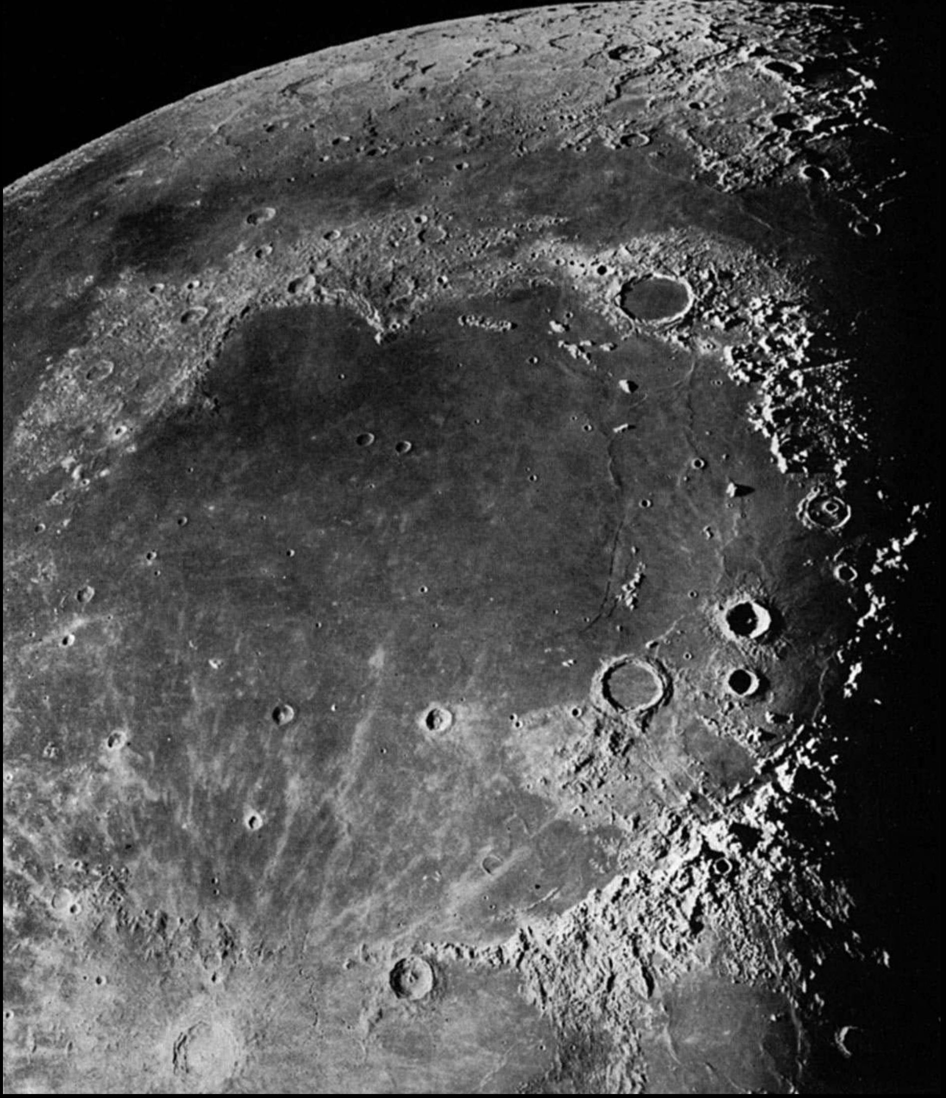
“Life’s a journey, not a destination” Aerosmith

HW1 is on the web page now and due next Monday at the beginning of class.

We will do the homework on ‘clickers’ in class on Monday using your written homework as your guide.

