The origins of the atmosphere and hydrosphere

Composition of the Atmosphere

Major Gases

Oxygen 20.95%

Nitrogen 78.08%

Argon .93%

Trace Gases .04%

Hydrogen .00005%
Krypton .0001%
Methane .0001%
Helium .0005%
Neon .0018%

Trace Gases

Carbon Dioxide .038%

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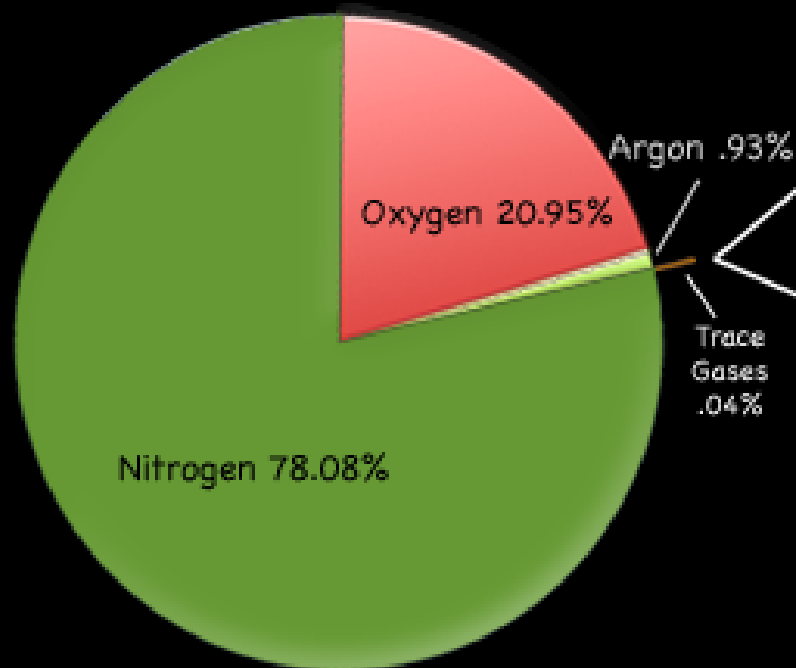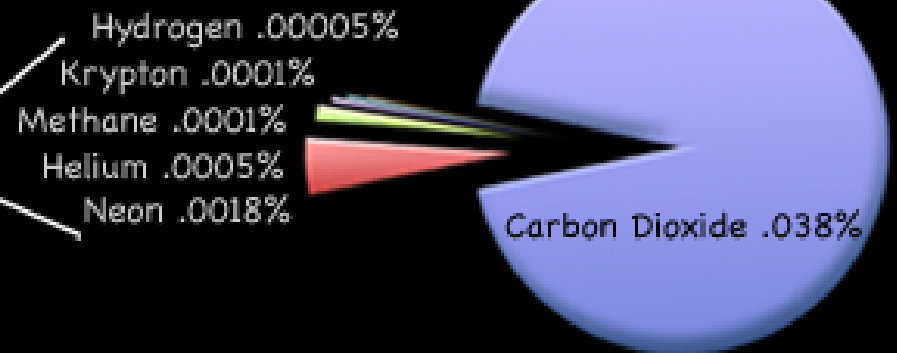
The atmosphere and hydrosphere represent the products of the outgassing of the Earth over geological time, primarily from volcanic activity. Yet the present-day composition of the atmosphere does not reflect that of volcanic volatiles. These are dominated by water vapour, carbon dioxide (CO_2) and sulfur dioxide (SO_2) with smaller amounts of nitrogen, halogens, hydrides and other more volatile compounds.

For about the first billion years of Earth's history, oxygen was only present in the atmosphere in trace amounts as a result of the breakdown of water vapour by UV radiation. However, this inorganic mechanism of releasing oxygen into the atmosphere produces only tiny amounts of free oxygen.

