Formation of the Earth's Atmosphere and Oceans

EAS 302
Lecture 10

Questions about Earth's Atmosphere and Hydrosphere

- When did they form?
- How did they form?
- Has have they evolved with time?
- Why is its atmosphere so different from those of its neighbors?

Comparing the Earth with its neighbors

	Earth	Venus	Mars	Jupiter	Titan
Surface Pressure (MPa)	0.101	9.12	.00061		0.162
N_2 (percent)	78.1	3.5	2.7		82
O_2	20.95	2×10^{-3}	0.13		
Ar	0.93	7×10^{-3}	1.6		12
CO_2	3.6×10^{-2}	96.5	95.3		
H_2O	0 to 4	2×10^{-2}	3×10^{-2}	<0.02	
Ne	1.8×10^{-3}	1.5×10^{-3}	2.8×10^{-4}	1×10^{-3}	
CH_4	1.7×10^{-4}	6×10^{-5}		0.1	3
He	5.2×10^{-4}	2×10^{-3}		7.2	
H_2	5.3×10^{-5}	1×10^{-3}		92.5	0.2

(But, Earth's hydrosphere is 200 times more massive than its atmosphere)

Isotopes Again!

- **Since our questions involve time, it should not be too surprising that we turn again to Nature's time-keepers, radioactive and radiogenic isotopes, for answers.**
- **Decay systems of interest:**
  - ^{129}I to ^{129}Xe (half-life 16 Ma)
  - ^{40}K to ^{40}Ar (half-life 1.25 Ga)
  - ^{244}Pu to ^{136}Xe (via fission - half life 82 Ma)
  - ^{4}He (all alpha decays, mainly U and Th)
- **In addition, Ne isotopes provide some useful constraints**
- **(Notice the focus on *noble gases*)**

Hypotheses:

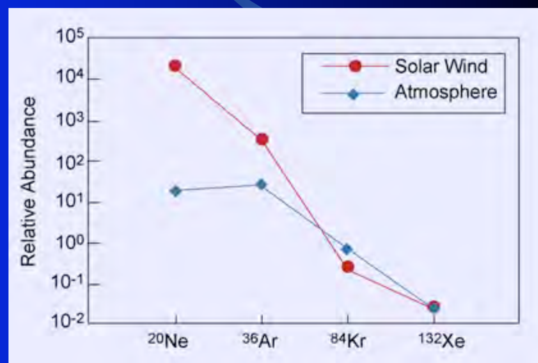
- (1) The atmosphere formed as gas from the solar nebula accreted to the Earth (i.e., gravitationally attracted)
- (2) The atmosphere (& hydrosphere) formed immediately by degassing of the Earth's interior.
  - (i.e., about the same time the Earth formed).
- (3) The atmosphere (& hydrosphere) formed slowly over geological time by degassing of the Earth's interior.
- (4) Atmosphere added by accreting comets through geologic time.

What do the hypotheses predict?

- During degassing (I.e., formation of the atmosphere), the daughters (Xe, and Ar) go into the atmosphere, while the parents remain in the solid Earth.
- Hypothesis (1)
  - Atmosphere should have a "solar" composition
- Hypothesis (2)
  - If the atmosphere formed before ^{129}I completely decayed away (80-160 Ma), we would expect $^{129}Xe/^{130}Xe$ to be higher in the solid Earth than in atmosphere (because of subsequent decay of ^{129}I to ^{129}Xe).
- Hypothesis (3) predicts the opposite of (2)
  - Atmosphere formation after complete ^{129}I decay leads to identical $^{129}Xe/^{130}Xe$ in Earth and atmosphere.
- Hypothesis (4)
  - Atmospheric should have cometary composition (it does not).

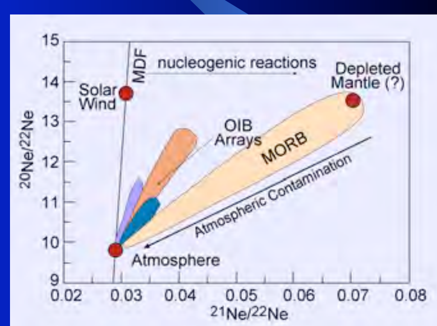
Comparing the Atmosphere to Solar Wind

- Compared to the solar wind (and presumably the Sun and solar nebula), Earth's atmosphere shows progressive depletion in lighter noble gases.
- If the Earth accreted an atmosphere from the solar nebula, it was likely lost.

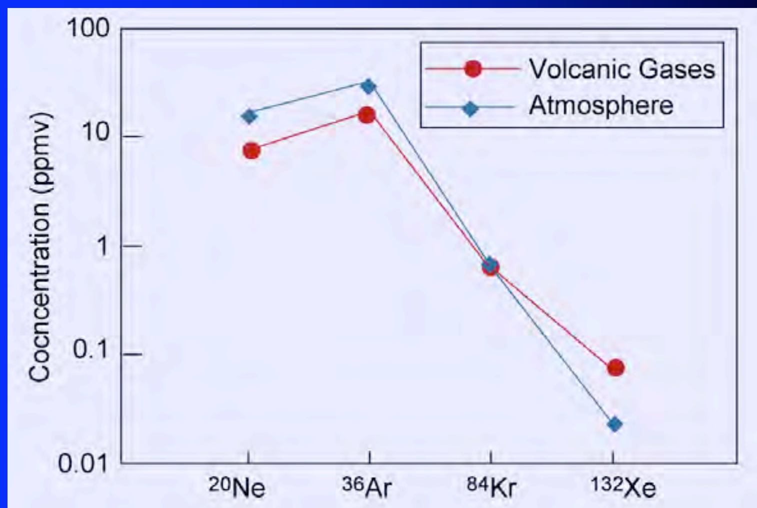


Ne Isotopes suggest atmospheric catastrophy

- The atmosphere is strongly depleted in the lightest Ne isotope - ^{20}Ne - compared to the solar wind, but also compared to Ne from the Earth's interior.
- The only plausible explanation is massive atmospheric loss
  - Which preferentially removed the lightest isotopes (those most likely to reach escape velocity).



