THE Hf-W ISOTOPIC SYSTEM AND THE ORIGIN OF THE EARTH AND MOON

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Question:

Can **Hf-W** system be used as a chronometer for the Earth formation and core differentiation?

1. Planet-building and core formation process

2. Radiometric dating using **Hf-W** system

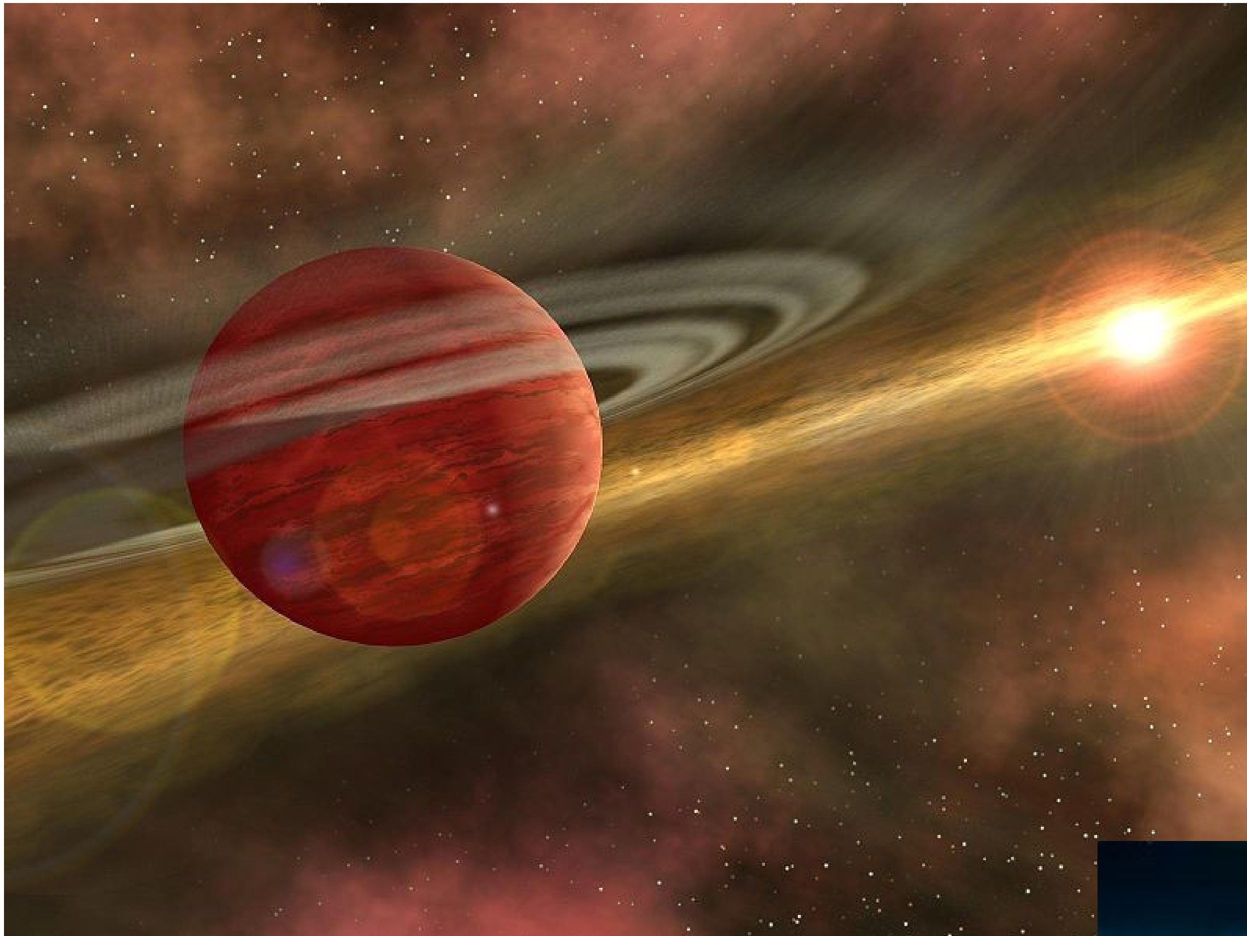
3. Chondritic meteorites

4. Two-stage **Hf-W** fractination model

5. Continuous **Hf-W** core formation model

6. **W** isotope model constraints from Moon, Mars, Vesta and meteorites

1. Planet-building and core formation process



Planetary embryos

“The Earth’s last collision”

Chemical complexities:
Rate of accretion *vs.* Rate of nebular cooling

A) $R_{ACCR} > R_{COOL}$

- Refractories (e.g. **W**) accrete first, and
- Planets start with partially formed iron cores

