics, Mechanisms, and Extent of Mixing

Mixing a stably-stratified fluid with a high-density deep outgassed layer and low-density shallow nebular component – as envisioned in e.g., (Saito and Kuramoto, 2018) – into a fully-mixed structure considered in this work requires an energy source and a fluid dynamical mechanism to channel that energy into mixing. We briefly discuss these considerations in turn. Towards the end of Martian accretion ($M_p \approx M_{Mars}$) the compositional boundary in a stratified atmosphere between an outgassed layer and a nebular layer is ≈1-2 planetary radii, depending on the outgassed volatile inventory. By contrast, in the fully-mixed hybrid atmospheres we calculate in Figure 1, the radius of the radiative-convective boundary (R_{rcb}), where most of the atmospheric mass resides, is ≈8.4-46.5 planetary radii. Mixing a heavy outgassed component therefore requires nearly as much energy as complete removal of this component from the planetary potential well. To within a factor of about two, the energy required to uniformly mix an outgassed heavy component into a hybrid atmosphere is:

$$W_{grav} \cong \frac{GM_p M_{CO2}}{R_p} \quad \text{(Eq. S-13)}$$

with W_{grav} the work done in lifting the heavy gas into the fully-mixed state. Because the mass of the outgassed inventory is always much less than the planetary mass for terrestrial planets, and because this mixing occurs in the context of accretionary energy budgets of order GM_p^2/R_p, it is clear that the energy for mixing was present during accretion. A uniform composition hybrid atmosphere requires a fluid dynamical mechanism to channel ≈10^{-4} of the accretional energy into mixing. Although dust-free layered atmospheric models sometimes place the compositional boundary above the convective region and predict little convective mixing (Saito and Kuramoto, 2018), dusty nebular atmospheres are more opaque and more likely to host an initial compositional boundary within the convective region. Because all gases are miscible, this picture of convective mixing is analogous to the problem of core erosion in the giant planets, where more dramatic heavy element redistribution scenarios have been considered (Stevenson, 1982). How much convective mixing actually takes place is difficult to predict from first principles. We suggest that the cosmochemical record (Fig. 2) can be used to empirically determine the degree of mixing on Mars.

A constraint on the extent of mixing in the accretionary Mars system is the apparent preservation of chondritic mantle volatiles in the presence of nebular contributions to the atmosphere. The persistence of the mantle-atmosphere volatile dichotomy may indicate one of several possible histories. First, it is possible that significant portions of silicate Mars may have already solidified at the time of the nebular capture, effectively isolating chondritic mantle volatiles from mixing with the captured atmosphere. Secondly, although we have considered fully-mixed hybrid atmospheres for the calculations of nebular capture, it is possible that the compositional gradient in the accretionary atmosphere was smooth, with a CO_2-dominated lower atmosphere gradually transitioning to an H_2-dominated upper atmosphere, effectively sealing off the silicate planet from nebular additions. Finally, it is possible that there once was complete homogenisation of the silicate-atmosphere hybrid volatile system on Mars, and that the chondritic character observed in the Martian mantle is the overprint of chondritic volatiles delivered during late accretion after the solidification and effective isolation of silicate Mars. At present, we have no way to clarify these scenarios other than to state that the persistence of the mantle-atmosphere dichotomy places constraints on the sequence of volatile acquisition, mixing, and isolation in the accretionary Mars system.