Atmopshere and Volcanic Gases: A better match



Earth's "grow your own" atmosphere

- **Dissimilarity of noble gas concentrations and Ne isotopes between the atmosphere and the solar wind suggests that even if the Earth managed to accrete an atmosphere from the solar nebula, that primordial atmosphere was lost.**
  - (Perhaps primitive atmosphere lost in Giant Impact.)
- **The most likely source of the Earth's atmosphere is outgassing of the Earth's interior**
  - (An alternative hypothesis, that comets colliding with the Earth have created the atmosphere, has some serious problems and has lost support).

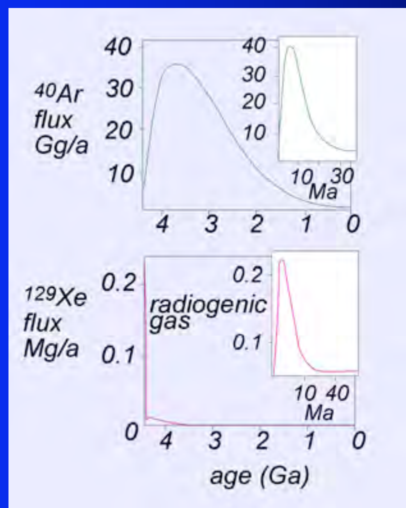
Hypotheses (Again)

- ~~**(1) The atmosphere formed as gas from the solar nebula accreted to the Earth (i.e., gravitationally attracted)**~~
- **(2) The atmosphere (& hydrosphere) formed immediately by degassing of the Earth's interior.**
  - (i.e., about the same time the Earth formed).
- **(3) The atmosphere (& hydrosphere) formed slowly over geological time by degassing of the Earth's interior.**

When did Degassing Occur?

- **Xe in magmatic gases from the Earth interior (e.g., volcanic gases) does have "excess" ^{129}Xe (i.e., higher $^{129}Xe/^{130}Xe$ than atmosphere).**
  - Therefore much of the atmosphere must have formed within 80-160 Ma of time 0 (last nucleosynthetic event).
- **However(!)**
  - Most of the Ar in the atmosphere is radiogenic (i.e., the product of ^{40}K decay).
    - $^{40}Ar/^{36}Ar$ ratio is ~300 in atmosphere (compared to <1 in Sun).
  - Most of this ^{40}Ar would have been produced *after* the first 80-160 Ma). Therefore, significant degassing must have also occurred later!
- **"Consensus" view is that >85%of atmosphere was produced by "*early catastrophic degassing*"; the rest through "continual" degassing.**

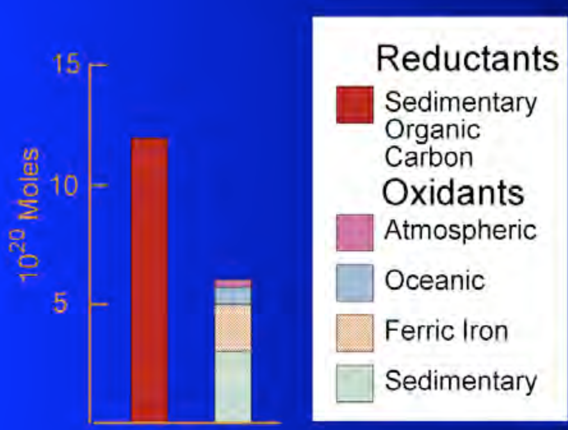
Argon and Xenon Degassing



Our unique atmosphere

- **Why does our atmosphere have so much O_2 when Venus and Mars have hardly any?**
- **Why is our atmosphere so poor in CO_2 compared to that of our neighbors?**
  - Where has all the carbon gone?
- **Answers to these questions are related.**

Inventory of Oxidants and Reductants in Earth's Crust & Atmosphere



Where has all the carbon gone?

- **Amount of reduced organic carbon in sediments exceeds the amount of carbon in the atmosphere (as CO_2) by a factor of 200.**
- **How did the carbon get there?**
  - This carbon represents the remains of once living organisms (almost entirely plants).
  - In other words, life, through photosynthesis, is partly responsible for the low levels of CO_2 in the atmosphere.
  - Corollary: life is entirely responsible for the presence of free oxygen in the atmosphere.
- **Far more carbon than this is stored in sediments as carbonate rocks.**
- **Oxidants and reductants don't balance.**
  - Oxidants (ferric iron) must have been "exported" to mantle.

When did the oceans form?

- H_2O would have been degassed from the Earth's interior simultaneously with gases of atmosphere.
- But, when was the Earth's surface cool enough for oceans to form?
- The 4.4 Ga zircon has $\delta^{18}O_{SMOW}$ up to 9‰.
  - This suggests the magma reacted with or contained material that had reacted with liquid water.
  - Earth's surface was apparently cool enough for oceans to form at 4.4 Ga!