B) $R_{ACCR} < R_{COOL}$

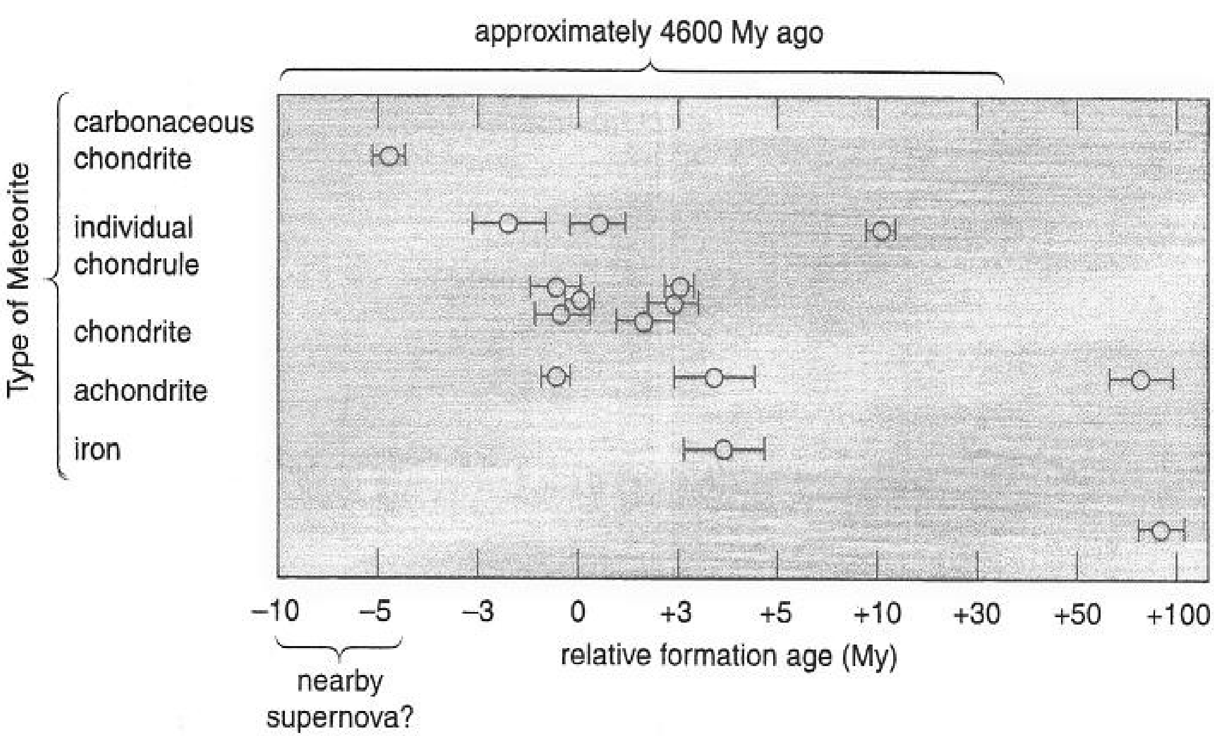
- Planetary matter is well mixed

Source of unstable radioactive elements?

^{129}I $T_{1/2} = 17$ Myr

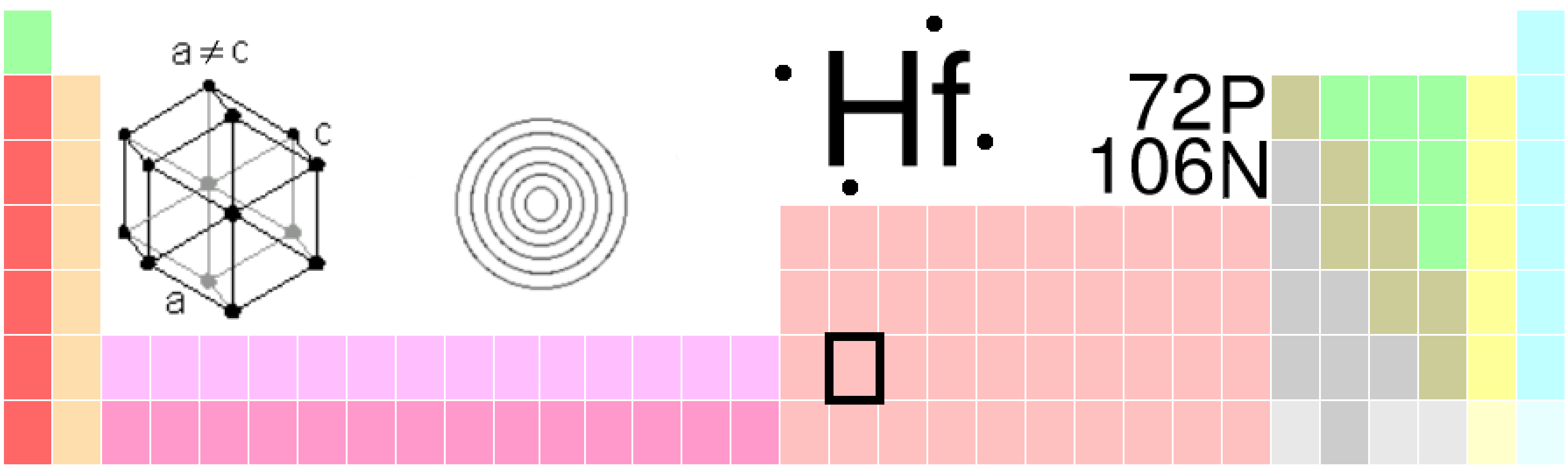
^{26}AL $T_{1/2} = 0.72$ Myr

^{182}Hf $T_{1/2} = 9$ Myr



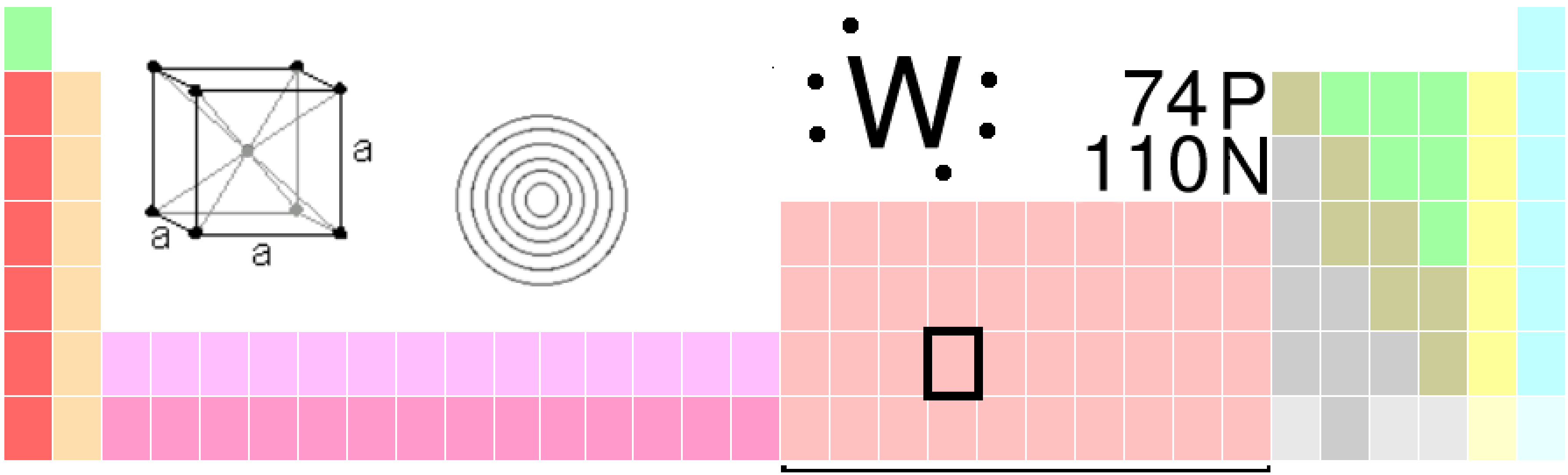
Hafnium

- Hafnium has many isotopes most of which are stable
- The most common is Hf-180 making up 35% of the natural abundance
- Hf-182 beta decays to W-182 with a half life of 9 Myr
- Lithophilic



Tungsten

•W-183 and W-182 have a natural abundance of 14.3% and 26.5% respectively
•Both are stable and W-182 is the daughter product of the Hf-182 decay.
•Siderophilic