Since the Earth's present atmosphere is oxygen rich and because all higher forms of life require free oxygen, there is an obvious need for some other source of oxygen. The most plausible source is oxygen-producing photosynthesis, a process that first evolved in cyanobacteria during the Archaean era (from 3.8 Ga to 2.5 Ga ago).

So, in part, our currently breathable atmosphere is a by-product of life and not a primary feature of the geosphere alone.

The evolution of the hydrosphere is also intimately linked with that of the atmosphere – water is a volatile compound and is only present on the Earth's surface because the surface temperature is below 100 ºC.

So to understand the origins of the atmosphere and hydrosphere our attention needs to be focused on those components of the present-day atmosphere that have a limited or negligible interaction with the modern biosphere, namely nitrogen and the inert gases.

An important factor dictating whether or not an object in the Solar System can retain an atmosphere is the strength of the gravitational field at its surface – the stronger the field, the stronger the gravitational forces acting on the molecules in the atmosphere. Without the gravitational field, those molecules moving away from the planet would be lost.

Even with the gravitational field, those molecules with particularly high velocities can still escape. This leads to the notion of escape velocity, which is the minimum velocity needed before a body has enough kinetic energy to escape from the surface of a planet (i.e. overcome its gravitational field). It can be shown that the escape velocity (Vesc) for a body of mass M and radius r is given by:

$$V_{esc} = (2GM/r)^{0.5}$$

Average velocity of the molecule is proportional to Its temperature

Some fraction of the molecules will always be travelling fast enough to overcome gravitational forces, allowing them to escape to space.

At low temperatures, this proportion is negligible, but at higher temperatures it becomes progressively more significant, until most molecules exceed the escape velocity for the planetary body.

relevant temperature is that at a level in the upper atmosphere above which the atmosphere is so thin that a molecule moving outwards has little chance of colliding with another, and so will escape if it has sufficient velocity.

Different gases have different molecular masses, so their average velocities are different at a given temperature. In order for a planetary body to retain a particular gas in its atmosphere for a period of time of the same order as the age of the Solar System, the average velocity of the molecules in the gas should be less than about one-sixth of the escape velocity. This condition is achieved on only a few planets and satellites.

