SOURCES OF VOLATILES TO EARTH

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Exoplanet discovery

In a press release on February 22, 2017, NASA announced the discovery of the most Earth-sized planets found in the habitable zone of a single star, called TRAPPIST-1. This system of seven rocky worlds—all of them with the potential for water on their surface—is an exciting discovery in the search for life on other worlds. There is the possibility that future study of this unique planetary system could reveal conditions suitable for life.

In February 2018, closer study of the seven planets suggested that some could harbor far more water than the oceans of Earth, in the form of atmospheric water vapor for the planets closest to their star, liquid water for others, and ice for those farthest away. The new study pinned down the density of each planet more precisely, making TRAPPIST-1 the most thoroughly known planetary system apart from our own.
Trappist-1 system

**TRAPPIST-1 System**

<table>
<thead>
<tr>
<th>Planet</th>
<th>Orbital Period</th>
<th>Distance to Star</th>
<th>Planet Radius</th>
<th>Planet Mass</th>
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<td>b</td>
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<td>1.09 $R_{\text{Earth}}$</td>
<td>0.85 $M_{\text{Earth}}$</td>
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**Solar System**

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<td>0.11 $M_{\text{Earth}}$</td>
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</table>
How to make a planet
molecular cloud Cepheus B – stellar nursery
Collapse of molecular cloud – settling of gas at midplane
Temperatures rises to ~2000 K

Don Dixon
Coalescence of dust grains
Growth of planetesimals (km size) $10^5$ years
Growth of planetary embryos (100 - >1000 km) – >10^6 years
Giant Impact (30 – 100 My)
Ice can be incorporated beyond the snow line
No volatiles (water) expected inside the snow line
What is the source of volatiles to Earth?
Sources and sinks considered

- Cometary addition
- Hydrodynamic escape
- Sequestration to core
- Chondrite addition
- Xe ionization
- Nebular ingassing
What is the source of volatiles for bodies within the ‘snow line’?

- Late accretion
Late Veneer (Accretion) – addition of chondritic material (80-130 Ma)
Late Accretion

**Pros**

• Source of HSE (Os, Ir, Ru, Rh, Pt, Pd, Re, Au) (0.5-1.0%)
• 1-2 % of carbonaceous chondrites needed for water
• D/H ratio of Earth and CM chondrites overlap

**Cons**

• $^{187}$Os/$^{188}$Os of Earth matches enstatite and ordinary chondrites, but not CM chondrites (Walker et al., 2002)
• Ru isotope ratios ($\varepsilon^{100}$Ru) of carbonaceous chondrites and Earth do not match (Fischer-Gödde et al. 2017)
• Xe/Kr ratios of Earth are very different from C chondrites
• Nitrogen isotopes do not match C chondrites
Ruthenium Isotopes

Fischer Gödde & Kleine (2017)
What is the source of water for bodies within the ‘snow line’?

• Late accretion?
• Comets?
Comets – rich in volatiles
Pros:

• High water content
• High $Xe/Kr$ composition of chondrites require another source - satisfied by comets

Cons:

• $D/H$ and $^{15}N/^{14}N$ ratios of most comets are too high – but not all.
• Some numeric simulations do not have a large cometary component.

Comets
What is the source of water for bodies within the ‘snow line’?

- Late veneer?
- Comets?
- Pebble accretion: ‘Pebbles’ sourced in the outer solar system were dragged into growing planetesimals during inward radial drift.
  - Brings in volatile rich material
  - Rapid planet formation
  - Requires nebula to be present
Pebble accretion trajectories

(a) geometric
$M_{pl} = 10^{-6}$
$\tau_s = 0.1$

(b) Safronov
$M_{pl} = 5 \times 10^{-3}$
$\tau_s = 0.1$

(c) settling
$M_{pl} = 0.05$
$\tau_s = 0.1$

(d) settling
$M_{pl} = 0.5$
$\tau_s = 0.1$

(e) gas-free
$M_{pl} = 0.5$
$\tau_s = \infty$

(f) deflection
$M_{pl} = 10^{-3}$
$\tau_s = 10^{-6}$

Reprinted from C.W. Ormel, 2017
What is the source of water for bodies within the ‘snow line’?