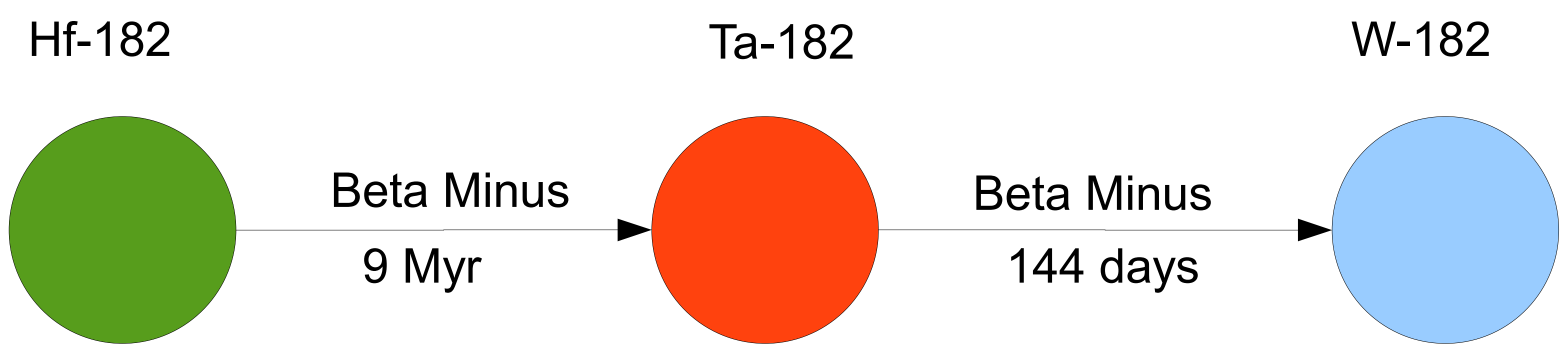


Beta Decay

n0 → p+ + e− + ve

- A neutron decays to a proton, electron and an anti-neutrino.
- The number of nucleons is unchanged, but the atomic number increases by 1

The Hf-W System

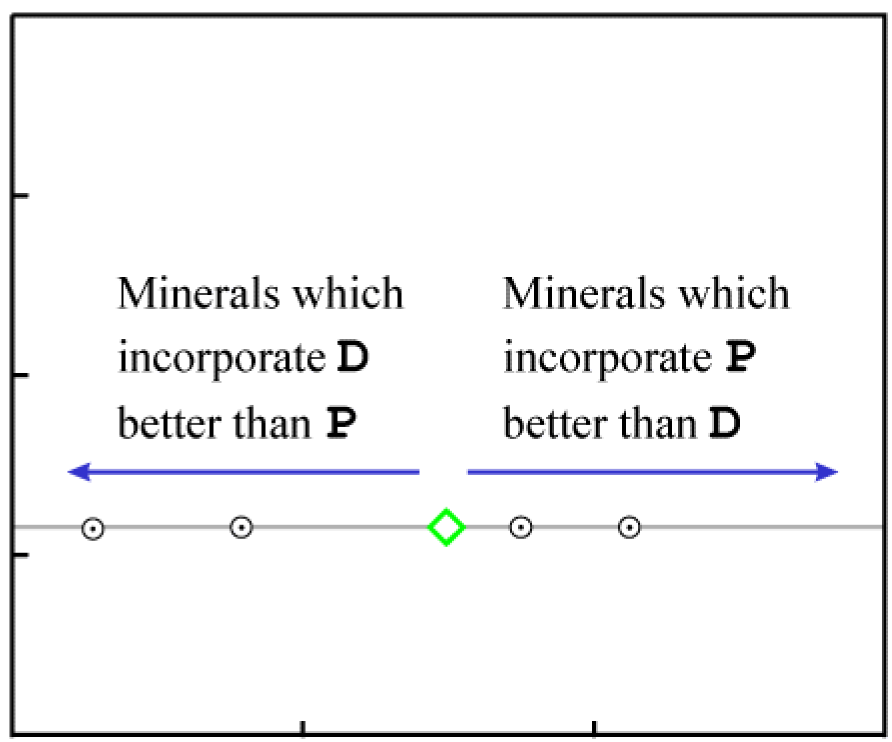


$$^{182}Hf(t) = {}^{182}Hf_0 e^{-\lambda t}$$

How Does Geochronometry Work?

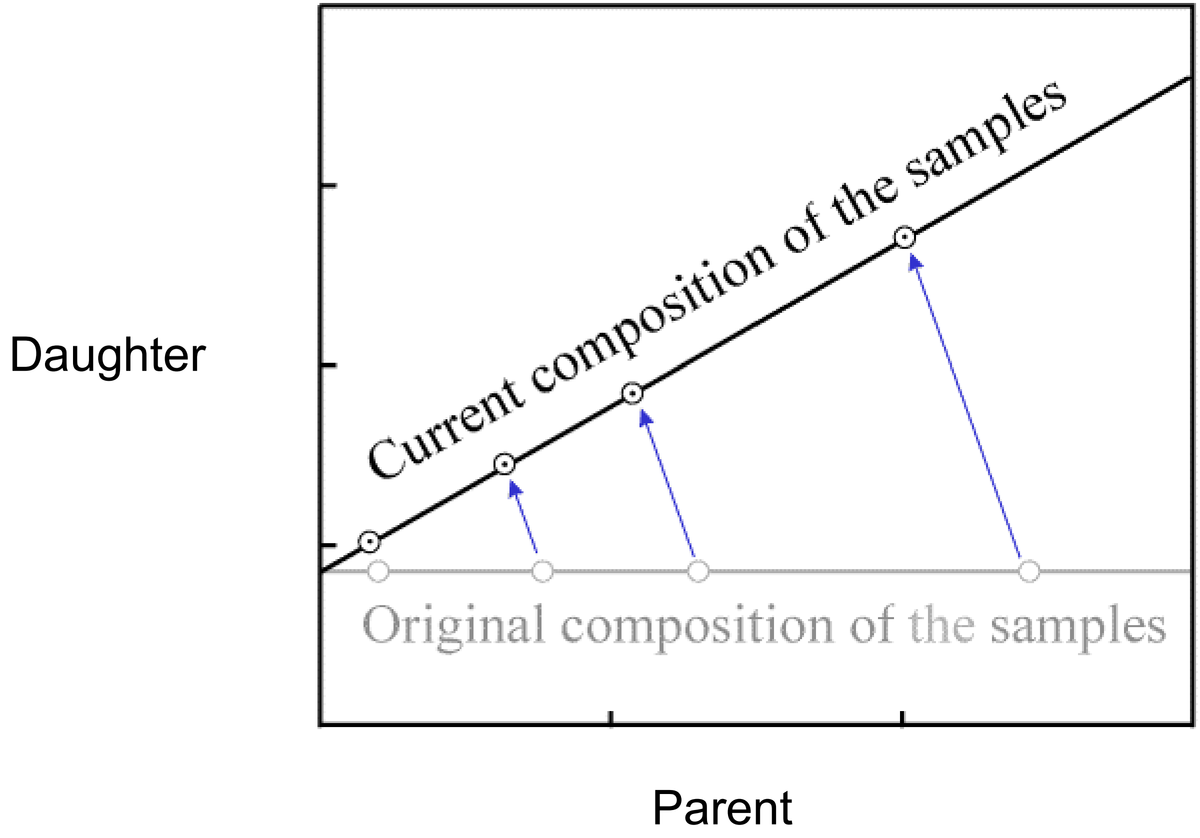
- As minerals form from a resevoir, they have different amounts of parent isotopes, but the same amount of daughter isotopes.
- As time moves forward the parent decays and the concentrations shift .