Figure thus defines the conditions under which a planet would lose or retain that gas over geological timescales, i.e. thousands of millions of years. The giant planets plot well above all the lines; they can therefore retain any of the gases. The Moon plots below all the lines – it can retain no gases.
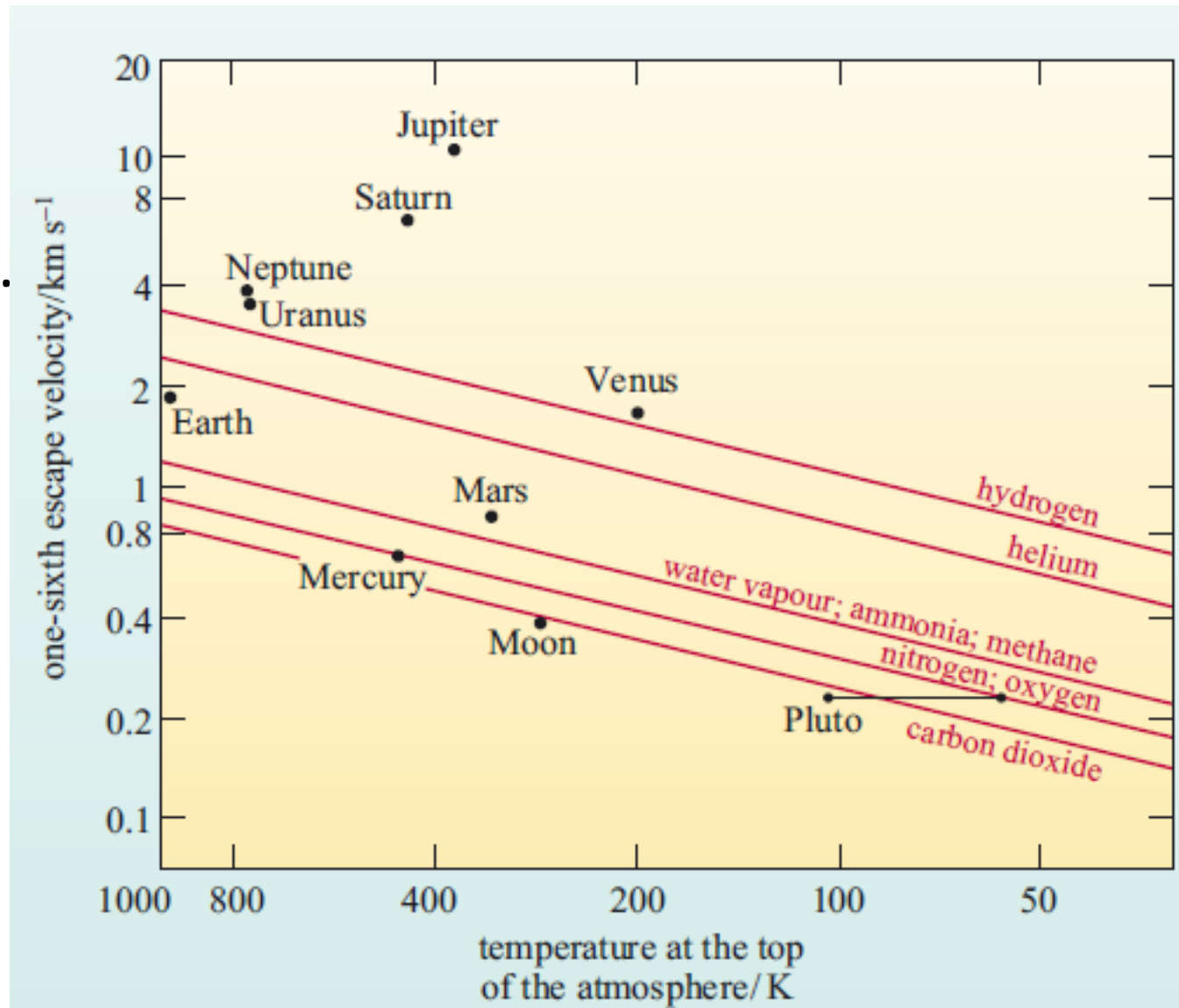
Nitrogen and the inert gases

Nitrogen is the most abundant ~**78.1%** in the atmosphere;

3rd most abundant is argon ~**0.93%**, one of the inert gases.

The remaining inert gases, **Ne, Kr**, and **Xe** are also found in small traces in the atmosphere. All are relatively un reactive elements in inorganic systems and, although nitrogen can be removed from the atmosphere (fixed) by bacterial activity, its presence in the atmosphere in relatively large quantities is a reflection of its **inorganic chemical inertness.**

Much attention has been paid to the isotopic composition of the inert gases both in the atmosphere and in the mantle because they can tell us much about the sources of the Earth's volatile elements.

In particular, the isotopes of Ar and Xe are significant because they are the daughter products of radioactive decay Schemes, which can be exploited to tell us about the timescales of planetary degassing.

The reason why Ar is one of the more abundant atmospheric gases is that it is dominated by one isotope, 40Ar. 40Ar is the daughter of radioactive 40K, which has a half-life of 1.28 Ga.

Xe is much less abundant than Ar, but one of its isotopes, 129Xe, is the daughter of 129I, but in this case the radioactive parent has a half-life of only 15.7 Ma.

What information can these two radioactive systems provide?

By analogy with short-lived isotopes in the solid Earth (e.g. Hf–W) and in meteorites (Mg–Al), the I–Xe couple provides information on the timescales of outgassing in the early phases of Earth evolution.

By contrast, the long half-life of 40K means that the isotope ratio of Ar reflects the history of planetary outgassing over the whole age of the Earth.