Baseline:
The Earth and Moon



3.5 Gyrs

200 Myrs

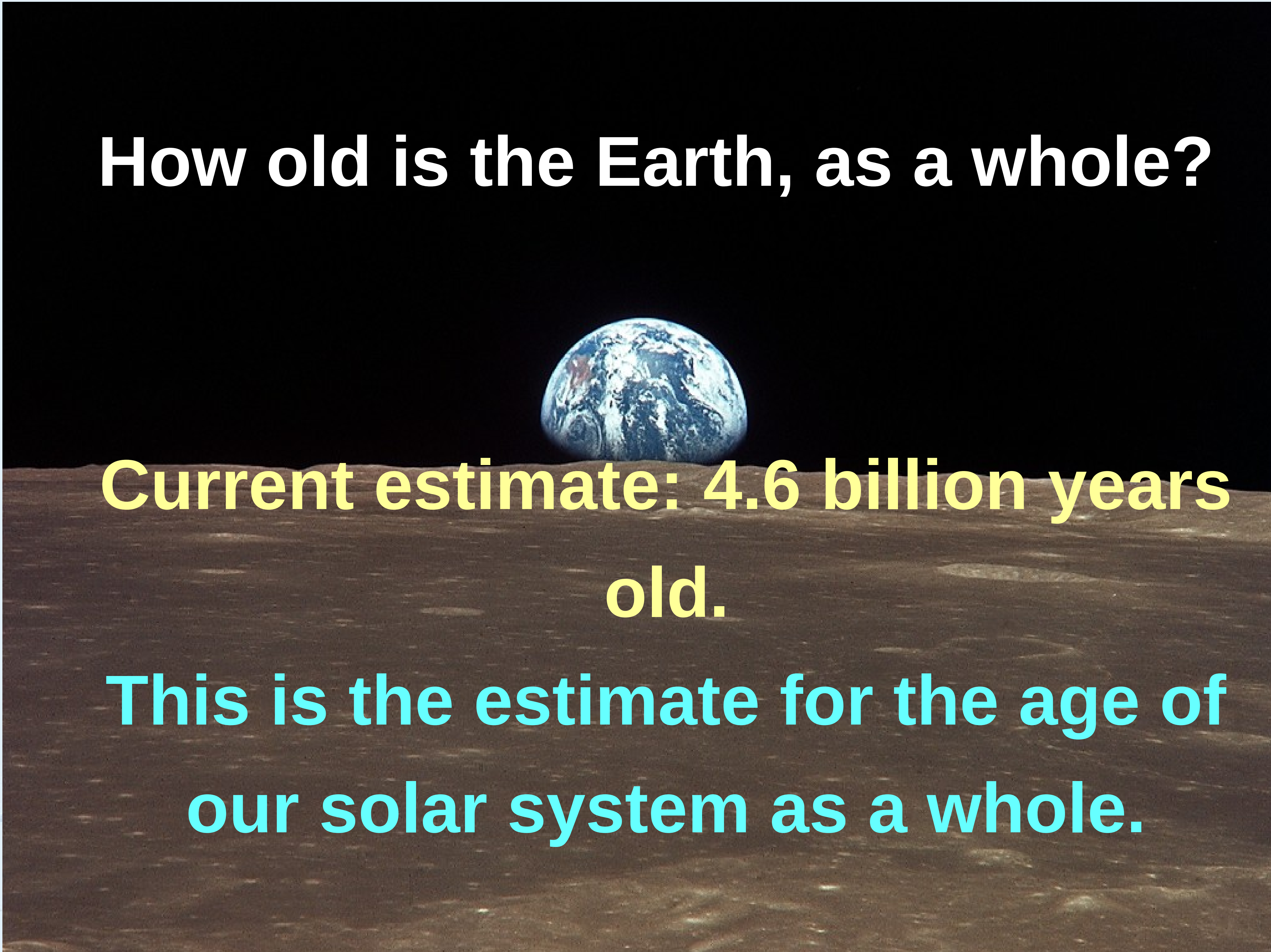
4-4.5 Gyrs

Surface age based on cratering

1) Smothered with craters; the surface is 4-4.5 billion years old. (e.g. Lunar Highlands)
2) medium (-heavy?) cratered; 3.5 billion years old. (e.g. Lunar maria)
3) lightly cratered; ~200-500 million years old. (e.g. Earth's surface)
4) no craters; <few million years old.

This is the yardstick against which all surface ages will be measured.

How old is the Earth, as a whole?



Current estimate: 4.6 billion years old.

This is the estimate for the age of our solar system as a whole.

The Moon is tidally locked to the Earth: It spins at the same rate of its orbit. So 1 side always faces the Earth.

The Earth-Moon system is *dynamic*. It seems like it is constant, but it is always changing.

Similarly, our solar system seems like the same ol' thing. But in fact it is in the process of changing all the time!!!!

What about the structure (insides) of the Earth?

What about the insides?

How deep into the Earth have we directly sampled?

A) 1% (40 miles)

B) 10% (400 miles)

C) 25% to the center

D) 50% to the center

E) 75% to the center

F) All the way to the center.

What about the insides?

How deep into the Earth have we directly sampled?

Deepest mine: TauTona- 2.4 miles

0.06% of the way.