Daughter



Parent

•After a sufficient number of half lives decay stops and the concentrations become fixed.
•It is important that we have stable isotopes of both the parent and daughter product.



$$\left(\frac{^{182}W}{^{183}W}\right)^{T} = \left(\frac{^{182}W}{^{183}W}\right)^{0} + \left(\frac{^{182}Hf}{^{183}W}\right)^{0} \left(1 - e^{-\lambda t}\right)$$

Present Amount

Original Amount

Contribution from Decay

$$\left(\frac{^{182}W}{^{183}W}\right)^{T} = \left(\frac{^{182}W}{^{183}W}\right)^{0} + \left(\frac{^{182}Hf}{^{183}W}\right)^{T} \left(e^{\lambda t} - 1\right)$$

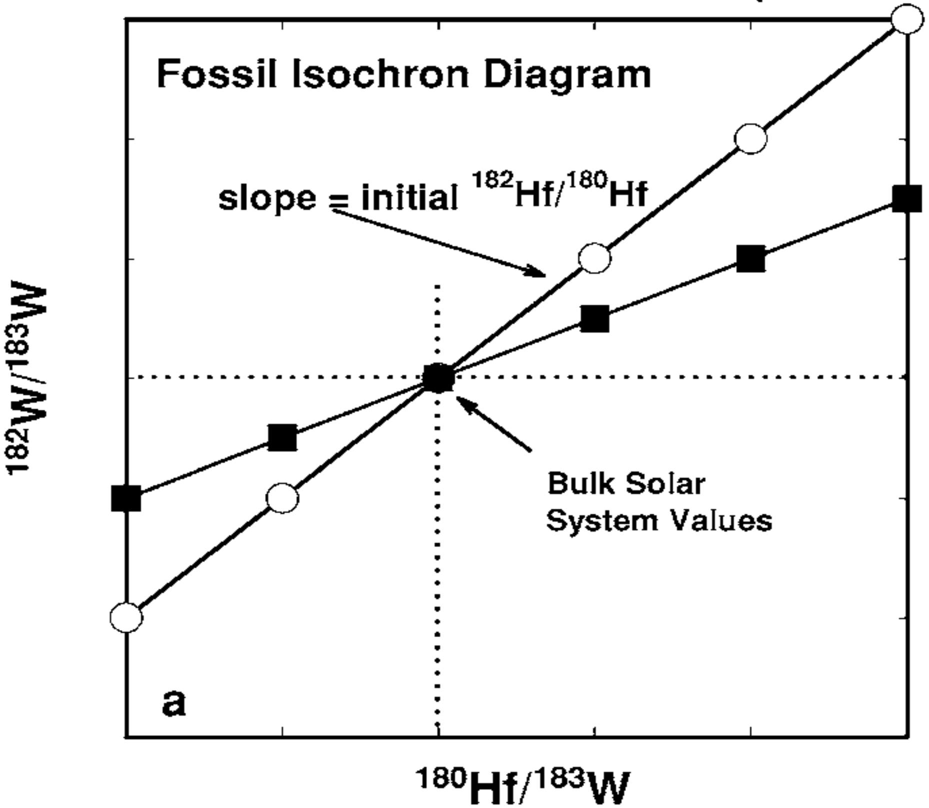
$$\left(\frac{{}^{182}W}{{}^{183}W}\right)^{T} = \left(\frac{{}^{182}W}{{}^{183}W}\right)^{0} + \left(\frac{{}^{180}Hf}{{}^{183}W}\right)^{T} \left(\frac{{}^{182}Hf}{{}^{180}Hf}\right)^{T} \left(e^{\lambda t} - 1\right)$$

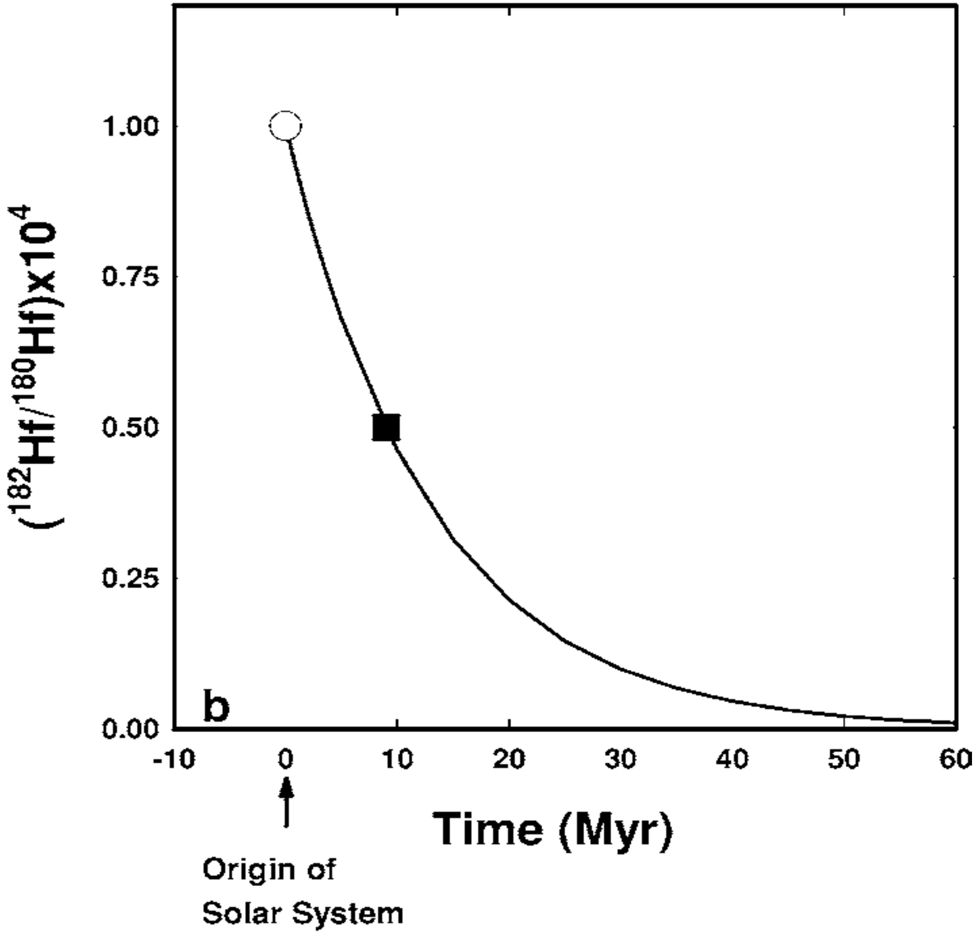
$$\left(\frac{{}^{182}W}{{}^{183}W}\right)^{T} = \left(\frac{{}^{182}W}{{}^{183}W}\right)^{0} + \left(\frac{{}^{180}Hf}{{}^{183}W}\right)^{T} \left(\frac{{}^{182}Hf}{{}^{180}Hf}\right)^{0} \left(1 - e^{-\lambda t}\right)$$

