初期地球における大気の起源と生命前駆物質

杉田精司、桑原秀治
東京大学

宇宙生命計算科学連携拠点
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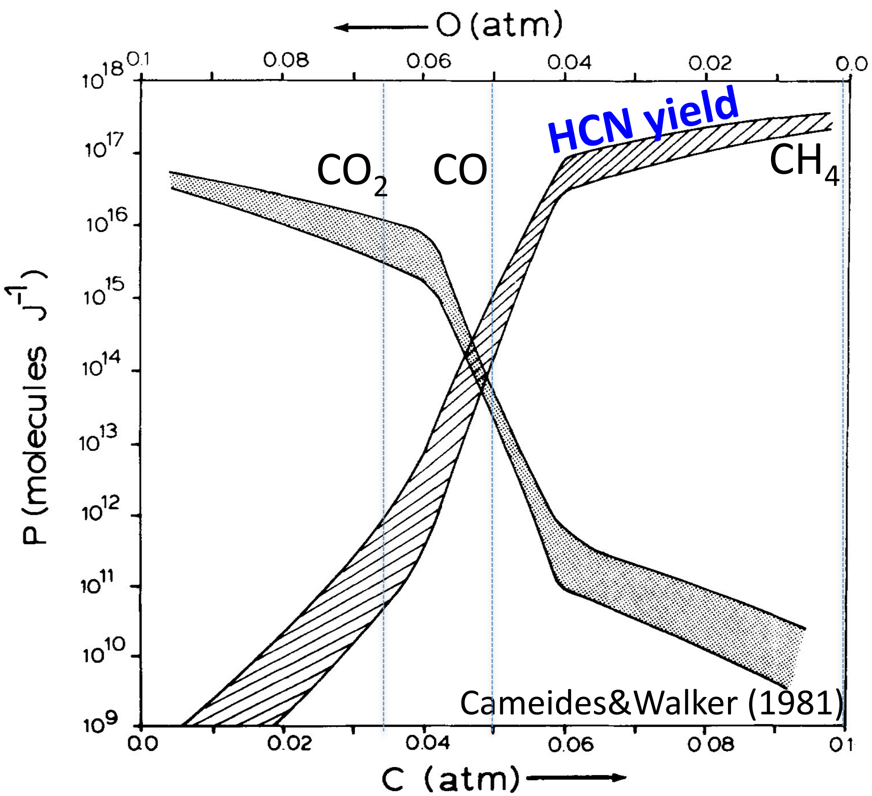
Supply of Life's Ingredients

- **Organic yields from atmospheric reactions depends strongly on its redox state.**
  - Organic yields:
    - $CH_4 >> CO >> CO_2$ (e.g., Fegley+1986 *Nature*; Stribling & Miller, 1987 *OoL*)



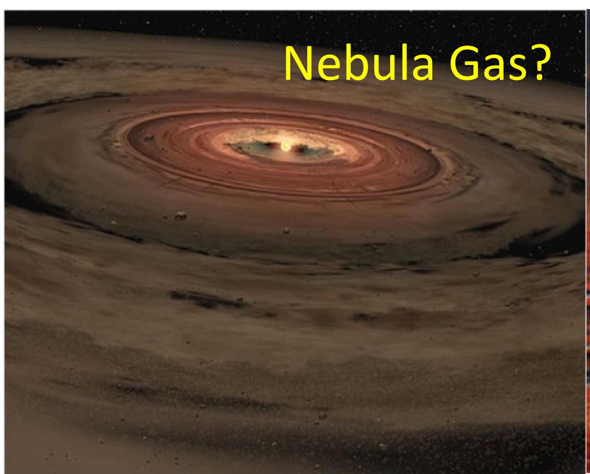
- **This trend do not depend strongly on specific chemical reaction mechanisms.**
  - Lightening (e.g, Miller, 1953 *Science*)
  - UV radiation (e.g., Sagan&Khare, 1971, *Science*)
  - Shockwaves (Barak and Bar-Nun, 1975, *OoL*)

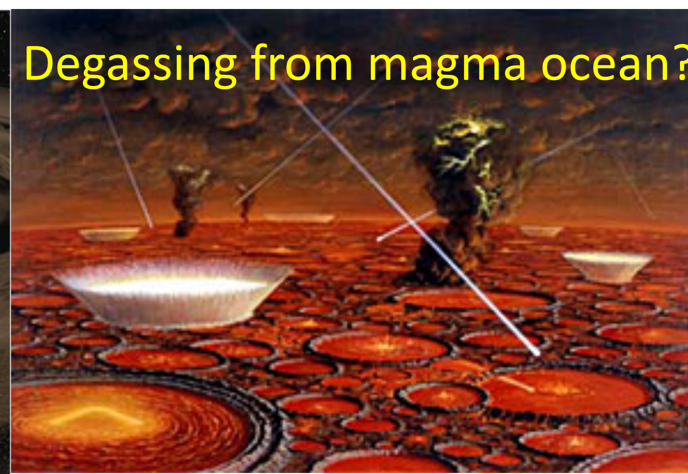
  ※ All of these are radical reactions.

- **A small amount (1000ppm) of CH_4 in a CO_2 atmosphere may yield a significant amount of HCN via photochemistry** (Zahnle+ 1986 *JGR*; Tian+ 2011 *EPSL*).

