# Early inner Solar System inferred from unique surface chemistry of Mercury

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Mercury is an end-member planet in many aspects: the distance to the Sun, the size, the amount of atmosphere, and the ratio of the core size to the planetary size. In addition to these previously known facts, the MESSENGER mission provides geochemical information that highlights the uniqueness of the planet. One of the most interesting fact is that the surface of Mercury is rich in sulfur and carbon; such volatile elements are expected to be depleted in Mercury because of a giant impact that leads to a large core size. In this presentation, we provide a consistent scenario that explains volatile-rich surface and a giant impact. The key is the redox state of the inner Solar System; if the environment is highly reducing, sulfur and carbon lose their volatility and behave as refractory elements. We hypothesize that a reducing environment was the result of infall of dust- (and thus carbon-) rich material from the outer part of the Solar System. Even if building blocks are composed of highly reduced material, the growth of a planet leads to an oxidized surface during core formation. Here, the key is the core-mantle boundary (CMB) pressure. A giant impact significantly reduces the CMB pressure for Mercury, turning its surface redox state back to its early stage.

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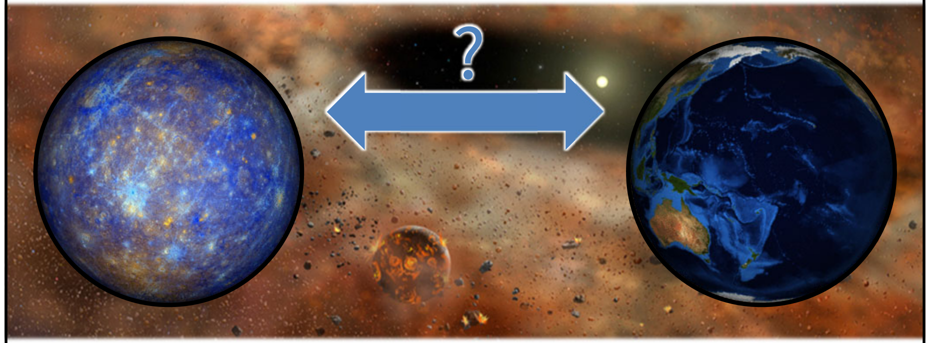
Gemini Observatory/AURA artwork by L. Cook

## Link to other planets?

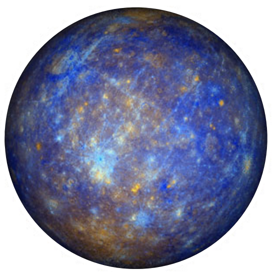



Mercury: NASA/JHUAPL/CIW; Earth: Reto Stöckli, NASA Earth Observatory

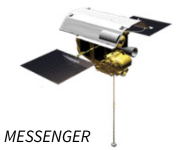
## Mercury: an extremely unique planet

- Innermost, smallest
- No ocean, no thick atmosphere
- Large core

*Mariner 10*



- No FeO
- Sulfur rich
- Carbon rich (?)

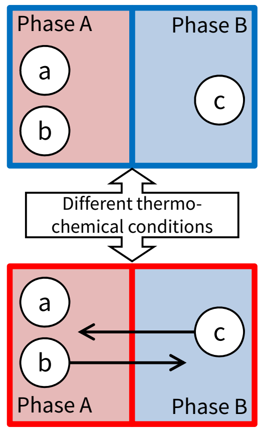


*MESSENGER*

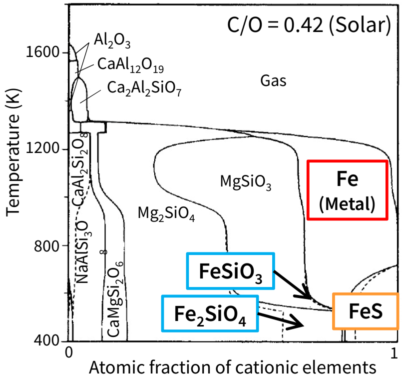
*Mariner 10*: NASA; *MESSENGER* and Mercury: NASA/JHUAPL/CIW

## How to infer the past

- **Partitioning of elements**
  - In nebula (low pressure): Gas or solid
    - Condensed material depends on the environment
  - Inside an early Mercury (high pressure): Silicate or metal (i.e., mantle or core)
    - Not all the solidified material can be observed if it goes to the deep interior