$$\left(\frac{{}^{182}W}{{}^{183}W}\right)^{T} = \left(\frac{{}^{182}W}{{}^{183}W}\right)^{0} + \left(\frac{{}^{180}Hf}{{}^{183}W}\right)^{T} \left(\frac{{}^{182}Hf}{{}^{180}Hf}\right)^{0}$$

Measure stable isotope concentrations, at the present time T
Derive past values of parent and daughter isotopes from these

^{182}Hf (half-life = 9 Myr) → ^{182}W





Stable Reference Isotopes: ^{183}W, ^{180}Hf

$$\left(\frac{^{182}W}{^{183}W}\right)^{T} = \left(\frac{^{182}W}{^{183}W}\right)^{0} + \left(\frac{^{180}Hf}{^{183}W}\right)^{T}\left(\frac{^{182}Hf}{^{180}Hf}\right)^{0} \leftarrow \text{Slope}$$

↑ Intercept

Planetary differentiation

Primary planetary materials:
Chondritic ratio of Hf/W (1.3)
Standard amount of ^{182}W, so
ε_W (CHUR) = 0

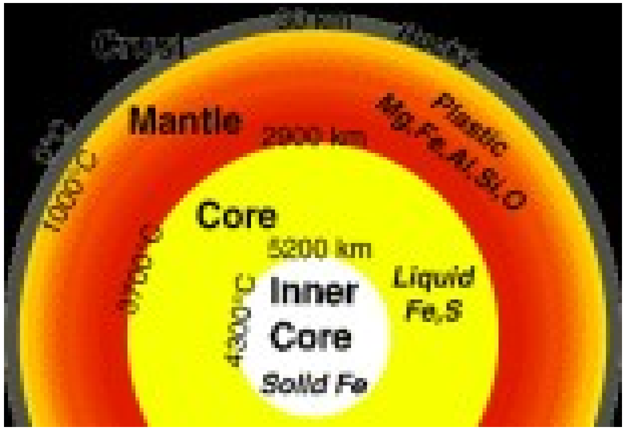
↓

Planetary differentiation

Lithophiles (Hf) ↙ ↘ Siderophiles (W)

Silicate (rocky part)
Hf/W > 10
High Hf/W causes production of a lot of ^{182}W compared to the original amount, so ε_W (CHUR) > 0

Iron core
Hf/W essentially 0
Low Hf/W means that only small amount of ^{182}W can be produced,
so ε_W (CHUR) < 0



Bulk Silicate Earth (**BSE**)

$$\varepsilon_{W(BSE)}(0) = \left[\frac{(^{182}W/^{183}W)^0}{(^{182}W/^{183}W)^0_{BSE}} - 1 \right] \times 10^4$$

CHondritic Unfractionated Reservoir (**CHUR**)

$$\varepsilon_{W(CHUR)}\ (0) = \left[\frac{(^{182}W/^{183}W)^0}{(^{182}W/^{183}W)^0_{CHUR}} - 1 \right] \times 10^4$$

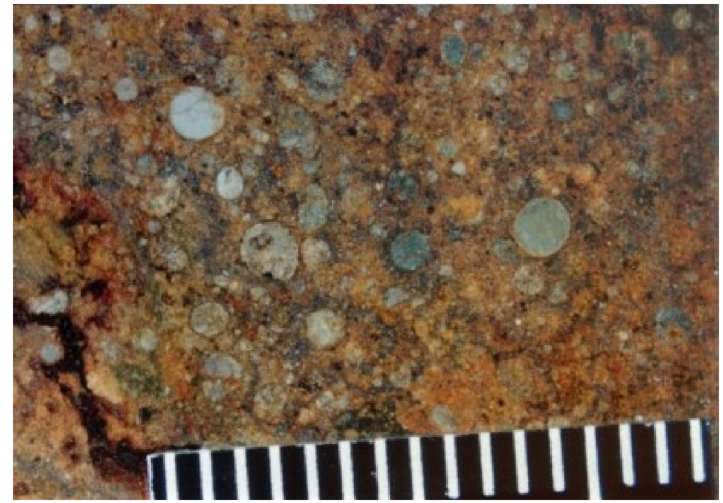
$$= \varepsilon_{W(BSE)j}(0) + 1.9$$

Meteorites

Differentiation

- Chondrites
  - Stony meteorites with “chondrules” (Gr. “seed”)
  - Building blocks of the planetary system
- Achondrites
  - Stony meteorites w/o “chondrules”
- Stone Irons
  - Resemble where the Earth core meets the mantle
- Irons
  - Resemble the outer core of the Earth

Chondrites



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Chondrules

Iron meteorites

IIAB

IVAB

Ages

A) Solidification age

B) Formation age

Many ancient meteorites have S.A. = F.A.