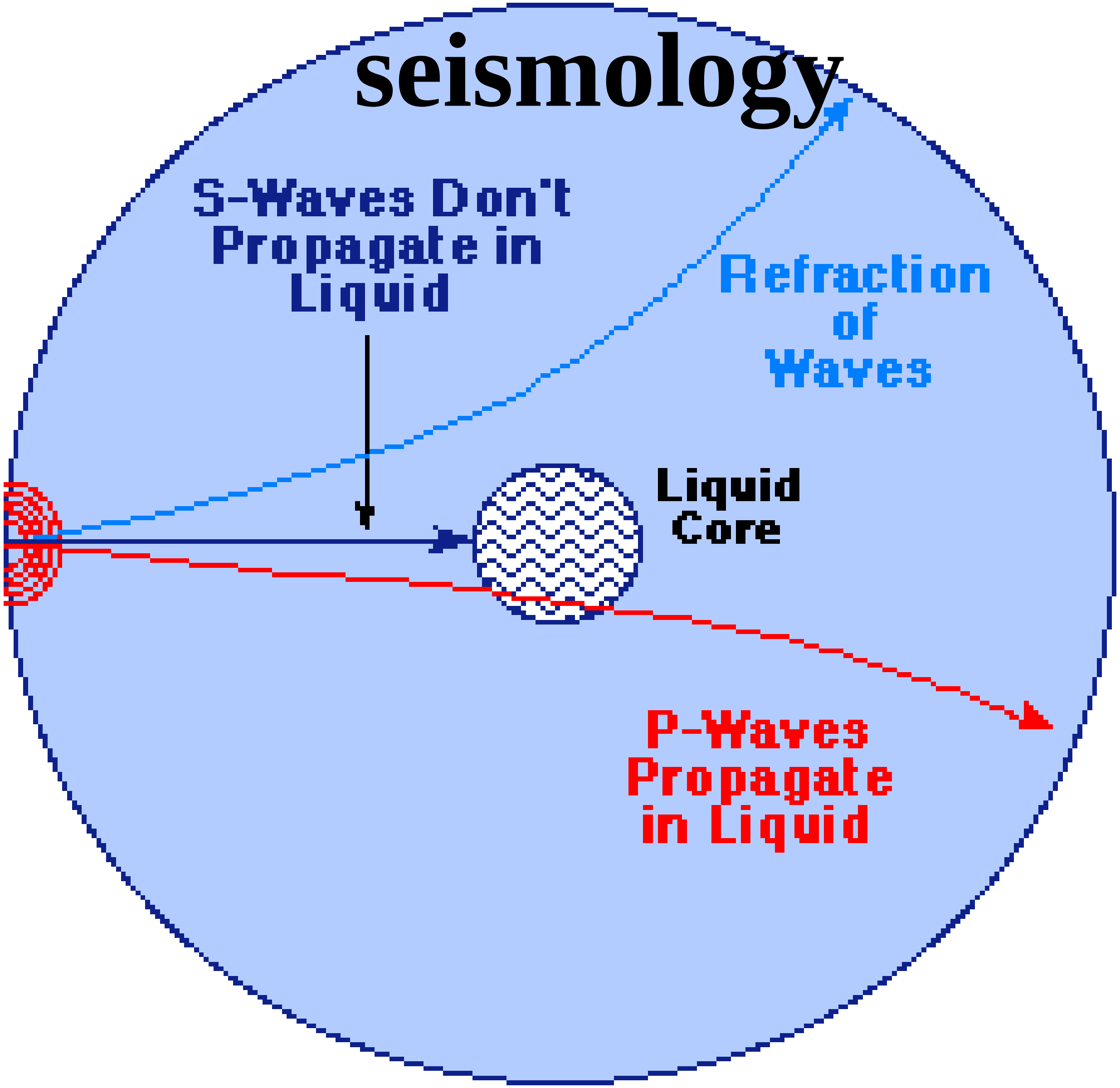
Marianas Trench: nearly 6.8 miles deep. 0.17% of the way.

Kola Superdeep Borehole: 7.5 miles deep. 0.19% of the way.