- Late veneer?
- Comets?
- Wet accretion: ‘Pebbles’ dragged into growing planetesimals during inward radial drift.
- Nebular Ingassing. Dissolution of solar nebula into a magma ocean?
Nebular ingassing:
Early in Solar System history, an $\text{H}_2$, He-rich nebular atmosphere would engulf the planets.
Ages of extant nebular disks

\[ f_{\text{disk}} = \exp\left(-\frac{t}{\tau_{\text{disk}}}\right) \]

\[ \tau_{\text{disk}} = 2.5 \text{ Myr} \]
Chondrules

Semarkona, ordinary chondrite
Ages of chondrules (form in presence of nebula)

Relative age after CAIs formation (Myr)

Dating based on $^{26}$Al decay -- $\lambda_{1/2} = 0.717$ My

Villeneuve et al. (2009)
Nebular atmosphere to magma ocean: A model for volatile capture during Earth accretion

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ABSTRACT

The origin and abundance of mantle volatiles present major questions for Earth's evolution. Here we quantify volatile capture from an atmosphere derived from the solar nebula during accretion, using a boundary layer model of magma ocean dynamics coupled to a nebular atmosphere model adapted to Earth formation. Key elements include (i) nebular atmosphere winds based on scaling laws for deep rotating fluids; (ii) water production at the magma surface; and (iii) gas transfer between magma and atmosphere based on the systematics of air-sea gas exchange by wind and diffusion. Provided the Earth accreted to 30% or more of its final mass in the presence of the solar nebula, the mantle is expected to have ingassed several ocean mass equivalents of water plus hydrogen, along with hundreds of petagrams of helium-3 and other light noble gases. In contrast to light gases, nebular ingassing does not provide the mantle with enough heavy noble gases to account for their present-day atmosphere abundances. Our model also predicts that thermal insulation by the nebular atmosphere led to very hot conditions in Earth's interior during accretion, with peak temperatures above 6000 K at the core-mantle boundary and possible dynamo conditions in the Early Hadean.
Peak Surface Temperature (K)

Solar Nebula Lifetime, Myr

Accretion Time, Myr
Ingassed $\text{H}_2$ & $\text{H}_2\text{O}$
-- ocean equivalents
Ingassed $^3\text{He}$

--exagrams $(10^{18} \text{ g})$
Our model for volatiles to Earth
1) Nebular Ingassing

Planet grows in presence of nebula. Magma ocean dissolves gases from dense atmosphere.
Nebula dissipates. Earth loses atmosphere, cools and exsolves dissolved gases. Loss by hydrodynamic escape.
3) Late addition

Cometary and chondritic material is added following planetary differentiation and Moon forming event.
4. Loss of Xe

Ionization of Xe in atmosphere leads to loss over Earth history
Simulation protocol
He, N, Ne, Ar, Kr, Xe

Nebular ingassing
- Composition is fixed
- *Vary amount by 0.01, 0.1, 1x*

Hydrodynamic escape
- Loss follows log loss vs. atomic mass
- Best fit to modern values

Late addition (comets and chondrites)
- Fit to Kr/Xe ratios
  - Variables: 1) comet composition
  - 2) chondrite composition (C vs E)
  - 3) Xe loss
Balance for Kr/Xe ratio of Earth:
Inputs: Ingassing, comets, chondrites
Loss: Xe ionization

\[ X_{\text{Xe-ing}} + x_{\text{chon}}C_{\text{Xe-chon}} + x_{\text{com}}C_{\text{Xe-com}} - X_{\text{Xe-loss}} = X_{\text{Xe-Earth}} \]

\[ X_{\text{Kr-ing}} + x_{\text{chon}}C_{\text{Kr-chon}} + x_{\text{com}}C_{\text{Kr-com}} = X_{\text{Kr-Earth}} \]
The solution!?