Fractionation via Hydrodynamic Escape

The current $^{36}Ar/^{84}Kr$ ratio in the Martian atmosphere is lower than that of a hybrid mixture by a factor of ≈50 (Fig. 3). To illustrate the capacity of extreme-ultraviolet (EUV) powered hydrodynamic escape of a primordial volatile inventory to generate large depletions in argon with only modest isotopic fractionation, we consider a simple model in which multiple major species are present (Zahnle *et al.*, 1990; Zahnle and Kasting, 2023). We arbitrarily define "major" species as those with mole fractions greater than 10%, and adopt a two-component (H_2-CO_2) model, neglecting a possible role for CO, CH_4, N_2, and He, which we assume would be present in minor abundances. After the crystallisation of the magma ocean, H_2O would condense in the lower atmosphere (Pahlevan *et al.*, 2022) such that water vapor is not expected to play a role in the loss processes of interest. Two-component hydrodynamic escape can be described with an equation of energy balance:

$$\phi_1 m_1 + \phi_2 m_2 = \frac{1}{4}\eta_{eff} S_{euv} \frac{R_p}{GM_p} \quad \text{(Eq. S-14)}$$

with ϕ_i [cm^{-2} s^{-1}] the number flux of component i out of the atmosphere, $m_1 (= 2\ amu)$ and $m_2 (= 44\ amu)$ the atomic mass of the two major constituents, η_{eff} the efficiency factor, which is a parameter (0-1) that represents the fraction of incoming EUV energy that is channelled into mass-loss, S_{euv} [erg cm^{-2} s^{-1}] is the EUV flux of the young Sun at the top of the atmosphere, and the factor of 4 reflects a spherical average. η_{eff} embodies all uncertainties of the energy budget into one parameter. According to (Zahnle and Kasting, 2023), S_{euv} is 133 erg cm^{-2} s^{-1} at Mars's heliocentric distance for the first few tens of millions of years of Solar System history. For these calculations, we adopt this value as a constant.

Solving for the two fluxes requires one additional constraint. Above the homopause, molecular diffusion exceeds eddy diffusion – by definition – such that the different species can partially separate via diffusion and assume different scale heights. In hydrostatic atmospheres, this separation populates the upper atmosphere in lighter species allowing for mass-fractionation accompanying non-thermal escape processes (Jakosky *et al.*, 2017). Such diffusive separation by mass also occurs in hydrodynamic outflows. One way to make the problem tractable is to assume an isothermal outflow, for which one can write the approximate relation (Zahnle and Kasting, 2023):

$$\phi_1\left(1+\frac{x_2}{x_1}\right)-\phi_2\left(1+\frac{x_1}{x_2}\right)=\frac{g(m_2-m_1)b_{12}}{k_BT} \quad \text{(Eq. S-15)}$$

with x_1 and x_2 the mole fraction of the 1st and 2nd component, g the gravitational acceleration, b_{12} [cm^{-1} s^{-1}] the binary diffusion coefficient of the gas pair, k_B Boltzmann's constant, and T the temperature of the escaping region. For concreteness, we adopt $T = 1{,}000\ K$ for all escape calculations. Binary diffusion coefficients measure the ease with which one gas diffuses through another. The values for binary diffusion coefficients for all gas pairs used in this work are listed in Table S-2. With Eq. S-14 and S-15, we can solve for the flux of H_2 (ϕ_1) and CO_2 (ϕ_2) as a function of the hydrodynamic escape efficiency parameter η_{eff}.

With fluxes of major species specified, the passive response of noble gases as witnesses of events can be described. For an increasingly vigorous outflow, increasingly massive gaseous species can be accelerated to space via frequent collisions with the outgoing gases. The outgoing flux (ϕ_j) of a trace species with given atomic mass (m_j) and mole fraction (x_j) can, in the isothermal approximation, be written (Zahnle and Kasting, 2023):

$$\frac{\phi_j}{x_j}\left(\frac{x_1}{b_{1j}}+\frac{x_2}{b_{2j}}\right)=\frac{g(m_2-m_j)}{k_BT}+\frac{\phi_2}{x_2}\left(\frac{x_1}{b_{12}}+\frac{x_2}{b_{2j}}\right)+\frac{\phi_1}{x_1}\left(\frac{x_1}{b_{1j}}-\frac{x_2}{b_{12}}\right) \quad \text{(Eq. S-16)}$$