Volatile Sources for the earliest atmospheres

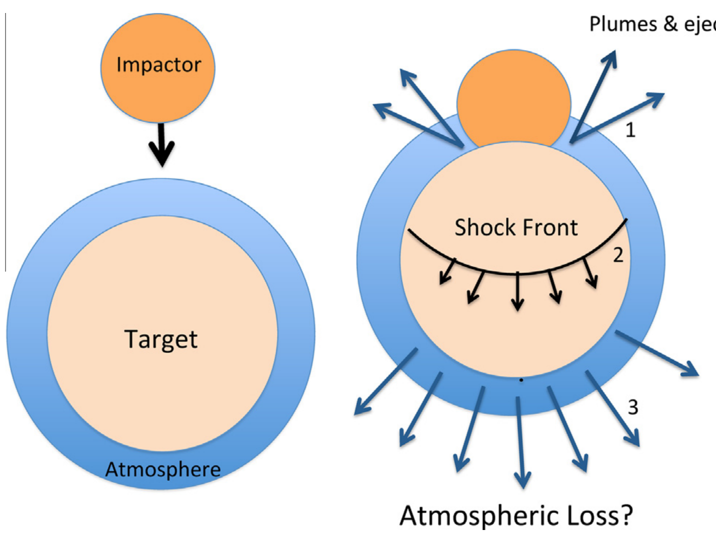
- Solar nebula (e.g., Lewis & Prinn 1984; Ikoma & Genda, 2006)
- Degassed from magma ocean during the main accretion phase (e.g., Abe & Matsui, 1985; Elkins-Tanton & Seager, 2008; Hirschmann, 2012)
- Volatiles delivered by meteoritic impacts after magma ocean solidification (e.g., Chyba, 1990; Alberde, 2009; Holland+, 2009)
- Different redox states and timings.
  - Nebula is clearly very reducing.
  - But the redox of the others are difficult to estimate.

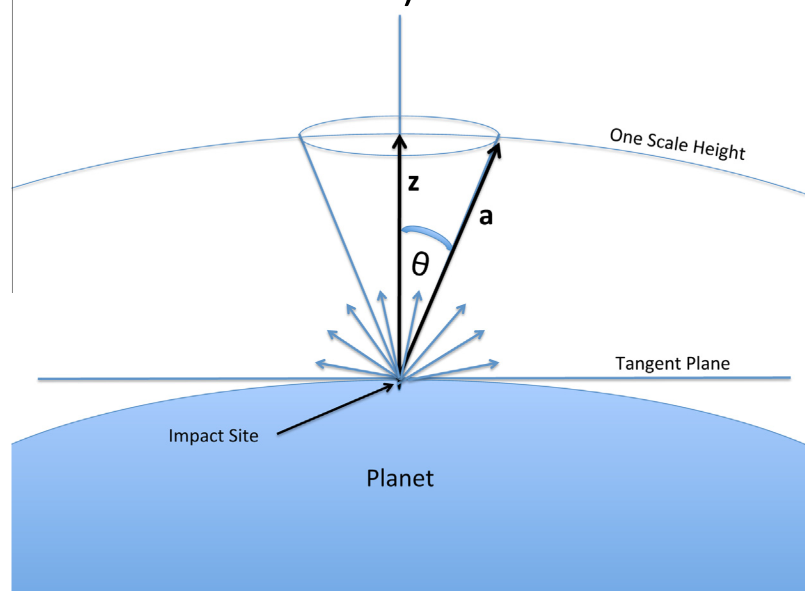




Loss of the earliest atmospheres

- Giant impacts would strip away the earliest atmosphere if H_2O is condensed to an ocean (Genda and Abe 2005 *Nature*).
  - Earth may have lost the nebular component of its atmosphere, but Venus may have retained.
  - Supported by noble gas abundance difference between Earth & Venus.
- Impacts by smaller planetesimals may be able to erode a pre-exiting atmosphere very efficiently (Schlichting+ 2015 *Icarus*).
- Impacts may have replaced the earliest atmosphere with an impact-generated atmosphere (de Niem+2012 *Icarus*).

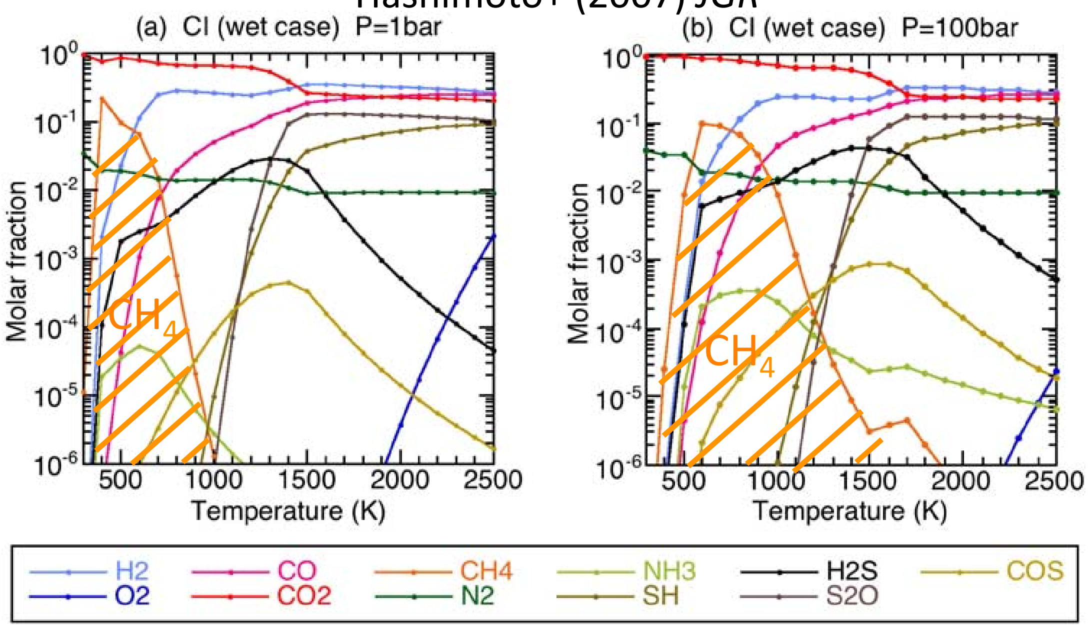




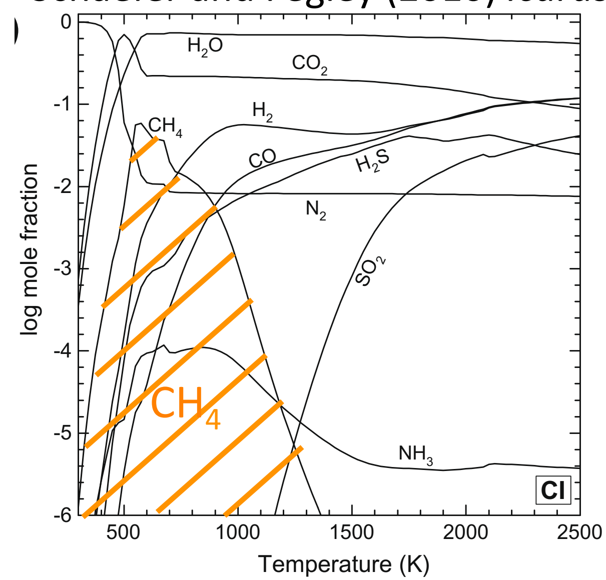
The Composition of Impact-generated atmosphere (Hashimoto+2007 *JGR*; Schaefer&Fegley 2010 *Icarus*)