\[ X_{\text{He-ing}} - X_{\text{He-hydrodynamic escape}} + x_{\text{chon}} C_{\text{He-chon}} + x_{\text{com}} C_{\text{He-com}} = X_{\text{He-Earth}} \]

\[ X_{\text{N}_2\text{-ing}} - X_{\text{N}_2\text{-hydrodynamic escape}} + x_{\text{chon}} C_{\text{N}_2\text{-chon}} + x_{\text{com}} C_{\text{N}_2\text{-com}} = X_{\text{N}_2\text{-Earth}} \]

\[ X_{\text{Ne-ing}} - X_{\text{Ne-hydrodynamic escape}} + x_{\text{chon}} C_{\text{Ne-chon}} + x_{\text{com}} C_{\text{Ne-com}} = X_{\text{Ne-Earth}} \]

\[ X_{\text{Ar-ing}} - X_{\text{Ar-hydrodynamic escape}} + x_{\text{chon}} C_{\text{Ar-chon}} + x_{\text{com}} C_{\text{Ar-com}} = X_{\text{Ar-Earth}} \]

\[ X_{\text{Kr-ing}} - X_{\text{Kr-hydrodynamic escape}} + x_{\text{chon}} C_{\text{Kr-chon}} + x_{\text{com}} C_{\text{Kr-com}} = X_{\text{Kr-Earth}} \]

\[ X_{\text{Xe-ing}} - X_{\text{Xe-hydrodynamic escape}} + x_{\text{chon}} C_{\text{Xe-chon}} + x_{\text{com}} C_{\text{Xe-com}} - X_{\text{Xe-ionized}} = X_{\text{Ar-Earth}} \]
Volatile species (ingassing)

10% C, 90% E chondrite, 100% ingas, $5 \times 10^{11}$ g Xe lost
After hydrodynamic escape
With late addition

2.9 \times 10^{21} \text{ g comet}

3.63 \times 10^{25} \text{ g chondrite}
<table>
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<th>Meas/Exp</th>
<th>Loss</th>
<th>Inassing</th>
<th>S.E.</th>
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Results

**Notes:**
- Data is presented in a table format with columns for Chon, Meas/Exp, Loss, Inassing, S.E., and various measurements.
- The table includes numerical values for different parameters and measurements.
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Xenon isotopes in 67P/Churyumov-Gerasimenko show that comets contributed to Earth’s atmosphere


The origin of cometary matter and the potential contribution of comets to inner-planet atmospheres are long-standing problems. During a series of dedicated low-altitude orbits, the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) on the Rosetta spacecraft analyzed the isotopes of xenon in the coma of comet 67P/Churyumov-Gerasimenko. The xenon isotopic composition shows deficits in heavy xenon isotopes and matches that of a primordial atmospheric component. The present-day Earth atmosphere contains 22 ± 5% cometary xenon, in addition to chondritic (or solar) xenon.
Measured cometary abundances and isotope ratios, C chondrite

Xe isotopes

air
E chondrites
comet
estimate
Measured cometary abundances and isotope ratios, E chondrite
Experimental cometary abundances and solar isotope ratios, C chondrite
Experimental cometary abundances and solar isotope ratios, E chondrite
Experimental cometary abundances and solar isotope ratios, C chondrite, Extreme mass dependent isotope fractionation
Ready for Krypton?

SCIENCE ADVANCES | RESEARCH ARTICLE

PLANETARY SCIENCE

Krypton isotopes and noble gas abundances in the coma of comet 67P/Churyumov-Gerasimenko

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The Rosetta Orbiter Spectrometer for Ion and Neutral Analysis mass spectrometer Double Focusing Mass Spectrometer on board the European Space Agency’s Rosetta spacecraft detected the major isotopes of the noble gases argon, krypton, and xenon in the coma of comet 67P/Churyumov-Gerasimenko. Earlier, it was found that xenon exhibits an isotopic composition distinct from anywhere else in the solar system. However, argon isotopes, within error, were shown to be consistent with solar isotope abundances. This discrepancy suggested an additional exotic component of xenon in comet 67P/Churyumov-Gerasimenko. We show that krypton also exhibits an isotopic composition close to solar. Furthermore, we found the argon to krypton and the krypton to xenon ratios in the comet to be lower than solar, which is a necessity to postulate an addition of exotic xenon in the comet.
Fig. 1. Isotopic composition of 67P/C-G krypton, normalized to $^{84}\text{Kr}$ and the SW composition [from (18)]. 67P/C-G errors reflect 1-σ SEM and calibration uncertainties for the corresponding averaging periods. In this format, SW-Kr is represented by the horizontal orange line. $^{83}\text{Kr}$ appears to be slightly depleted relative to solar. The red line represents a mix of different nucleosynthetic components [the so-called G-Kr and N-Kr components; (17, 20)]. For the G-Kr composition, we consider the weak s-process composition having low $^{86}\text{Kr}/^{84}\text{Kr}$ ratios (20). The best fit was obtained for a proportion of 5% G-Kr in cometary krypton.
Results