To calculate isotopic fractionation, an equation like Eq. S-16 is written for each of the isotopic species, keeping in mind that in some cases the binary diffusion coefficient of two gases noticeably changes upon isotopic substitution (Table S-2). The fractionation factor (α) is the ratio of the ($^{36}Ar/^{38}Ar$) of the outflowing gas relative to that of the atmosphere from which it is sourced:

$$\alpha=\frac{(\phi_{36\mathrm{Ar}}/x_{36Ar})}{(\phi_{38\mathrm{Ar}}/x_{38Ar})} \quad \text{(Eq. S-17)}$$

With an expression for the fractionation factor (α), the evolution of the Martian atmosphere $^{36}Ar/^{38}Ar$ ratio (R_{final}) as a function of the initial ratio ($\mathrm{R}_{initial}$) and the fraction of ^{36}Ar remaining (F) at the conclusion of the hydrodynamic episode can be related with the Rayleigh fractionation formula:

$$\mathrm{R}_{final}=\mathrm{R}_{initial}F^{\alpha-1} \quad \text{(Eq. S-18)}$$

In the case of Kr, no mass-dependent fractionation is detectable in the Martian atmosphere (Pepin, 1991). The hybrid mixture model requires that Mars preserve its nebular heritage by experiencing negligible mass-selective Kr escape for the duration of the hydrodynamic episode. In the context of the adopted two-component (H_2-CO_2) model, this leads to the requirement that the escape fluxes (ϕ_1, ϕ_2) remain below their critical values for Kr entrainment. The critical fluxes can be expressed by setting ϕ_j=0 in Eq. S-16. The corresponding joint constraint on $\phi_1$and ϕ_2 can be used, in concert with Eq. S-14 and S-15, to define the conditions for the onset of Kr escape. Importantly, there is a range of outgoing fluxes sufficiently low as to retain Kr while sufficiently high to lose ^{36}Ar and ^{38}Ar indiscriminately enough to be consistent with the observations (Fig. 4). We propose these fluxes characterise losses from the hybrid atmosphere.

Finally, because the diffusion properties of Kr and Xe are similar, Kr retention also implies Xe retention. Hence, the Xe loss required to reproduce the Kr/Xe ratio (Fig. 3) and Xe isotopic mass-fractionation in the Martian atmosphere must be due to another process. By measurement of trapped atmospheric gases in Martian meteorites, it has recently been inferred that the isotopic evolution of Martian Xe took place over hundreds of millions of years (Cassata *et al.*, 2022). As on the Earth, where Xe isotopic evolution apparently persisted for two gigayears (Avice *et al.*, 2018), the Xe loss process may have involved ionisation (Zahnle *et al.*, 2019). If so, the xenon loss may have been decoupled from the hydrodynamic loss episode of the hybrid Martian atmosphere as neutral atoms and molecules calculated here.

Magnitude of Impact Erosion

A solar-like krypton isotopic composition of the Martian atmosphere argues against substantial mass-selective loss of krypton. Given that krypton escape from present-day Mars is thought to be negligible (Kurokawa *et al.*, 2021), and that the hydrodynamic escape episode we have proposed for massive argon loss would have excluded krypton, the question arises as to what process could have depleted the krypton inventory from its massive initial endowment down to its observed abundance in the rarefied Martian atmosphere. The only known loss process capable of eliminating atmospheric gases indiscriminately with respect to mass is impact erosion (Melosh and Vickery, 1989; Zahnle, 1993; Brain and Jakosky, 1998; Shorttle *et al.*, 2024), a type of hydrodynamic outflow that occurs on dynamical timescales. If the acquisition of solar-like krypton was due to Martian capture via mixing in a solar nebula component, as we propose, then the initial krypton inventory can be used to place constraints on the magnitude of impact erosion in sculpting the Martian atmospheric inventory over its entire history. As an example, we consider a nebular capture scenario in which Mars acquires 1.2×10^{20} kg of solar-composition gas, equivalent to 30 bars of a H_2-He-rich atmosphere at the Martian surface (Fig. 1). A solar composition gas is composed of 80 parts per billion by weight (ppbw) krypton (Lodders, 2003), corresponding to a primordial krypton inventory of 9.6×10^{12} kg, to be compared with the present-day krypton inventory of 1.5×10^{10} kg. This comparison suggests that non-fractionating impact erosion must have drawn down the Martian atmospheric volatile inventory by nearly three orders of magnitude, a conclusion regarding early losses previously reached using independent arguments (Zahnle, 1993; Marty and Marti, 2002).