- Chondrites will yield reducing gas; rich in C and H.
  - CI, CM, CV, LL, L, H…
- Molecular composition is uncertain; H_2+CO or CH_4+H_2O depending on quench *T*.
  - An accurate *P*-*T* path is needed.
  - F/T Catalyst may be needed for CH_4 formation (*cf*, Kress&McKay 2004 *Icarus*).
  - H_2 is easier to escape from planets.
  - CH_4 can form organics more efficiently (e.g., McKay and Borucki, 1997 *Science*).

Hashimoto+ (2007) *JGR*

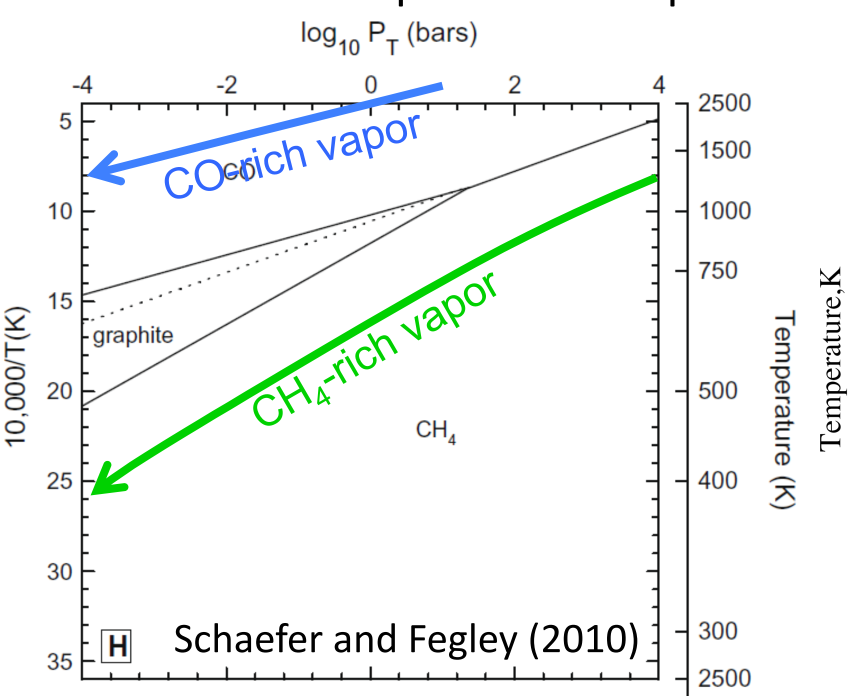


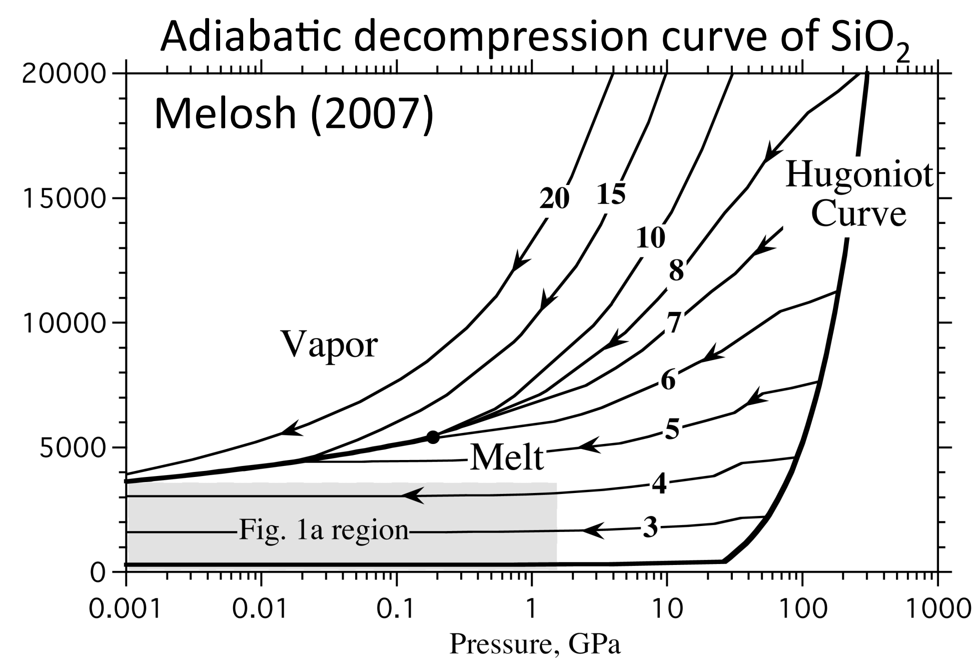
Schaefer and Fegley (2010) *Icarus*



Chemical reactions within impact vapor plumes

- How does the molecular composition of the impact vapor evolve?
  - Initial shock compression/heating lead to rapid thermal equilibriation.
    - Recent >10 km/s laser shock experiments indicate that typical planetary-velocity impacts vaporize silicates (Kraus+, 2012 *JGR*; Kurosawa+, 2012 *JGR*)
  - Subsequent adiabatic decompression leads to cooling.
    - When chemical reaction is caught up by cooling, reaction quenches.
    - Chemical reaction keep up with adiabatic cooling until pressure reaches the ambient pressure, radiative cooling will take over.
    - Resulting molecular composition depends on the *P*-*T* path.
    - Adiabatic paths in *P*-*T* space are usually very complicated!