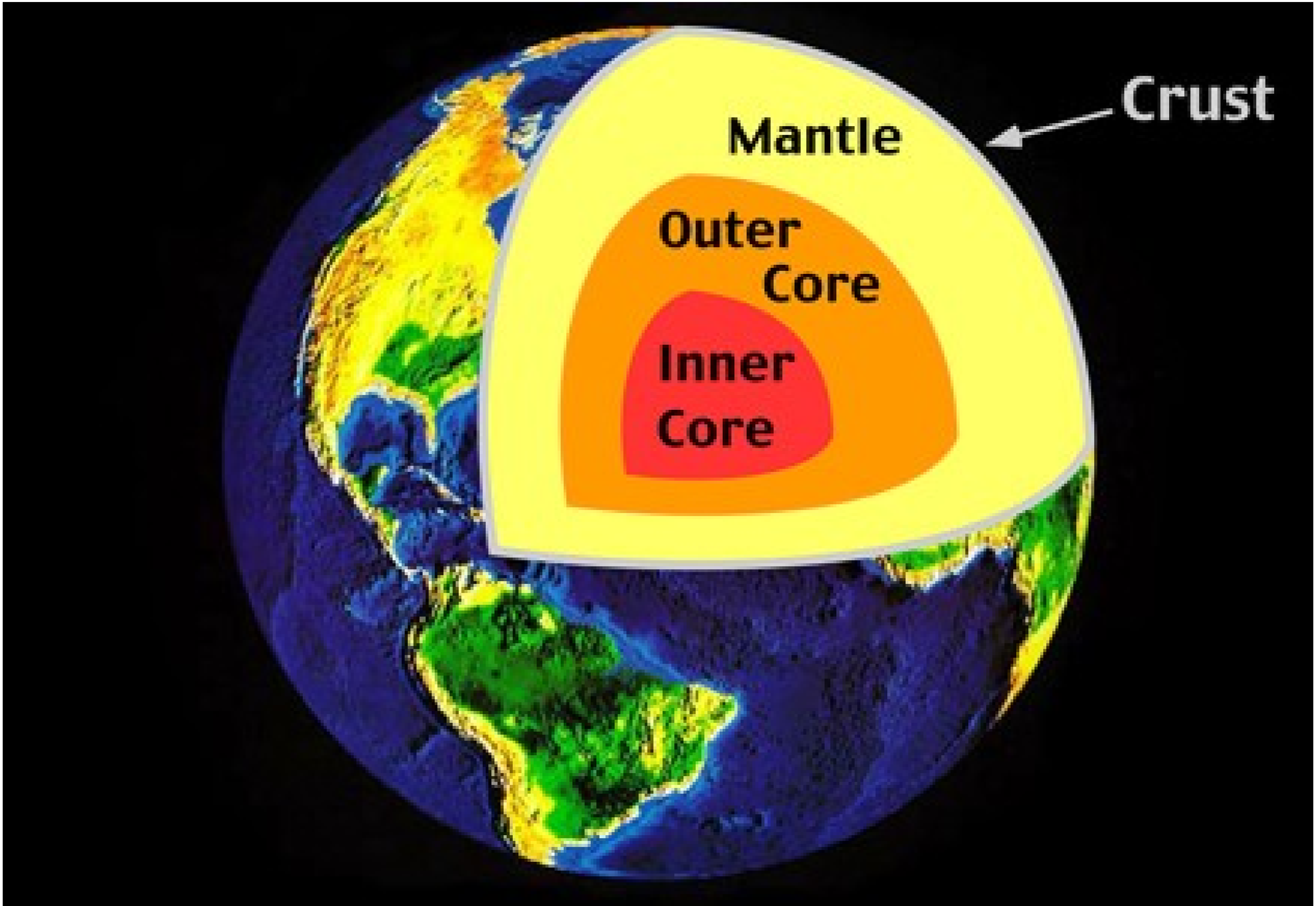
What about the insides?

If we haven't directly sampled it, how do we know what is at the center of the Earth, or the Moon?

The structure of the Earth using seismology



The Earth's structure: Density=5.5g/cc



What is the Earth is made of?

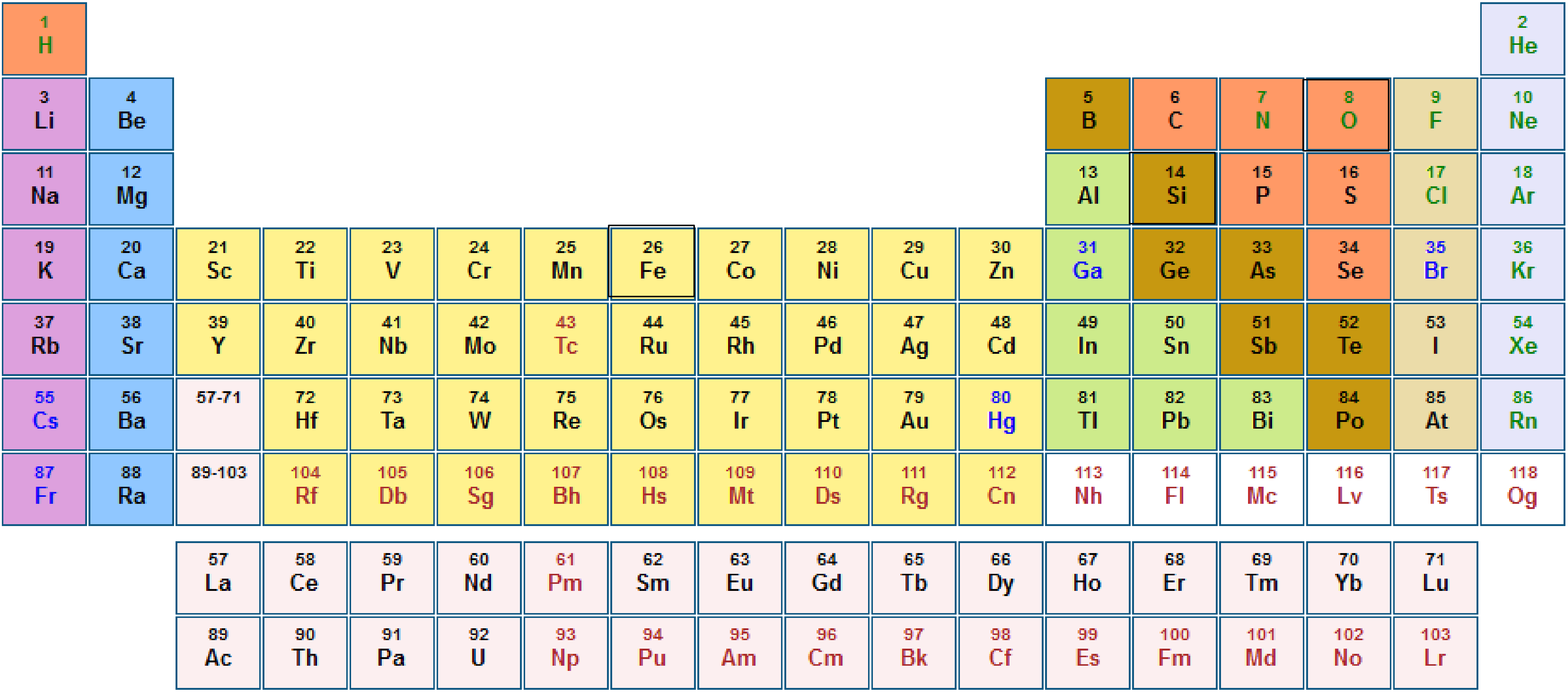
- Atmosphere: 78% Nitrogen, 21% Oxygen, 1% Argon, 0.03% CO_2
- Oceans: Water of course, but also salt (Sodium) and Carbon
- Crust: Oxygen, Silicon, Aluminium, Iron, Calcium, Sodium
- Mantle: Silicates and Magnesium and Iron
- Outer Core (liquid): Mostly Iron, some Nickel (4%) and 10% other (mostly Oxygen).
- Inner Core (solid): Mostly Iron, same as the outer core.