Ar and Xe isotopes and the evolution of the Atmosphere

The effects of planetary outgassing on the
1. K–Ar and
2. I–Xe radioactive Systems

Gradual Degassing of the system-

The simple situation in which the atmosphere gradually forms from the mantle by degassing. Early in Earth history there is a period when the 129Xe/130Xe ratio evolves rapidly, because of the decay of 129I, until it reaches a maximum value when all the 129I has decayed.

(a)
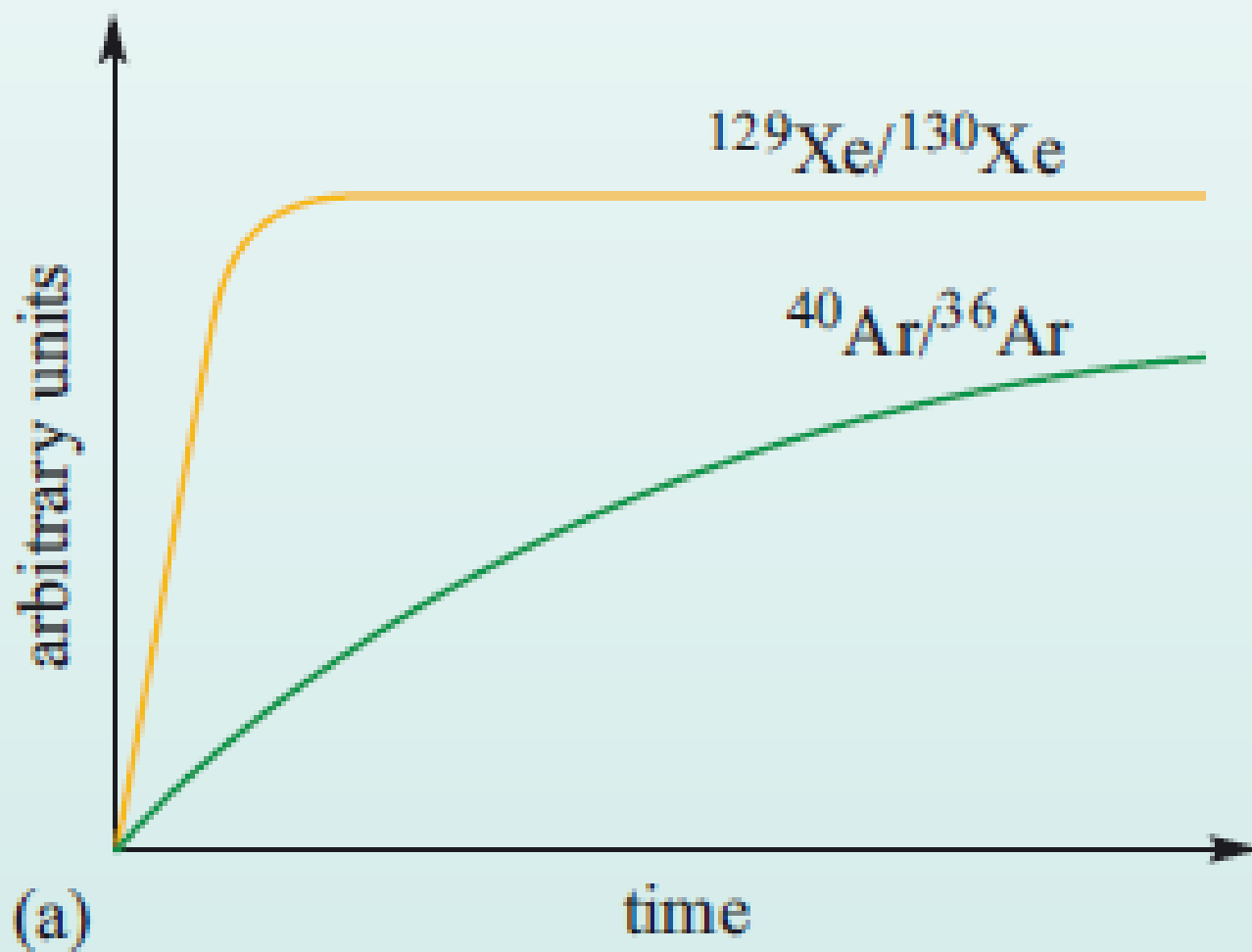
What will be the consequences for the 129Xe/130Xe ratios of the mantle and atmosphere if degassing occurs after all the 129I has decayed?