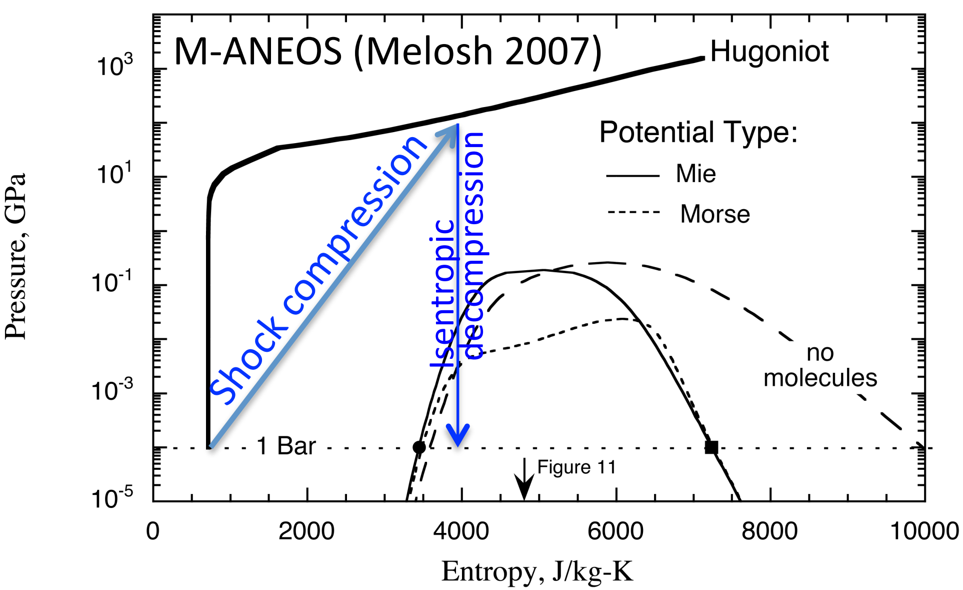
“Entropy matching” method

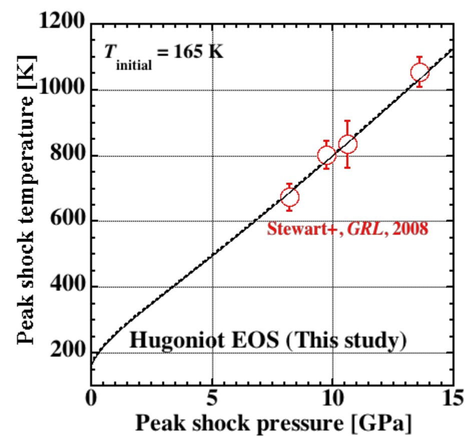
- Calculate the entropy gain ΔS due to impact heating (Sugita+ 2012 *SCCM*).
  - ΔS can be obtained with integration along Hugoniot and Vs-Up and *Cv* data.

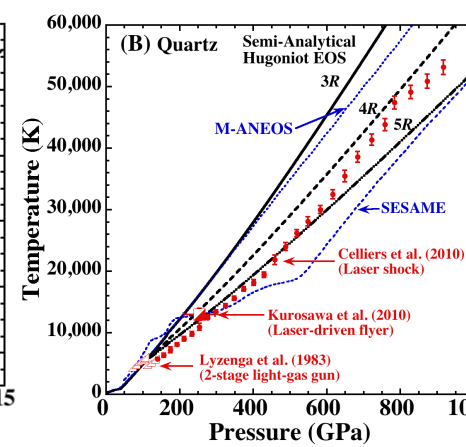
$$\frac{dT}{dU_p} = C_o \Gamma_o T \frac{(U_s - U_p)^{q-1}}{U_s^{q+1}} + \frac{sU_p^2}{C_v U_s} \qquad \frac{dS}{dU_p} = \frac{sU_p^2}{TU_s}$$

- Calculate the equilibrium composition for different *S* around quenching *T*.
  - Thermochemical codes based on ideal-gas EOS can be used (e.g., Gordon & McBride, 1994).
- Estimate the quenching *T* to obtain the terminal molecular composition.

※ The basic idea was given by Stevenson (1987) *AREPS*.







Sugita+ (2012) *SCCM*

Entropy gain of impactors during shock compression

(Kuwahara and Sugita 2015 *Icarus, 257,* 290–301)

■ Controlling factors

1) Impact velocity (terminal accretion)

Mars: ~10 km/s (*S*=~3kJ/K/kg)

Earth: ~16 km/s

- On ocean (*S*=~3.2 kJ/K/kg)
- On land (*S*=~4.6 kJ/K/kg)

Venus: ~18 km/s (*S*=~5 kJ/K/kg)

(Raymond+, 2013)

2) Target properties

Mars: Land (silicates)