What does this tell us?

- Crust: Oxygen, Silicon
- Mantle: Silicates and Magnesium
- Outer Core (liquid): Mostly Iron
- Inner Core (solid): Mostly Iron

Look at where the elements O (crust) Si (crust/mantle), and Fe (core) are on the periodic table of elements.

The Periodic Table

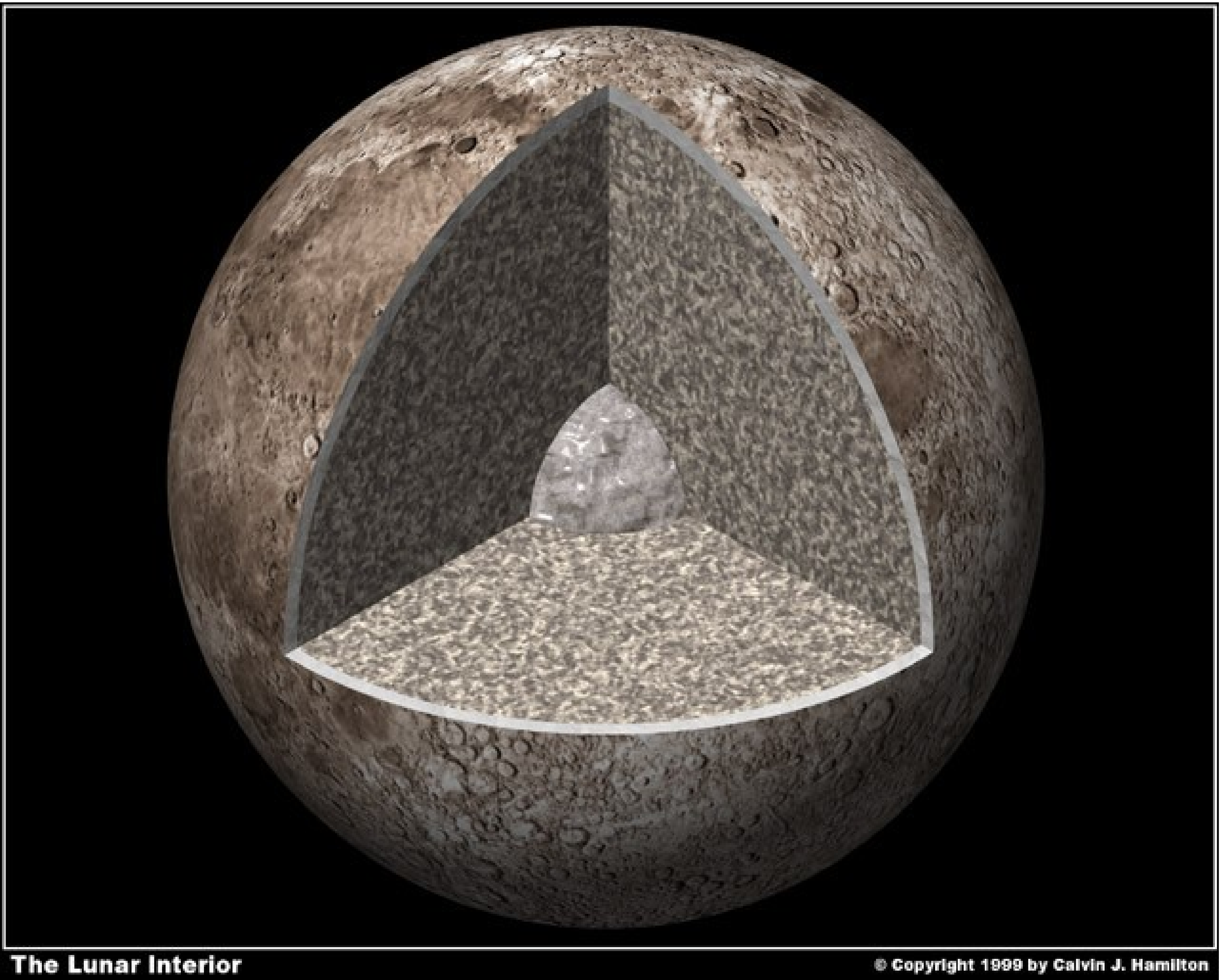


1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

What does this tell us?

- That the Earth is differentiated! The heavy stuff settled to the center.
- This means the Earth must at one time have been completely molten (liquid).

The Moon's structure



Also crust, mantle, and core, but the density is much lower (3.3 g/cc).

The Earth-Moon connection

- The Moon has exactly the same oxygen isotope ratios as the Earth. Mars, Venus, and asteroids do not.
- The composition of the Moon is essentially the same as Earth's crust.
- The Earth has a large iron core, the Moon has a very small core
- The mean density of the Earth is 5.5g/cc while the Moon's is 3.3g/cc (Note:Water is 1g/cc)

A more basic question

How does a planet (any planet!) get a moon?

How does a planet get a moon?

- It forms along with the planet:
- Captured:
- Split from planet:
- Formed from a ring of material that was made by a giant collision.

What are the consequences of each of these?

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Composition and Orbit

How does a planet get a moon?

- **It forms along with the planet: Expect orbit to lie in plane of rotation. Orbit should be over spin equator. Composition should be similar (if mass is). Core ratio should be similar.**
- **Captured:**
- **Split from planet:**
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- **Split from planet: Planet spins so fast that a moon is "flung" off the surface. Requires a lot of angular (spin) momentum. The system must keep this momentum. Must orbit over the spin equator. Composition should be that of the crust (no core).**
- **Formed from a ring of material that was made by a giant collision.**

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- **Formed from a ring of material that was made by a giant collision. A lot of parameters: how large were the bodies, at what angle/speed did they hit, what was the conditions on the original bodies at the time?**

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- **Formed from a ring of material that was made by a giant collision.**
- **The best answer is determined by orbit/spin and composition/density.**

For our Moon:

Collision!

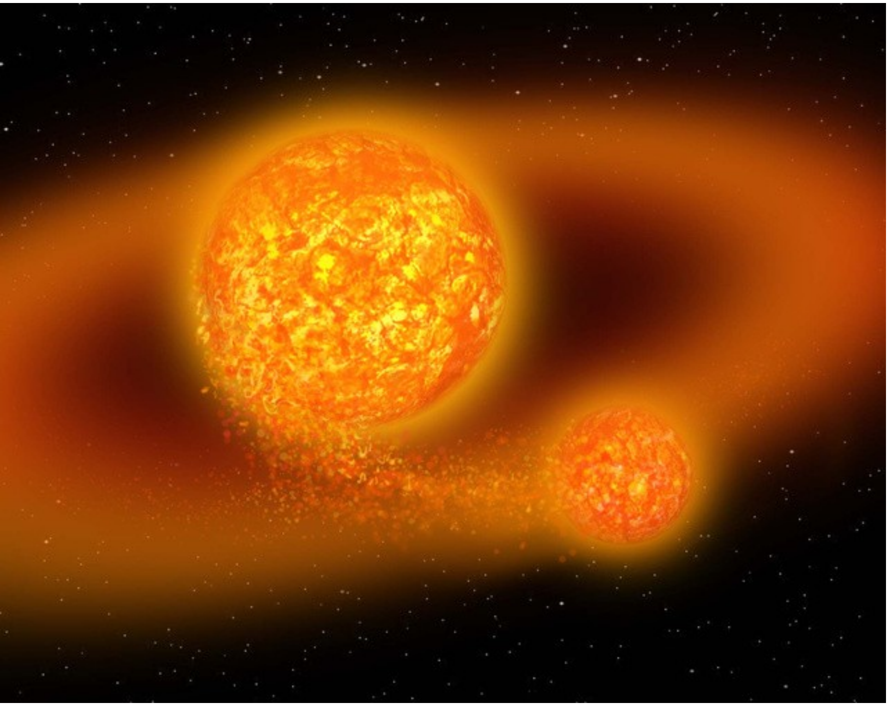
Evidence:

1) Composition: isotopes found in Moon rocks are similar to Earth's crust, dissimilar to Mars and Venus.