Ans. They will be **identical**.

The critical issue concerns the timing of the degassing event relative to the half-life of 129I.

How the isotope ratio of 129Xe/130Xe varies if degassing occurs before all the 129I has decayed and degassing was not gradual but an event?

If the atmosphere formed as the result of a major outgassing event, t1, early in Earth history while 129I was active, then the fractionation of Xe into the atmosphere and the preferential retention of I in the mantle would result in greater 129Xe production in the mantle

(b)
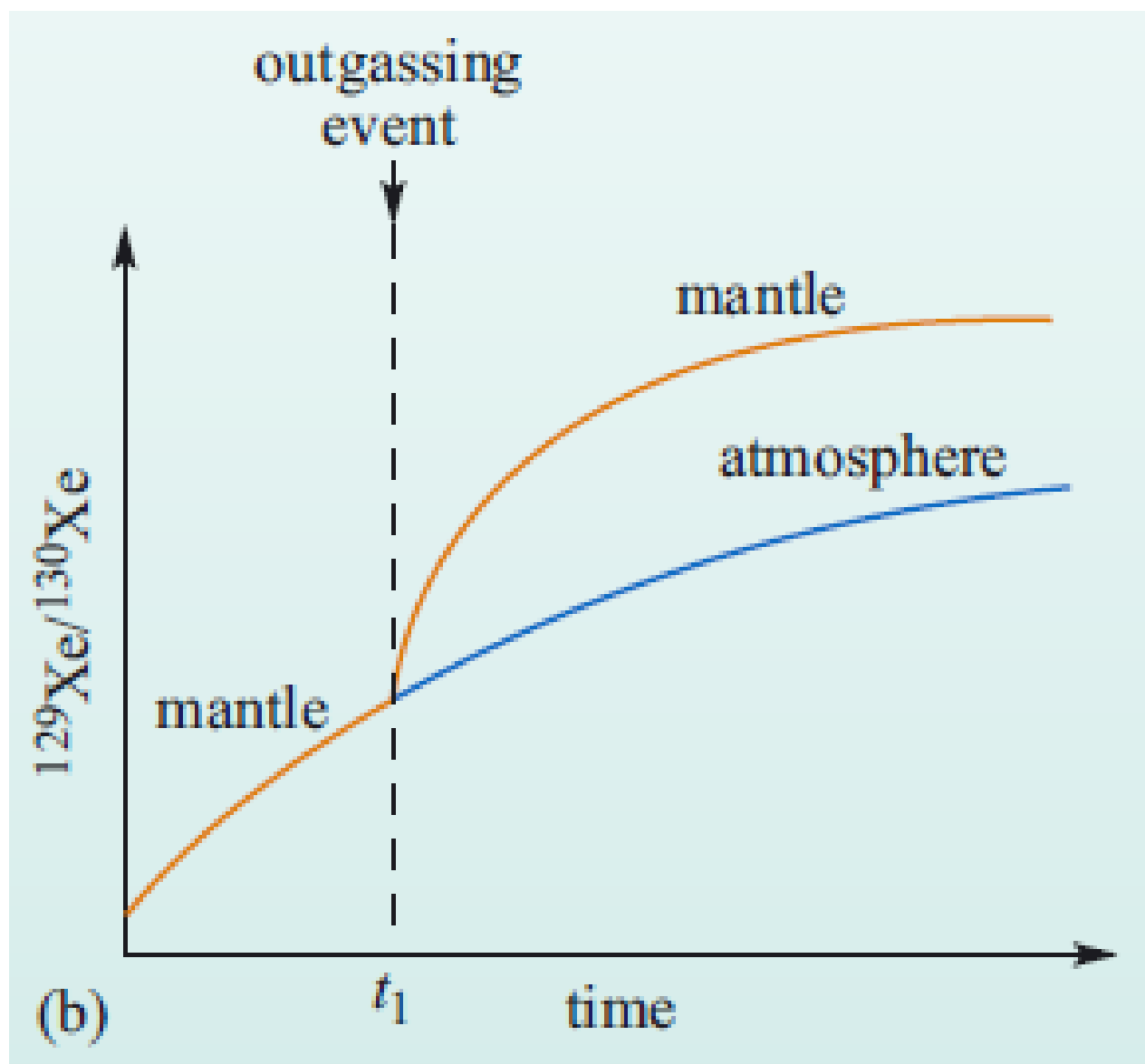
Note that the important measurement to make is not the Ar and Xe isotope ratios of the atmosphere, but those of the mantle.