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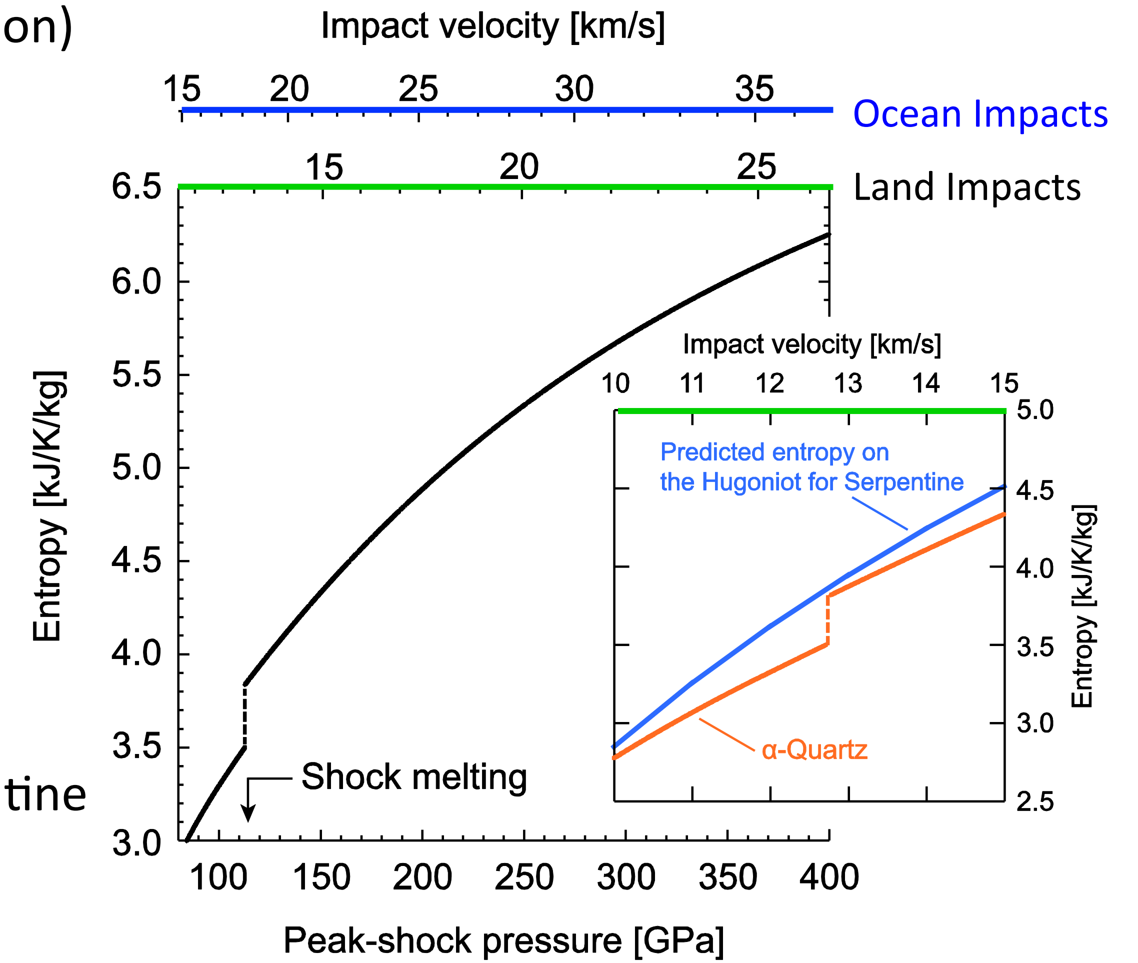
3) Projectile properties

Approximate with quartz/serpentine



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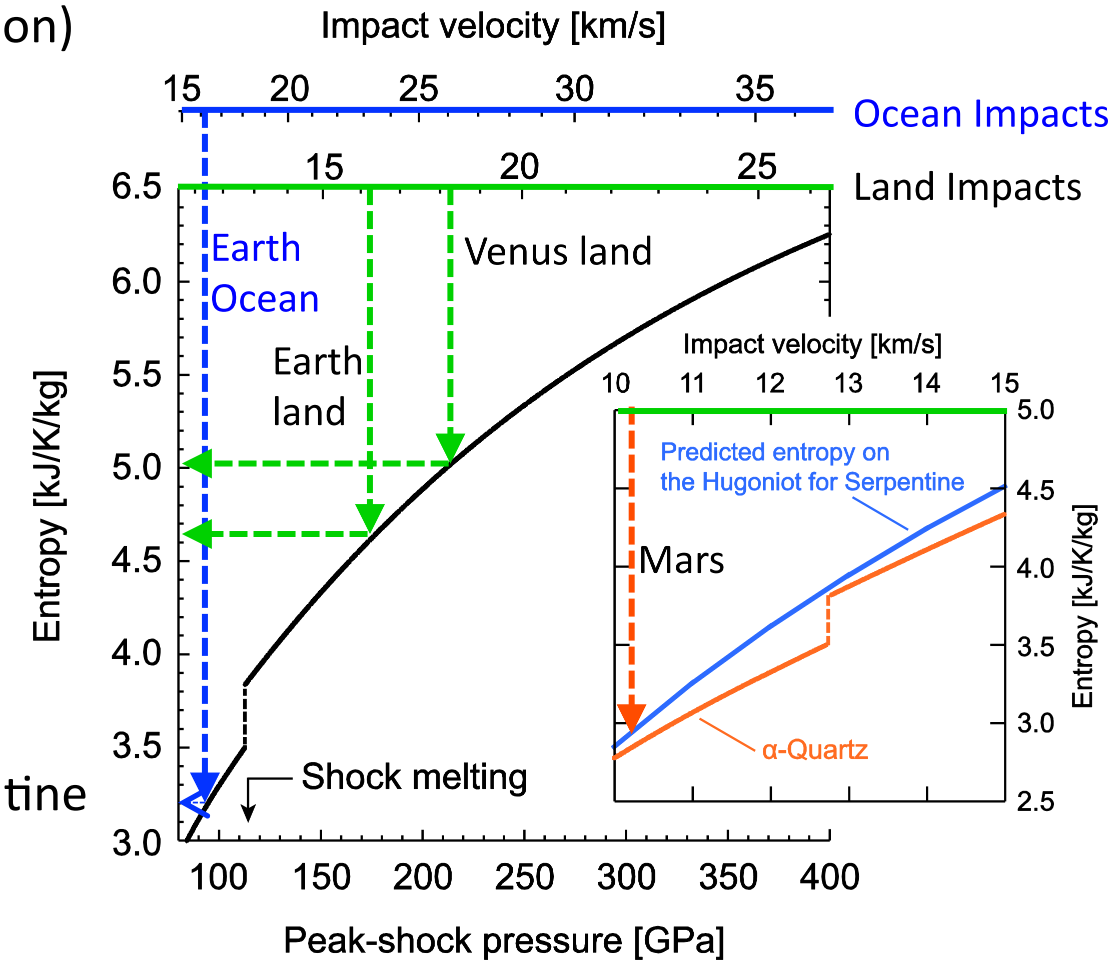
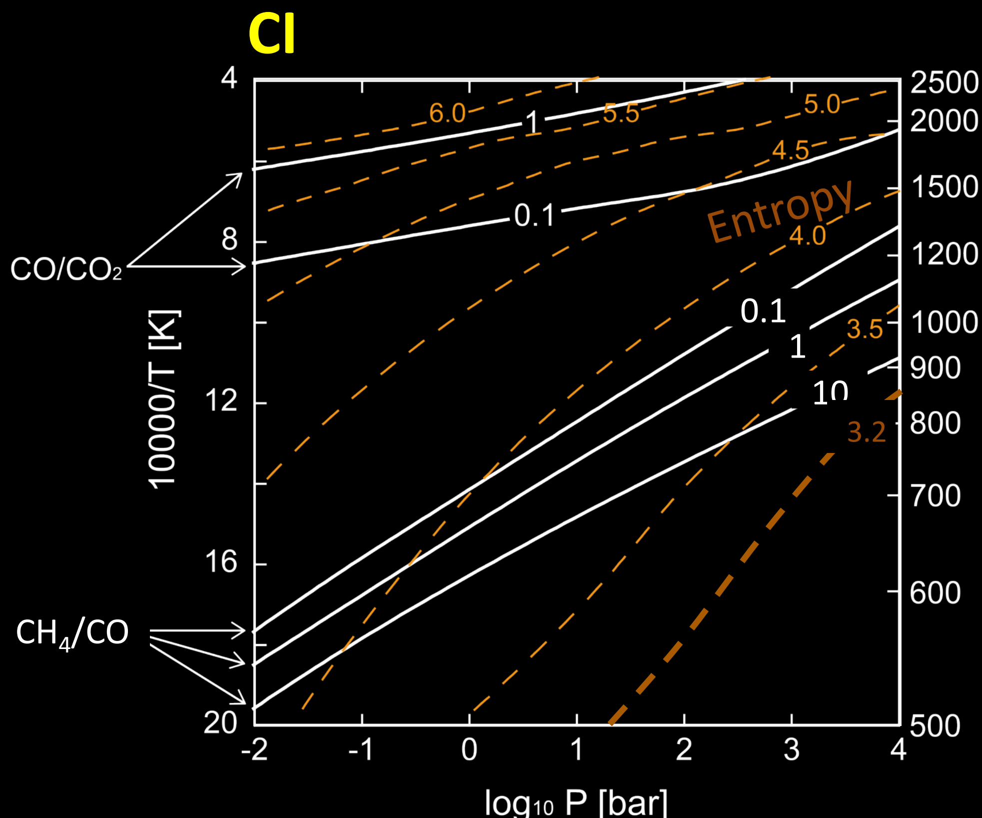