The age of solar system ~4.566 Gy

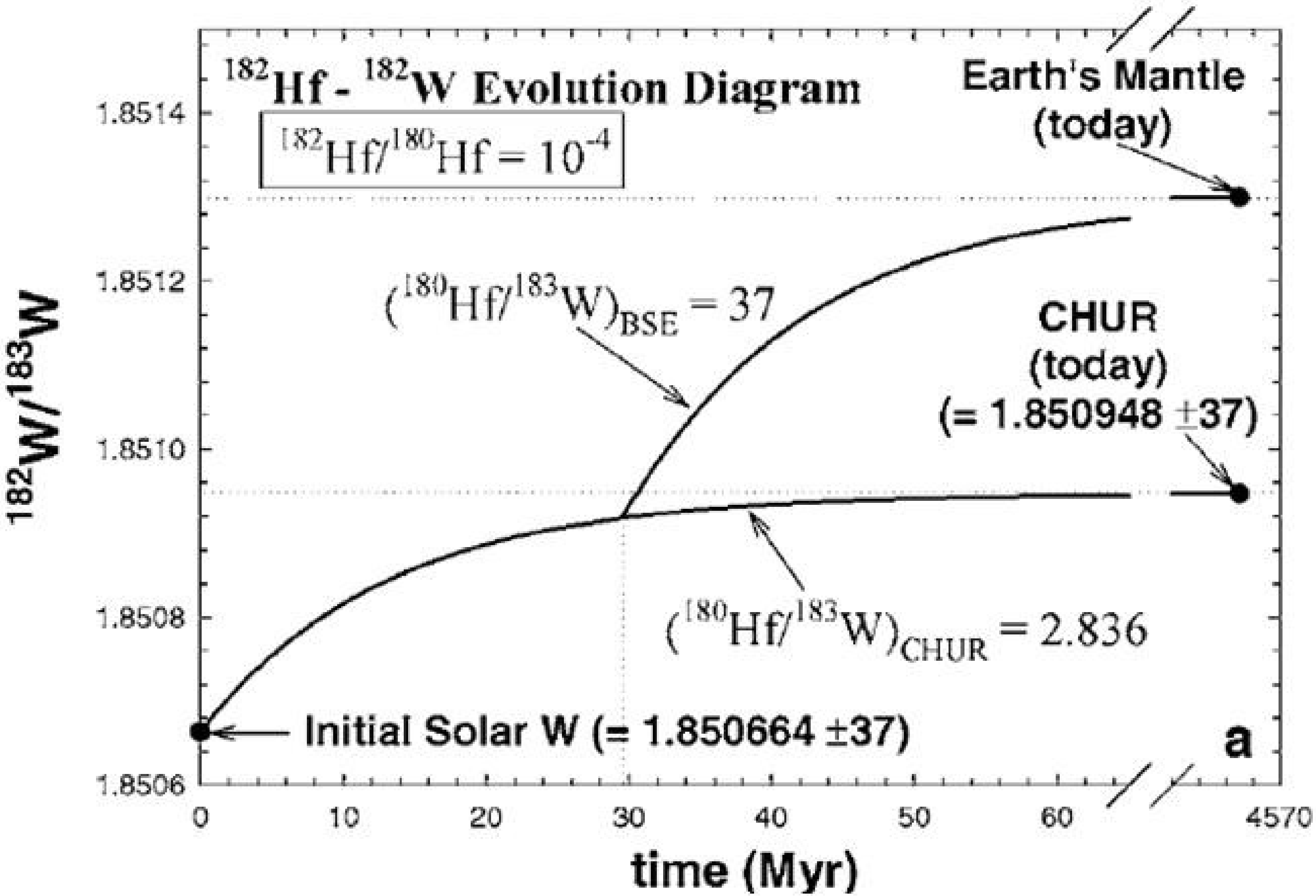
Two-stage **Hf-W** fractionation model

$$\varepsilon^{*}_{W(CHUR)j}(t) = q_W \left(\frac{^{182}Hf}{^{180}Hf}\right)_{T_0} f_j^{Hf/W}[e^{-\lambda t_{2stage}} - e^{-\lambda t}]$$