The reason for this is that any outgassing event or process extracts virtually all of the Xe or Ar from the mantle and so the radioactive clock is reset.

Because all the volatile elements eventually end up in the atmosphere, its isotope composition reflects the sum total of all outgassing events and processes throughout Earth history.

Hence the measurement of Xe isotopes in the Earth's mantle provides a means of distinguishing between early, catastrophic planetary outgassing as opposed to gradual outgassing over the whole of Earth history.

Making isotope measurements of Ar and Xe in the mantle is extremely difficult and enormous care needs to be taken to avoid atmospheric contamination, both of the samples and in the measuring instruments.

However, the most successful measurements show that both the 129Xe/130Xe and the 40Ar/36Ar ratios of the mantle are high relative to the atmosphere.

This observation requires early and extensive degassing of the mantle to generate high parent/daughter ratios in the mantle early enough to have an effect on the I–Xe system.

Taken together, the Xe and Ar isotope ratios of the present-day mantle show that between 80% and 85% of the atmosphere was outgassed extremely early in Earth history, and given that the half-life of 129I is only 15.7 Ma this suggests that outgassing occurred within the first few tens of millions of years after accretion.

Water

The evolution of the hydrosphere is intimately linked with that of the atmosphere because water is also a volatile compound.

Until recently, there were competing views as to the origin of the Earth's water-
1. One was that the Earth accreted as a dry body and its water was subsequently added through cometary impact.
2. The alternative view was that the Earth inherited its water from water-bearing minerals in the undegassed interiors of planetary embryos, and that this was outgassed, along with Xe and Ar, early in Earth history.

The evidence suggests that the early Earth experienced intense meteoritic bombardment and must have been hot. Therefore, that surface conditions were too extreme for the young Earth to have a liquid hydrosphere and that much of the initial water was lost to space.

However, current models suggest that with the presence of a dense early atmosphere the pressures at the surface of the Earth beneath this atmosphere would have been high enough to ensure that a significant proportion of water and other volatiles were retained in solution.

This debate was partially resolved with the measurement of the deuterium/hydrogen (D/H) ratio in three comets, using both space probe measurements (the Giotto probe to comet Halley) and two ground based measurements of radio and infra-red emissions.

All three measurements agree within experimental uncertainty and show that deuterium (heavy hydrogen) is twice as abundant relative to hydrogen in comets as it is in the terrestrial hydrosphere. Such a major distinction effectively rules out comets as a major source of the Earth's water.

Thus the preferred model for the evolution of the hydrosphere is that it degassed from the mantle, and that this material was ultimately derived from water-bearing grains that became incorporated into planetesimals and eventually into planetary embryos.