1. The vast majority of He, Ne and Ar were supplied by nebular ingassing.
2. $3 \times 10^{21}$ g of comet and $4 \times 10^{25}$ g (90% NC, 10% CC) chondrite were supplied to Earth.
3. Kr was almost entirely supplied by comets.
4. 98% of $\text{N}_2$ and >80% of Xe was supplied by chondrites.
5. Nitrogen isotope ratios balance, but nitrogen isotope compositions require a predominantly E chondrite source. (This is supported by isotope systems: $^{187}\text{Os}/^{188}\text{Os}$, $\varepsilon^{100}\text{Ru}$, $\varepsilon^{50}\text{Ti}$, $\varepsilon^{54}\text{Cr}$).
6. Xe and Kr isotopes do not work if measured comet values are used.
0-10 My: Early H-rich atmosphere in presence of solar nebula

- H-rich atmosphere
  - 100 to 1000 bars

- Surface
  - T ~ 2000 K
  - Low D/H

- Ingassing of $H_2$, $H_2O$, rare gases

- Core grows
  - Transfer of Fe and FeH$_x$

- FeO reduced to Fe and FeH$_x$
  - $f(O_2)$ decrease

- Planet is not yet full-size. Core grows due to FeO reduction
Loss of $H_2$ raises $f(O_2)$ from IW-1 to FMQ.

- The reaction $H_2O \rightarrow H_2 + \frac{1}{2} O_2$ ($H_2O/H_2$ increases)
- $Fe^{2+}O + \frac{1}{2}O_2 = Fe^{3+}O_{1.5}$
- Oxidation of $Fe^{2+}$ to $Fe^{3+}$ ($Fe^{3+}/Fe^{2+}$ increases)
Loss of 1 ocean’s worth of hydrogen raises the $f(O_2)$ from IW-1 to FMQ
Mars Magma Ocean H$_2$ Ingassing; Ocean mass equivalents

0.3x Earth Mass Nebular Atmosphere Wind Mixing, IW–1 Total Oceans of Hydrogen

Solar Nebula Lifetime, Myr

Accretion Time, Myr
Earth Magma Ocean H₂ Ingassing; Ocean mass equivalents
Super-Earth \((2M_E)\) Magma Ocean \(H_2\) Ingassing; Ocean mass equivalents
Ocean depth vs. mass

Planet radius \((R/R_E) = 1.3\)

Habitable zone
Summary of events

Stage 1: Protoplanetary Disk

• Planetary embryos form in the protoplanetary disk in <10 My
• High P-T atmosphere forms. Surface melts – magma ocean.
• Multiple oceans worth of hydrogen ingas
• Large amounts of $^3$He ingassed.
• Insufficient heavy noble gases are ingassed
Stage 2: Protoplanetary disk dispersal

- Pressure release. Degassing of H$_2$
- Raises $f$(O$_2$) from IW-1 (iron stable) to present value of FMQ (water stable)
- Loss of light noble gases by hydrodynamic escape
- Addition of $\sim$1 % chondrites explains heavy noble gas deficit
Conclusion

• Nebular ingassing of H$_2$ may be an important mix to Earth’s water inventory.

• Eliminates radiogenic isotope ‘mismatch’ between Earth and chondrites.