Supplementary Tables

Table S-1 Adopted elemental abundances in relevant cosmochemical reservoirs

Element	H chondrite[1,2]	EH chondrite[1,2]	Chondritic mixture[3] (55% H 45% EH)	Solar[4]	Martian atmosphere[5,6]
H	0.000459	0.001309	0.0008415	1E12	16.2
C	0.0001	0.000342	0.0002088	2.88E8	0.16
N	2.43E-6	0.00004	1.934E-05	7.94E7	8.8E-3
Ne	1.00E-11	3.80E-12	7.210E-12	8.91E7	6.3E-7
Ar	1.11E-12	1.63E-11	7.961E-12	4.17E6	1.9E-6
Kr	2.14E-13	2.50E-13	2.304E-13	2.29E3	6.1E-8
Xe	3.82E-14	6.11E-13	2.958E-13	2.24E2	6.8E-9

[1] H, C, N (Schaefer and Fegley, 2017)
[2] Ne, Ar, Kr, Xe (Schultz *et al.*, 1991; Patzer and Schultz, 2002)
[3] Chondritic mixture model for Mars (Sanloup *et al.*, 1999)
[4] Corrected for heavy element settling in the Sun (Lodders, 2003)
[5] H from a ≈500 m global equivalent layer (GEL) of water (Di Achille and Hynek, 2010)
[6] C, N, Ne, Ar, Kr, Xe from (Halliday, 2013)

Table S-2 Binary diffusion coefficients for hydrodynamic escape model

Gas pair	b (cm^{-1} s^{-1})	Source or scaling
H_2-CO_2	4.1×10^{19} $(T/1000)^{0.75}$	(Zahnle and Kasting, 1986)
^{36}Ar-H_2	5.0×10^{19} $(T/1000)^{0.75}$	(Zahnle and Kasting, 1986)
^{38}Ar-H_2	5.0×10^{19} $(T/1000)^{0.75}$	Scaled from ^{36}Ar-H_2
^{84}Kr-H_2	4.4×10^{19} $(T/1000)^{0.76}$	(Zahnle and Kasting, 1986)
^{36}Ar-CO_2	$1 \times 10^{19}(T/1000)^{0.75}$	(Zahnle and Kasting, 2023)
^{38}Ar-CO_2	$0.985 \times 10^{19}(T/1000)^{0.75}$	Scaled from ^{36}Ar-CO_2
^{84}Kr-CO_2	$0.78 \times 10^{19}(T/1000)^{0.75}$	Scaled from ^{36}Ar-CO_2[1]

[1] Scaling across elements requires kinetic diameters.: Ar: 340 pm; Kr: 360 pm; CO_2: 330 pm

Data Availability Statement

All data and code necessary to conduct the calculations and to produce the results displayed in Figures 1-4 have been released to Zenodo (Pahlevan *et al.*, 2025).