2) Core to crust ratio is too small for simultaneous formation

3) Orbital momentum is too small for the spin-off theory. The Moon's core is too large too.

4) Evidence of ring of molten material around the early Earth.

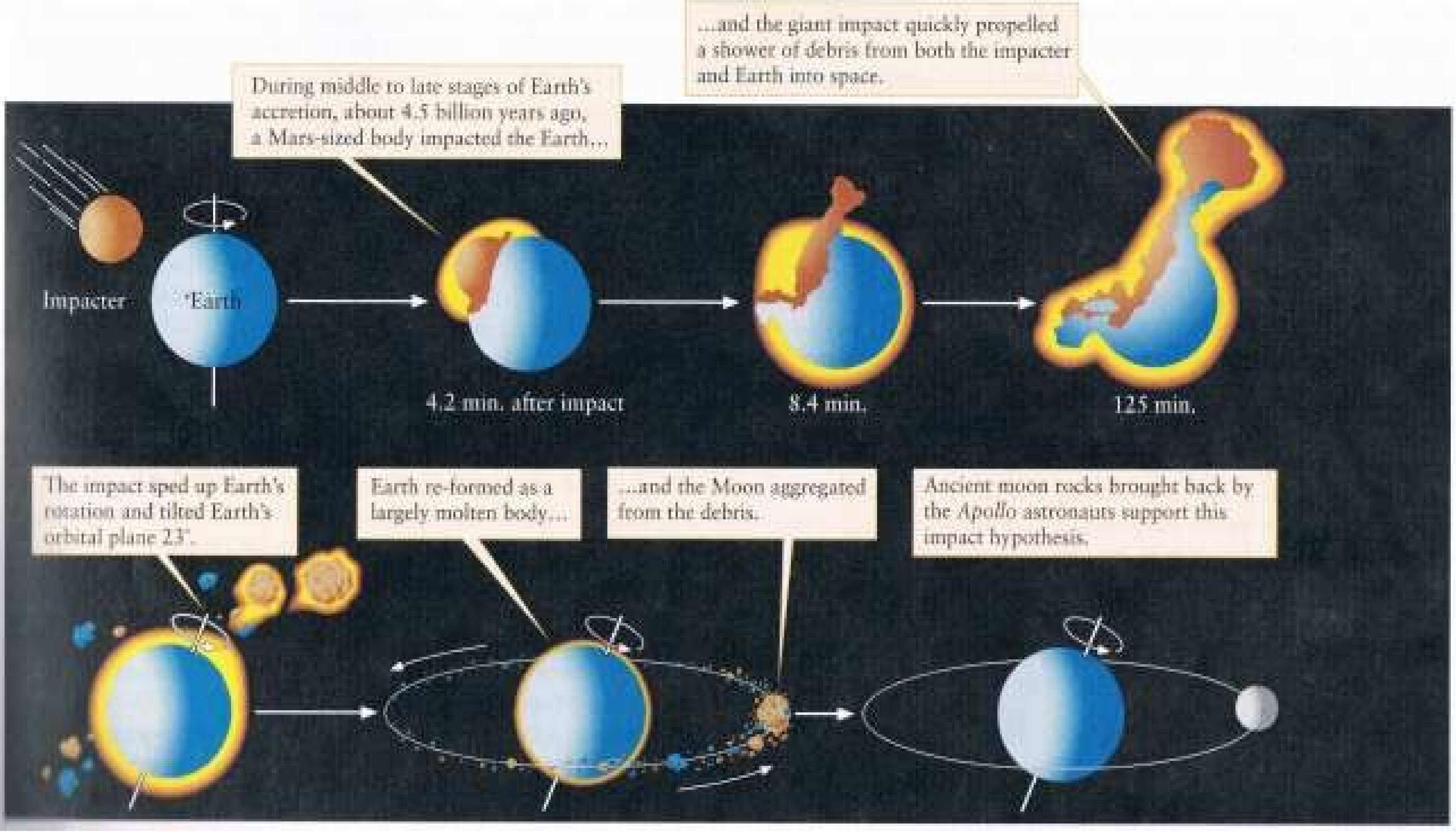


An object about the size of Mars hits the Earth.

Material is ejected high enough to orbit the Earth.

This material forms a ring.

The ring is then gobbled up by the biggest pieces that combine to form the Moon.



During middle to late stages of Earth's accretion, about 4.5 billion years ago, a Mars-sized body impacted the Earth...

...and the giant impact quickly propelled a shower of debris from both the impacter and Earth into space.

The impact sped up Earth's rotation and tilted Earth's orbital plane 23°.

Earth re-formed as a largely molten body...

...and the Moon aggregated from the debris.

Ancient moon rocks brought back by the *Apollo* astronauts support this impact hypothesis.

Thermodynamic simulations explain the Moon's composition

According to the simulations, more than half of the Moon accreted from volatile-poor molten rock that orbited Earth for decades following a giant impact.