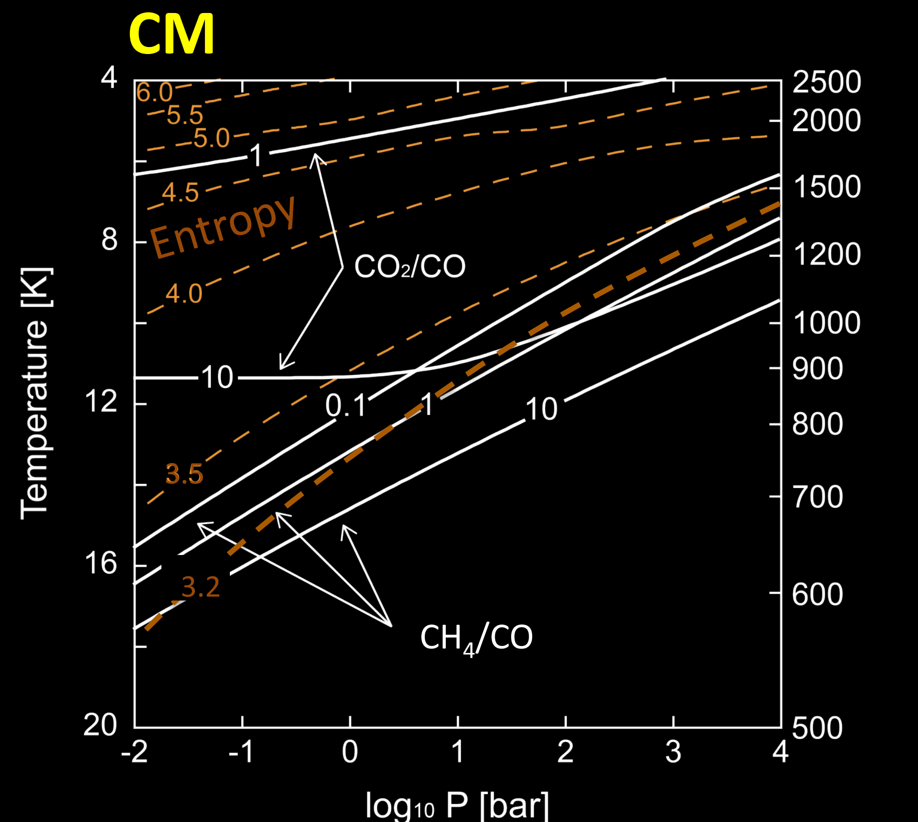
■ The range of the entropy gain

3 – 5 kJ/K/kg

■ Gibbs free energy minimization code (CEA) (Gordon & McBride, 1994)

The composition of carbon species of CI-CM vapor





- A low *S* vapor is favorable for formation of polyatomic molecules (i.e., CH_4).
- Impacts on Mars and ocean on Earth generate CH_4-rich vapor **without catalyst**, because CH_4 is stable from the before the vapor cooling.