Supplementary Information References

Avice, G., Marty, B., Burgess, R., Hofmann, A., Philippot, P., Zahnle, K., Zakharov, D. (2018) Evolution of atmospheric xenon and other noble gases inferred from Archean to Paleoproterozoic rocks. *Geochimica et Cosmochimica Acta* 232, 82-100. https://doi.org/10.1016/j.gca.2018.04.018
Bell, K., Lin, D. (1994) Using FU Orionis outbursts to constrain self-regulated protostellar disk models. *Astrophysical Journal* 427, 987-1004. https://doi.org/10.1086/174206
Brain, D.A., Jakosky, B.M. (1998) Atmospheric loss since the onset of the Martian geologic record: Combined role of impact erosion and sputtering. *Journal of Geophysical Research: Planets* 103, 22689-22694. https://doi.org/10.1029/98JE02074
Cassata, W.S., Zahnle, K.J., Samperton, K.M., Stephenson, P.C., Wimpenny, J. (2022) Xenon isotope constraints on ancient Martian atmospheric escape. *Earth and Planetary Science Letters* 580, 117349. https://doi.org/10.1016/j.epsl.2021.117349
Chambers, J. (2017) Steamworlds: atmospheric structure and critical mass of planets accreting icy pebbles. *The Astrophysical Journal* 849, 30. https://doi.org/10.3847/1538-4357/aa91d0
Di Achille, G., Hynek, B.M. (2010) Ancient ocean on Mars supported by global distribution of deltas and valleys. *Nature Geoscience* 3, 459. https://doi.org/10.1038/ngeo891
Ginzburg, S., Schlichting, H.E., Sari, R.E. (2016) Super-Earth Atmospheres: Self-consistent Gas Accretion and Retention. *The Astrophysical Journal* 825, 29. https://doi.org/10.3847/0004-637X/825/1/29
Halliday, A.N. (2013) The origins of volatiles in the terrestrial planets. *Geochimica et Cosmochimica Acta* 105, 146-171. https://doi.org/10.1016/j.gca.2012.11.015
Hayashi, C. (1981) Structure of the solar nebula, growth and decay of magnetic fields and effects of magnetic and turbulent viscosities on the nebula. *Progress of Theoretical Physics Supplement* 70, 35-53. https://doi.org/10.1143/PTPS.70.35
Hayashi, C., Nakazawa, K., Mizuno, H. (1979) Earth's melting due to the blanketing effect of the primordial dense atmosphere. *Earth and Planetary Science Letters* 43, 22-28. https://doi.org/10.1016/0012-821X(79)90152-3
Ikoma, M., Genda, H. (2006) Constraints on the Mass of a Habitable Planet with Water of Nebular Origin. *The Astrophysical Journal* 648, 696. https://doi.org/10.1086/505780
Jakosky, B.M., Slipski, M., Benna, M., Mahaffy, P., Elrod, M., Yelle, R., Stone, S., Alsaeed, N. (2017) Mars' atmospheric history derived from upper-atmosphere measurements of 38Ar/36Ar. *Science* 355, 1408-1410. https://doi.org/10.1126/science.aai7721
Kittel, C., Kroemer, H. (1998) Thermal physics. American Association of Physics Teachers. https://doi.org/10.1119/1.19072
Kurokawa, H., Miura, Y.N., Sugita, S., Cho, Y., Leblanc, F., Terada, N., Nakagawa, H. (2021) Mars' atmospheric neon suggests volatile-rich primitive mantle. *Icarus* 370, 114685. https://doi.org/10.1016/j.icarus.2021.114685
Lee, E.J., Chiang, E., Ormel, C.W. (2014) Make super-Earths, not Jupiters: Accreting nebular gas onto solid cores at 0.1 AU and beyond. *The Astrophysical Journal* 797, 95. https://doi.org/10.1088/0004-637X/797/2/95
Lodders, K. (2003) Solar system abundances and condensation temperatures of the elements. *The Astrophysical Journal* 591, 1220. https://doi.org/10.1086/375492
Marty, B., Marti, K. (2002) Signatures of early differentiation of Mars. *Earth and Planetary Science Letters* 196, 251-263. https://doi.org/10.1016/S0012-821X(01)00612-4
Melosh, H.J., Vickery, A.M. (1989) Impact erosion of the primordial atmosphere of Mars. *Nature* 338, 487-489. https://doi.org/10.1038/338487a0
Pahlevan, K., Schaefer, L., Elkins-Tanton, L.T., Desch, S.J., Buseck, P.R. (2022) A primordial atmospheric origin of hydrospheric deuterium enrichment on Mars. *Earth and Planetary Science Letters* 595, 117772. https://doi.org/10.1016/j.epsl.2022.117772
Pahlevan, K., Schaefer, L., Porcelli, D. (2025) A hybrid origin for the Martian atmosphere. *Zenodo* 10.5281/zenodo.14947895.