# Condensates in a high temperature

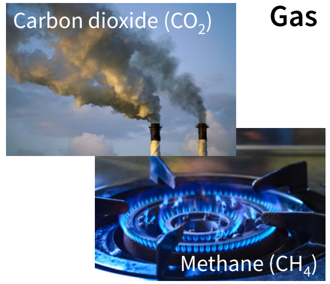



[Adapted from Wood & Hashimoto, 1993]

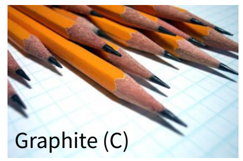
- Mercury's building block may be formed from material condensed in a high-temperature region of the solar nebula
- **Iron condenses as Fe (metal) at a high temperature**
  - Iron oxides (FeO) and sulfides (FeS) forms when temperature is sufficiently low
  - FeO: < 1000 K
  - FeS: < 800 K

# Redox state matters

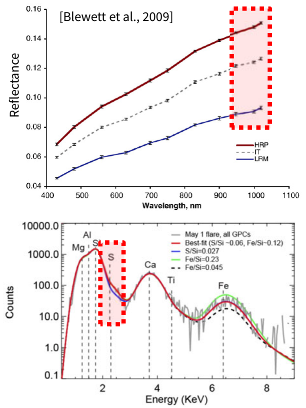
- Redox = Reduction-Oxidation reaction
  - Reduction: Gain of electrons ($CO_2 \rightarrow C \rightarrow CH_4$)
  - Oxidation: Loss of electrons ($CH_4 \rightarrow C \rightarrow CO_2$)




Different phases under the same temperature and pressure



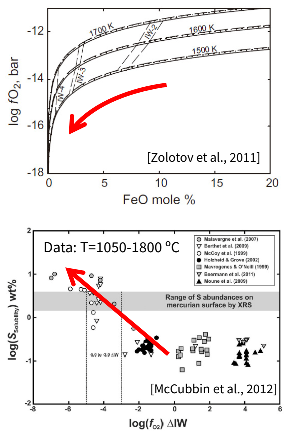

# *MESSENGER* Observations




[Adapted from Nittler et al., 2011]

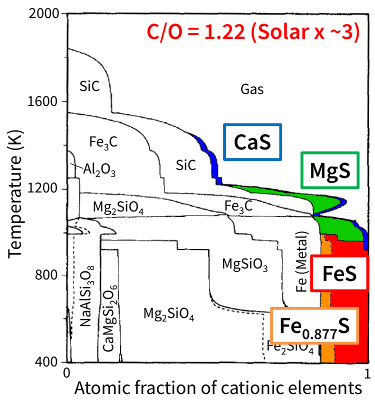
- Depleted in FeO [e.g., Blewett et al., 2009]
  - No strong absorption at ~1 μm
  - **Consistent with a high-temperature origin** of building blocks
- Enriched in sulfur [e.g., Nittler et al., 2011]
  - X-ray and gamma-ray indicate S of ~2 wt%
  - **Seems to be *inconsistent* with a high-temperature origin** of building blocks
  - In addition, S should go to the metallic core
    - S condenses as FeS

# Redox state of Mercury's mantle




- Low FeO and high S content in silicate both require a low oxygen fugacity ($fO_2$) [e.g., Zolotov et al., 2011]
  - $2xFe + O_2 = 2Fe_xO$
  - $MgS\ (melt) + 0.5\ O_2 = MgO\ (melt) + 0.5\ S_2$
  
  $O_2$-poor
- Mercury's building blocks should be formed under a **reducing (i.e., O-depleted) condition**
  - Why? What removes Oxygen?

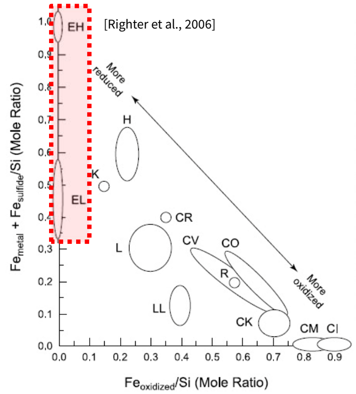
## Idea: Carbon-rich environment




[Adapted from Wood & Hashimoto, 1993]

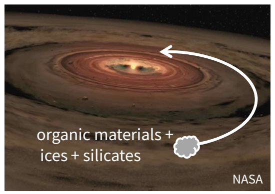
- Consumption of O by CO formation at a high temperature
  - CO is stable gas
- Expected consequences on surface chemistry
  - FeO-depleted and S-rich solids
  - Correlation between Ca and S [Weider et al., 2012]
  - Carbon [e.g., Peplowski et al., 2016]
  - **Consistent with *MESSENGER* observations!**