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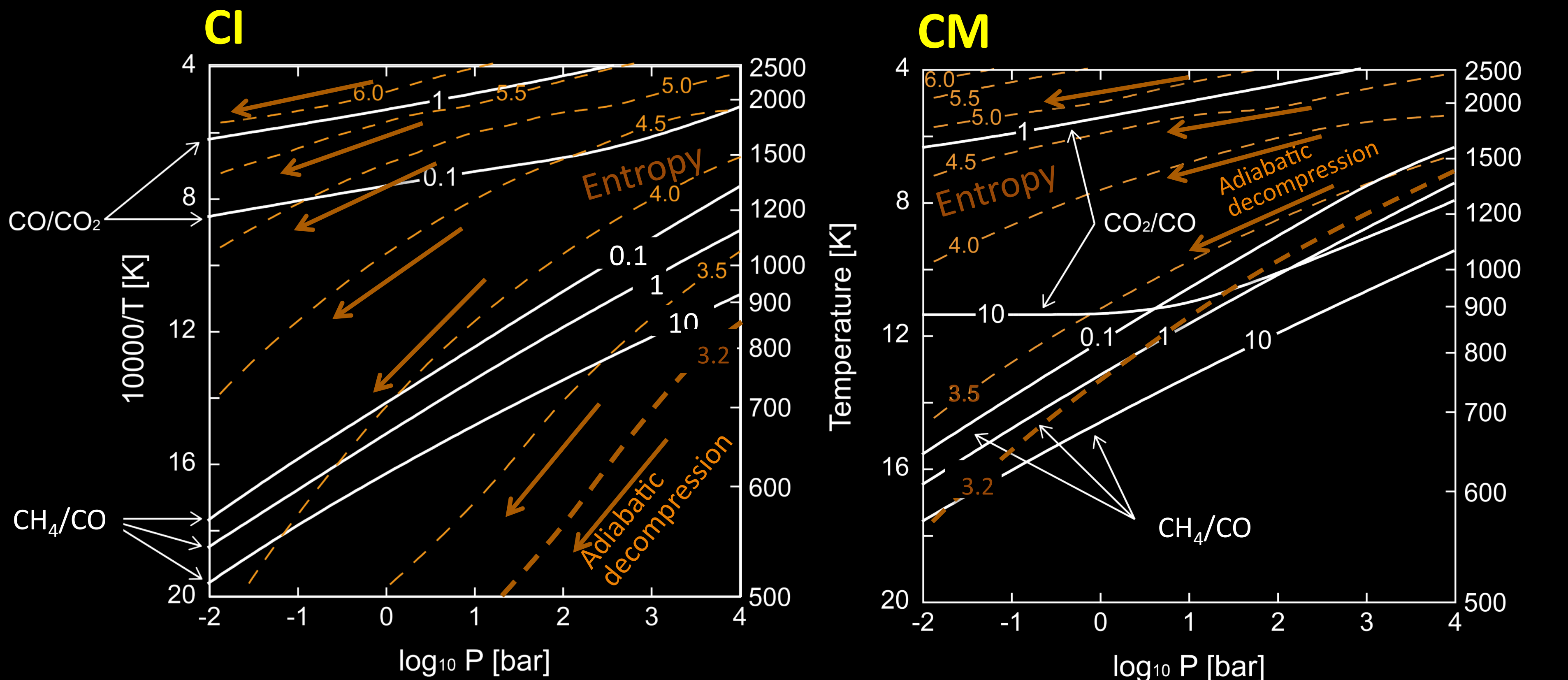

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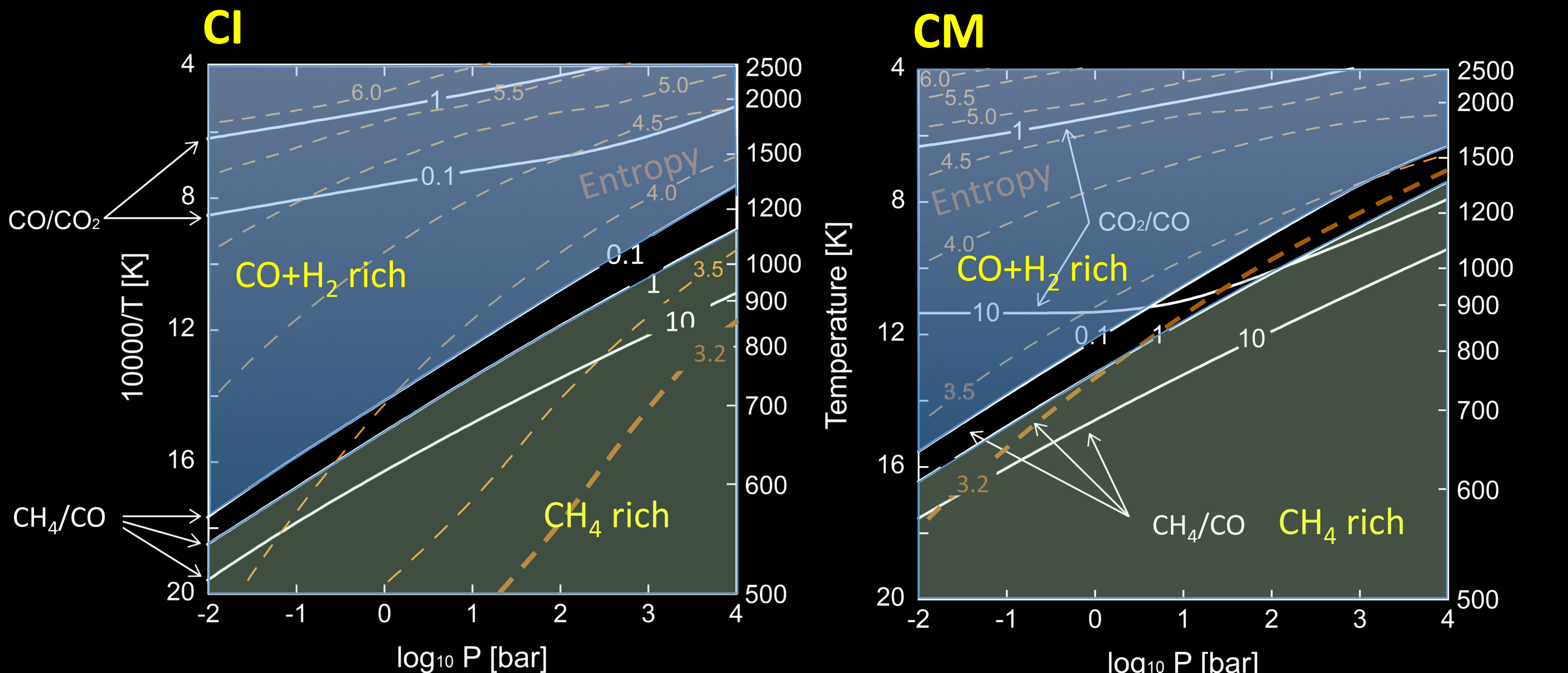