Patzer, A., Schultz, L. (2002) Noble gases in enstatite chondrites II: The trapped component. *Meteoritics & Planetary Science* 37, 601-612. https://doi.org/10.1111/j.1945-5100.2002.tb00841.x
Pepin, R.O. (1991) On the origin and early evolution of terrestrial planet atmospheres and meteoritic volatiles. *Icarus* 92, 2-79. https://doi.org/10.1016/0019-1035(91)90036-S
Piso, A.-M.A., Youdin, A.N. (2014) On the Minimum Core Mass for Giant Planet Formation at Wide Separations. *The Astrophysical Journal* 786, 21. https://doi.org/10.1088/0004-637X/786/1/21
Saito, H., Kuramoto, K. (2018) Formation of a hybrid-type proto-atmosphere on Mars accreting in the solar nebula. *Monthly Notices of the Royal Astronomical Society* 475, 1274-1287. https://doi.org/10.1093/mnras/stx3176
Sanloup, C., Jambon, A., Gillet, P. (1999) A simple chondritic model of Mars. *Physics of the Earth and Planetary Interiors* 112, 43-54. https://doi.org/10.1016/S0031-9201(98)00175-7
Schaefer, L., Fegley, B. (2017) Redox States of Initial Atmospheres Outgassed on Rocky Planets and Planetesimals. *The Astrophysical Journal* 843, 120. https://doi.org/10.3847/1538-4357/aa784f
Schultz, L., Weber, H., Begemann, F. (1991) Noble gases in H-chondrites and potential differences between Antarctic and non-Antarctic meteorites. *Geochimica et Cosmochimica Acta* 55, 59-66. https://doi.org/10.1016/0016-7037(91)90399-P
Shorttle, O., Saeidfirozeh, H., Rimmer, P.B., Laitl, V., Kubelík, P., Petera, L., Ferus, M. (2024) Impact sculpting of the early martian atmosphere. *Science advances* 10, eadm9921. https://doi.org/10.1126/sciadv.adm9921
Stevenson, D.J. (1982) Formation of the giant planets. *Planetary and Space Science* 30, 755-764. https://doi.org/10.1016/0032-0633(82)90108-8
Zahnle, K., Kasting, J.F., Pollack, J.B. (1990) Mass fractionation of noble gases in diffusion-limited hydrodynamic hydrogen escape. *Icarus* 84, 502-527. https://doi.org/10.1016/0019-1035(90)90050-J
Zahnle, K.J. (1993) Xenological constraints on the impact erosion of the early Martian atmosphere. *Journal of Geophysical Research: Planets* 98, 10899-10913. https://doi.org/10.1029/92JE02941
Zahnle, K.J., Gacesa, M., Catling, D.C. (2019) Strange messenger: A new history of hydrogen on Earth, as told by Xenon. *Geochimica et Cosmochimica Acta* 244, 56-85. https://doi.org/10.1016/j.gca.2018.09.017
Zahnle, K.J., Kasting, J.F. (1986) Mass fractionation during transonic escape and implications for loss of water from Mars and Venus. *Icarus* 68, 462-480. https://doi.org/10.1016/0019-1035(86)90051-5
Zahnle, K.J., Kasting, J.F. (2023) Elemental and isotopic fractionation as fossils of water escape from Venus. *Geochimica et Cosmochimica Acta* 361, 228-244. https://doi.org/10.1016/j.gca.2023.09.023