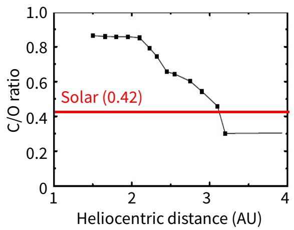
## Highly reduced material: Enstatite chondrites




- Uncommon type (a few %) of meteorites
- Unique major elemental composition
  - No FeO
  - CaS is a major sulfide
  - Similar to the surface of Mercury [Nittler et al., 2011]
- **Isotopic composition is identical to the Earth**
  - Major building blocks of the Earth?

## Spiral infall of dust particles

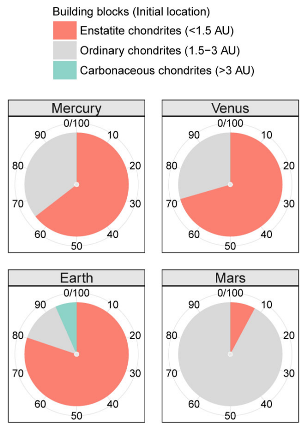



- Dusts and gases both rotate around the Sun
- Dusts feel head wind and get closer to the Sun
- As a dust particle approaches the Sun, ices evaporate first because of temperature increase
- Then **organic materials evaporate, leading to a carbon-rich (and thus reducing) inner solar nebula**

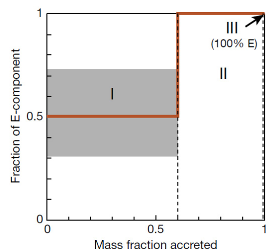
C/O estimates based on evaporation experiments of organic material
[Nakano et al., 2003]

## Building blocks of planets



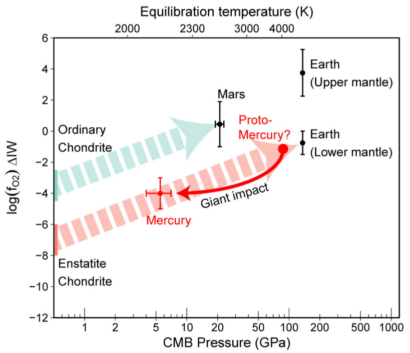

- **Enstatite chondritic material is expected to be the dominant building block of Mercury, Venus, and the Earth** [Rubie et al., 2015; Brasser et al., 2017]

[Based on Brasser et al., 2017]




Earth's building blocks with time inferred from isotopic compositions of various elements
[Dauphas, 2017]

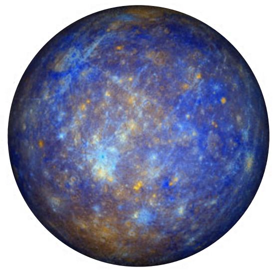
## Evolution of the mantle redox state




Mercury: McCubbin et al. [2012], Hauck et al. [2013]
Earth: Frost & McCammon [2008], Dziewonski & Anderson [1981]
Mars: Wadhwa [2001], Rivoldini et al. [2011]; OC: Grossman et al. [2008]
EC : Javoy et al. [2010]; Eq. Temp.: Rubie et al. [2015]

- Growth of a planet oxidize its mantle [e.g., Javoy, 1995]
  - $SiO_2$ (silicate) + 2Fe (metal) = Si (metal) + 2 FeO (silicate) (High-*P*)
  - The early Earth may be as reducing as Mercury
- **Giant impact on Mercury turned its redox state back**
  - Current Mercury may be similar to the growing stage of the Earth

## Summary



- MESSENGER revealed that the surface chemical composition of Mercury is unique, indicating a highly reducing condition
- High C/O ratio of the inner Solar nebula achieved by infalling of carbon-rich dust particles is inferred
- Enstatite chondrites may be a major building blocks not only of Mercury but also of the Earth (+ Venus)
- Mercury's unique surface may provide insights on the growing stage of terrestrial planets

Original image credit: NASA/JHUAPL/CIW

## Next steps


© Spacecraft: ESA/ATG medialab;
Mercury: NASA/JPL

- Isotopic composition & abundance of carbon on Mercury (landing?)
- High temperature/pressure experiments to understand the chemical composition of the cores
- Study of proto-Mercury
- Redox state of Venus mantle
- Exploration of enstatite chondritic (E-type) asteroids
- …