It's widely thought that our Moon emerged out of an oblique collision between Earth and a body the size of Mars (see the article by Dave Stevenson, PHYSICS TODAY, November 2014, page 32). That now 40-year-old hypothesis was born in the aftermath of the Apollo missions, which returned hundreds of kilograms of lunar rock. Analysis of the material revealed a moon whose bulk chemical composition is largely the same as that of Earth's mantle but for a striking depletion of water and relatively volatile elements such as potassium and other alkali metals.

Early on, researchers suggested that the volatiles may simply have boiled off and been lost as the Moon formed from the hot disk of molten rock and gas launched into Earth orbit, and the idea remained popular for decades. Recent studies, however, have shown that Earth's gravity and frequent collisions among atoms in the protomoon's viscous magma prevented their escape.

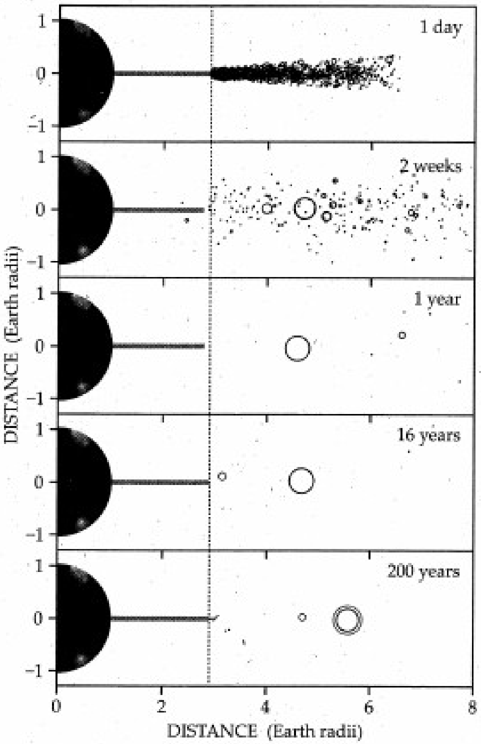
Using computer simulations that track the thermodynamic evolution of that Earth-orbiting disk, Robin Canup and Julien Salmon of the Southwest Research Institute and their colleagues Bruce Fegley Jr at Washington University in St. Louis and Channon Visscher at Dordt College now quantitatively explain how the depletions could have arisen.[1] In their account, the Moon formed in two distinct accretion stages, separated by a decade or so, that likely produced inner and outer layers with different compositions. Giant impacts were common in our solar system during the final stages of Earth's evolution 4.5 billion years ago, and knowing how the Moon was made is central to understanding our own and other terrestrial planets.

A lunar two-step

The new work builds on Canup and Salmon's previous dynamical simulations of the giant impact.[2] As shown in the figure, just 24 hours after the impactor struck, about two lunar masses of material (a mixture of 90% melt and 10% vapor) settled into a planar orbit spanning more than six Earth radii. The massive disk started clumping from local gravitational instabilities in the molten rock. At distances beyond a planet's so-called Roche limit, self-gravitating satellites retain their integrity against tidal forces. And within weeks any melt that found itself beyond Earth's Roche limit of 2.9 Earth radii coalesced into thousands of moonlets, each tens to hundreds of kilometers across; the first 40% of the Moon formed within months from those moonlets.

Inside the Roche limit, though, any developing clumps were quickly sheared apart. As a result, the inner disk cooled more slowly due to its smaller surface area and local heating. Turbulence caused the inner disk to gradually spread, and as material migrated beyond the Roche limit over the next few centuries, it formed its own moonlets, which were then accreted as the remaining 60% of the Moon.

That migration was initially stalled for about a decade, though, because of gravitational interactions known as orbital resonances between the inner disk and the first batch of moonlets. The moonlets set up density waves in the disk—akin to tidal bulges on Earth—that robbed the disk of angular momentum. The interaction generated a positive torque on the moonlets, which drove them outward, and a negative torque on the inner disk, which contracted its



SNAPSHOTS OF THE PROTOLUNAR DISK. Within a day after a giant impact that likely formed our Moon, a disk of molten and vaporized rock orbits an almost completely molten Earth (red) and extends several Earth radii. Beyond the Roche limit of 2.9 Earth radii—the distance at which self-gravitating clumps of molten rock are no longer torn apart by the planet's tidal forces—outer-disk material (black) can persist and coalesce into moonlets. Inside the Roche limit, inner-disk material (yellow) remains a turbulent liquid–gas mixture a few kilometers wide. Gravitational interactions drive the moonlets outward, where they assemble within months into an object nearly half the mass of the Moon, and compress the disk inward. The confinement stalls the accretion of new moonlets from the inner disk for a decade or so, but much of that inner-disk material eventually accretes onto the Moon until the Moon spirals out of reach of newly spawned moonlets. (Adapted from ref. 2 and updated by Julien Salmon.)

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