• Explains source of $^3$He to Earth, but still requires chondritic addition (heavy noble gases)

• Explains Earth’s highly oxidized upper mantle

• Suggests that an Earth-sized body is the ‘Goldilocks’ size for advanced life.
Do we have evidence for the solar component in the terrestrial planets?
Baffin Islands

$\delta D \text{ (‰ VSMOW)}$

Earth mantle

Degassing trend

Hallis et al. Science, 2015
Ingassing Model Assumptions

- Nebular atmosphere: 85% H\(_2\), 15% He; 3He/4He=1.67e-4
- Nebular atmosphere lasts through accretion
- Accretion times: Earth=1-20Myr; Mars=1-5Myr
- Uniform accretion rate, dM/dt=constant
- Power law dependence of atm pressure on planet mass
- Global magma ocean
- Linear dependence of surface gas concentration C\(_s\) on partial pressure
- Gas flux depends on surface age: \( \bar{f} = 2\rho_m\Delta C(\kappa/\pi\Delta \tau)^{1/2} \)
- H & He diffusivity in magma: 5e-9 m\(^2\)/s
- H\(_2\) solubility 4e-4 @ 1kb; He solubility 1.3e-5 @ 1kb
Does the timeline work?

• Planetary embryo formation (Mars-sized or greater) – 1 – 5 My
• Age of the nebula (2-6 My) and up to 10 My (TW Hydrae – a T-Tauri star 80% the size of the Sun – 10 My).
Hill Radius – 1.5 million km
$f(\text{H}_2\text{O})/f(\text{H}_2 + \text{H}_2\text{O})$

$\log_{10} f(\text{O}_2)$

Initial post-impact mantle $f(\text{O}_2)$ value

IW-1

Moon & 4 Vesta

Mars mantle

Mars crust

Earth

$f(\text{O}_2)$ upper limit

QFM

Sharp et al., EPSL, 2013
Free parameters in our model

- **Ingassing**: Amount ingassed: We consider 0.01, 0.1 and 1.0 times our best estimate.

- **Hydrodynamic escape**: Loss is determined in order to best fit the equation

  \[
  \log \left( \frac{N}{N_o} \right) = m(Mass) + b
  \]

  where \(N_o\) is ingassed amount, \(N\) is present day amount, \(m\) is related to H flux

- **Late addition**: C chondrites, E chondrites, or some combination are considered. Comet compositional data are either measured from comet 67P/G-C or from ice formation experiments.

- **Xe loss**: The amount of ionized Xe lost is treated as a free parameter. Mass dependent Xe isotope fractionation factor (\(\alpha\)) is treated as a free variable.
The solution!? 

\[ X_{\text{He-ing}} - X_{\text{He-hydrodynamic escape}} + x_{\text{chon}} C_{\text{He-chon}} + x_{\text{com}} C_{\text{He-com}} = X_{\text{He-Earth}} \]

\[ X_{N_2-\text{ing}} - X_{N_2-\text{hydrodynamic escape}} + x_{\text{chon}} C_{N_2-\text{chon}} + x_{\text{com}} C_{N_2-\text{com}} = X_{N_2-\text{Earth}} \]

\[ X_{\text{Ne-ing}} - X_{\text{Ne-hydrodynamic escape}} + x_{\text{chon}} C_{\text{Ne-chon}} + x_{\text{com}} C_{\text{Ne-com}} = X_{\text{Ne-Earth}} \]

\[ X_{\text{Ar-ing}} - X_{\text{Ar-hydrodynamic escape}} + x_{\text{chon}} C_{\text{Ar-chon}} + x_{\text{com}} C_{\text{Ar-com}} = X_{\text{Ar-Earth}} \]

\[ X_{\text{Kr-ing}} - X_{\text{Kr-hydrodynamic escape}} + x_{\text{chon}} C_{\text{Kr-chon}} + x_{\text{com}} C_{\text{Kr-com}} = X_{\text{Kr-Earth}} \]

\[ X_{\text{Xe-ing}} - X_{\text{Xe-hydrodynamic escape}} + x_{\text{chon}} C_{\text{Xe-chon}} + x_{\text{com}} C_{\text{Xe-com}} - X_{\text{Xe-ionized}} = X_{\text{Ar-Earth}} \]