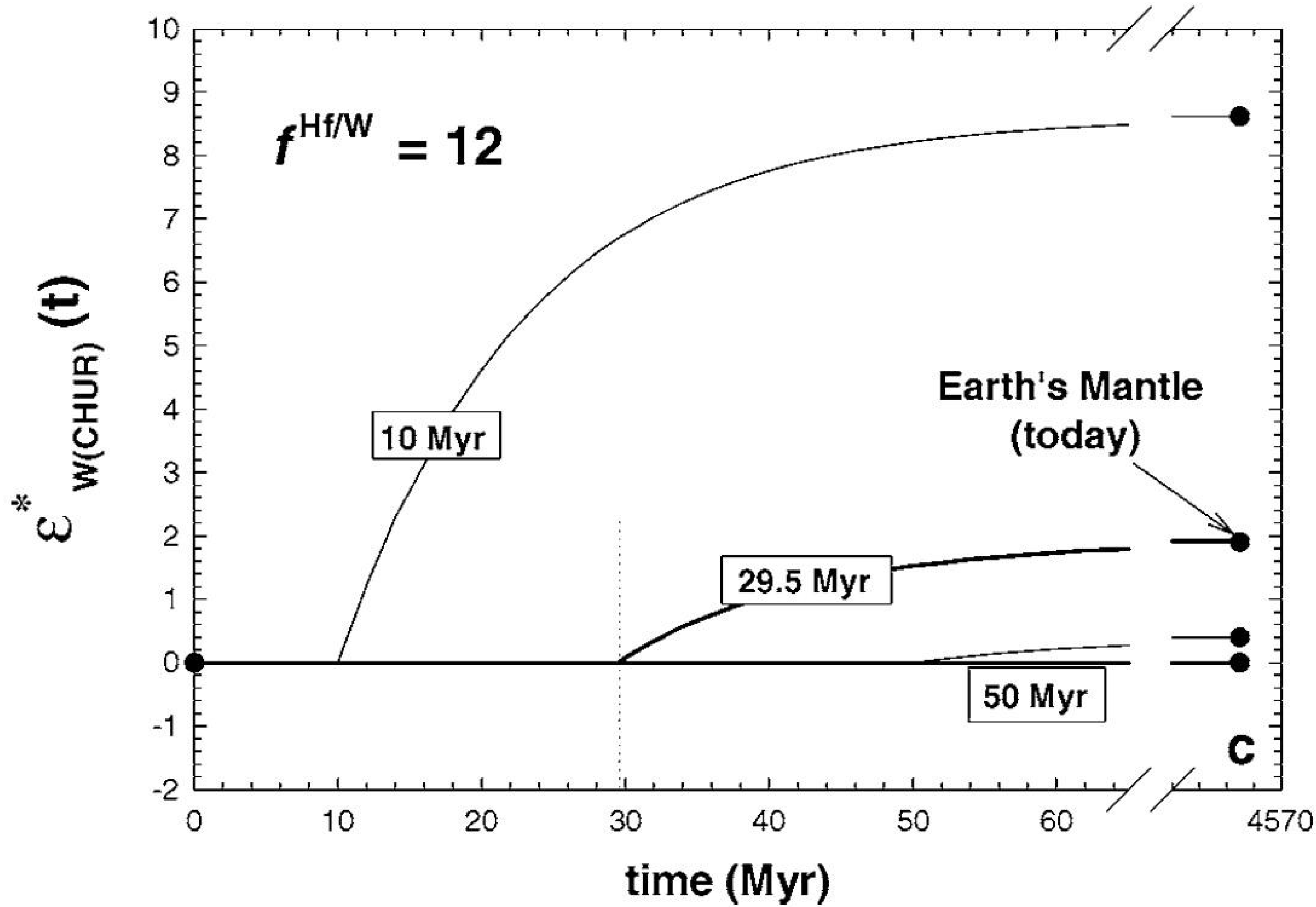
$$t_{2stage} = T_0 - T_{cf}$$

$$q_W = 10^4(^{180}\mathrm{Hf}/^{182}\mathrm{W})^0_{CHUR} = 1.55 \times 10^4$$

$$t_{2stage} = \frac{1}{\lambda}\ln\left[\frac{\left(\frac{^{182}Hf}{^{180}Hf}\right)_{T_0}\left[\left(\frac{^{180}Hf}{^{183}W}\right)_j - \left(\frac{^{180}Hf}{^{183}W}\right)_{CHUR}\right]}{\left(\frac{^{182}W}{^{183}W}\right)^0_j - \left(\frac{^{182}W}{^{183}W}\right)^0_{CHUR}}\right]$$

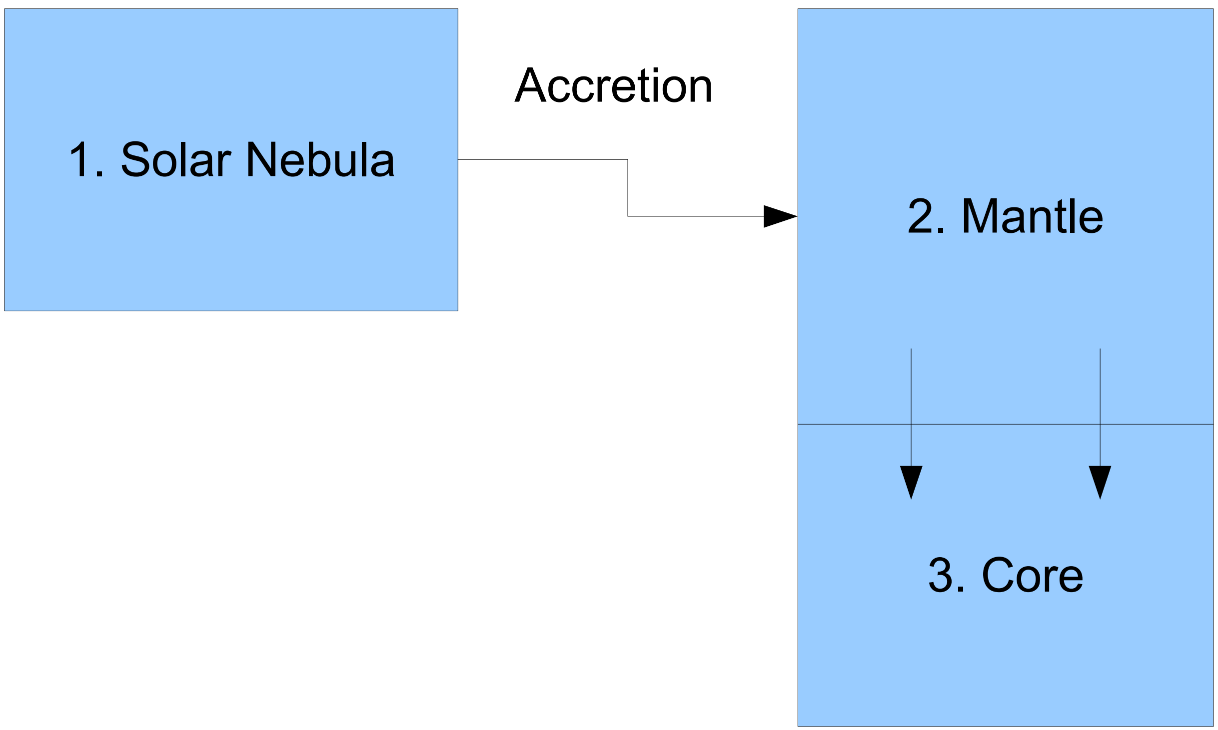


^{182}Hf-^{182}W evolution in early Solar System



^{182}Hf-^{182}W evolution relative to ε_W(CHUR)

Continuous Model



Fractionation

$$f_i^{Hf/W} = \frac{\left(^{180}Hf/^{183}W\right)_j}{\left(^{180}Hf/^{183}W\right)_{CHUR}} - 1$$

A measure of how separated Hf and W have become

Transport of Stable Species

$$d_{i23} = \frac{c_{i3}}{C_{i2}} \qquad \gamma = \frac{\dot{M}_{23}}{\dot{M}_{12}}$$

$$\frac{C_{i2}}{C_{i1}} = \frac{1}{(d_{i23} - 1)\gamma + 1} \qquad \frac{C_{i3}}{C_{i1}} = \frac{d_{i23}}{(d_{i23} - 1)\gamma + 1}$$

Transport of Parents

$$f_2^{r/s} = \frac{\gamma(d_{s23} - d_{r23})}{(d_{r23} - 1)\gamma + 1}$$

$$f_3^{r/s} = \frac{(\gamma - 1)(d_{s23} - d_{r23})}{d_{s23}((d_{r23} - 1)\gamma + 1)}$$

Since d_r23 = 0, we have:

$$f_2^{r/s} = \gamma \frac{d_{s23}}{1 - \gamma}$$

$$f_3^{r/s} = -1$$

Transport of Daughter Isotope

For the specific case of Hf-182 we have that concentrations of daughter products don't vary much over earth's history, and the system is extinct. These give simplifications which lead to the forms:

$$\epsilon_{W(CHUR)} = 10^4 \frac{C_{^{182}Hf\,1}(0)}{C_{^{182}W\,1}(0)} \lambda f_2^{H/W} I(\lambda, t)$$

$$I(\lambda, t) = \int_0^t \left(\frac{M_2(x)}{M_2(t)}\right)^{1+f_2^{r/s}} e^{-\lambda x} dx$$

$$\epsilon_{d3} = \frac{-\epsilon_{d2}}{f_2^{r/s}}$$

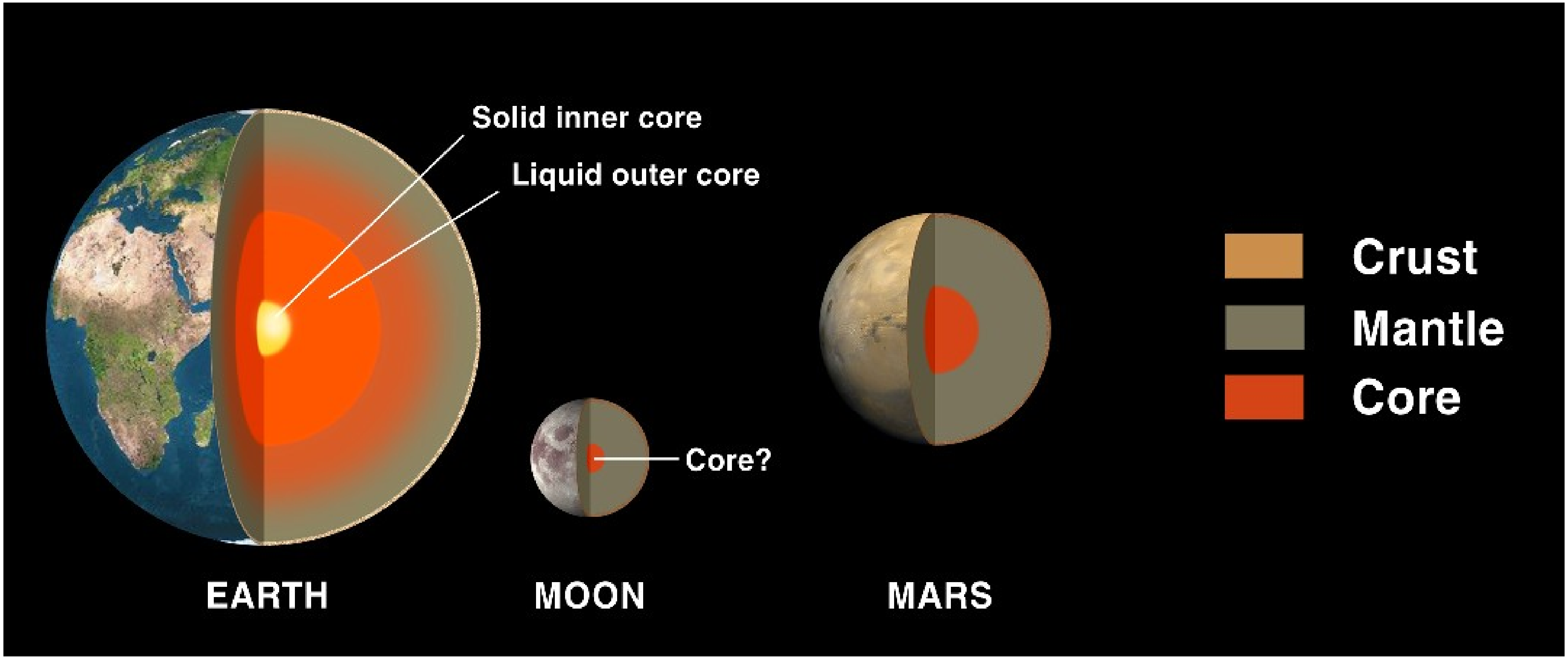
W isotope model constraints

TABLE 2 The isotopic composition of tungsten and chemical fractionations of various planetary mantles and cores

	Mantle $\varepsilon_{W(BSE)}$ (0)	Mantle $\varepsilon_{W(CHUR)}$ (0)	Core $\varepsilon_{W(BSE)}$ (0)	Core $\varepsilon_{W(CHUR)}$ (0)	Mantle $f^{Hf/W}$	t_{2stage} (Myr)	Core mass fraction (γ)	$D_W^{met/sil}$
Earth	*≡0*	1.9 ± 0.2	−2.06 ± 0.05	−0.16 ± 0.05	*12 ± 2*	29.6	*0.325*	24.9
Moon	*1.3 ± 0.4*	3.2 ± 0.4	−2.08 ± 0.05	−0.18 ± 0.05	*18 ± 2*	28.1	*<0.02, 0.325*	>882, 37
IAB	19.1	21	*−3.30 ± 0.15*	−1.40 ± 0.15	(15)	<2.8	*0.2*	60
IIAB	22.1	24	*−3.50 ± 0.36*	−1.60 ± 0.36	(15)	<2.9	*0.2*	60
IIIAB	29.5	31.4	*−3.99 ± 0.60*	−2.09 ± 0.60	(15)	<0.5	*0.2*	60
IVA	30.8	32.7	*−4.08 ± 0.69*	−2.18 ± 0.69	(15)	<0.5	*0.2*	60
IVB	29.2	31.1	*−3.97 ± 0.42*	−2.07 ± 0.42	(15)	~0	*0.06*	235
Vesta	*17 ± 2*	19 ± 2	−3.17 ± 0.34	−1.27 ± 0.34	*15 ± 2*	2.6	*0.2*	60
Mars—S source	*0.5 ± 0.5*	2.4 ± 0.5	−3.10 ± 0.52	−1.20 ± 0.52	*2.0 ± 0.8*	3.3	*0.2*	8
Mars—NC source	*2.5 ± 0.5*	4.4 ± 0.5	−2.63 ± 0.25	−0.73 ± 0.25	*6 ± 1*	9.7	*0.2*	24

Values in italics are primary data (see text for sources), other values are inferred from these. Numbers in parentheses are best guesses.

Cores of terrestrial planets



Earth	t_{2stage} = 28.1 Myr
Moon	t_{2stage} = 29.5 Myr
Mars	t_{2stage} = 3.3/9.7 Myr
Iron meteorites	t_{2stage} < 2.8 Myr

Asteroid *Vesta*

- Eucrites (“easily discerned”)
- Vesta’s mantle t_{2stage} = 2.6 Myr