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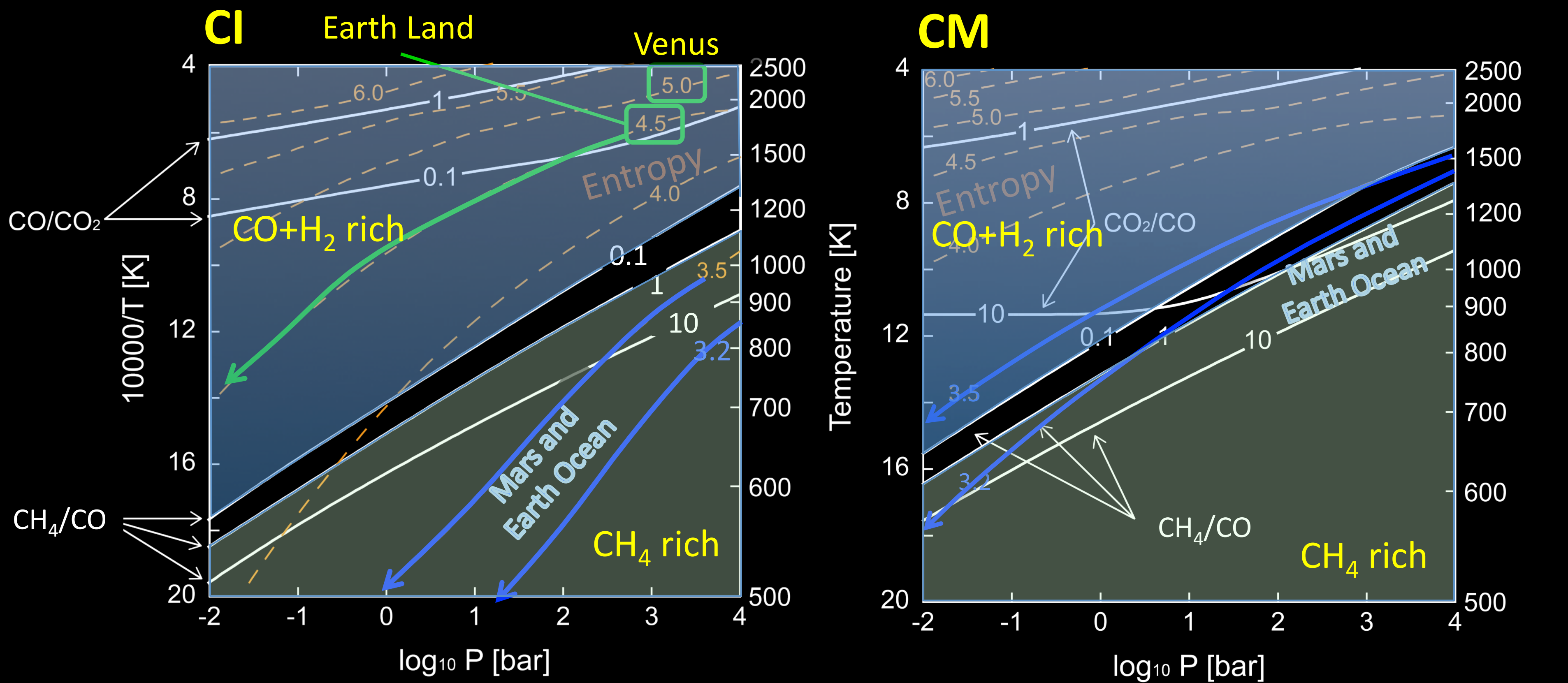

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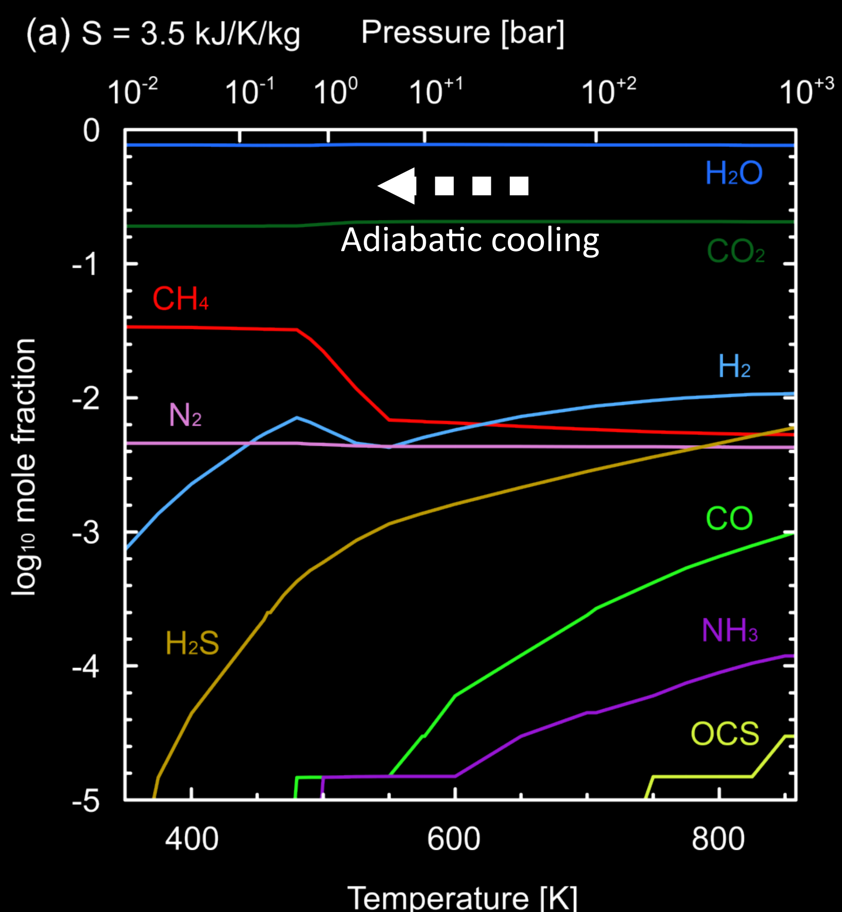
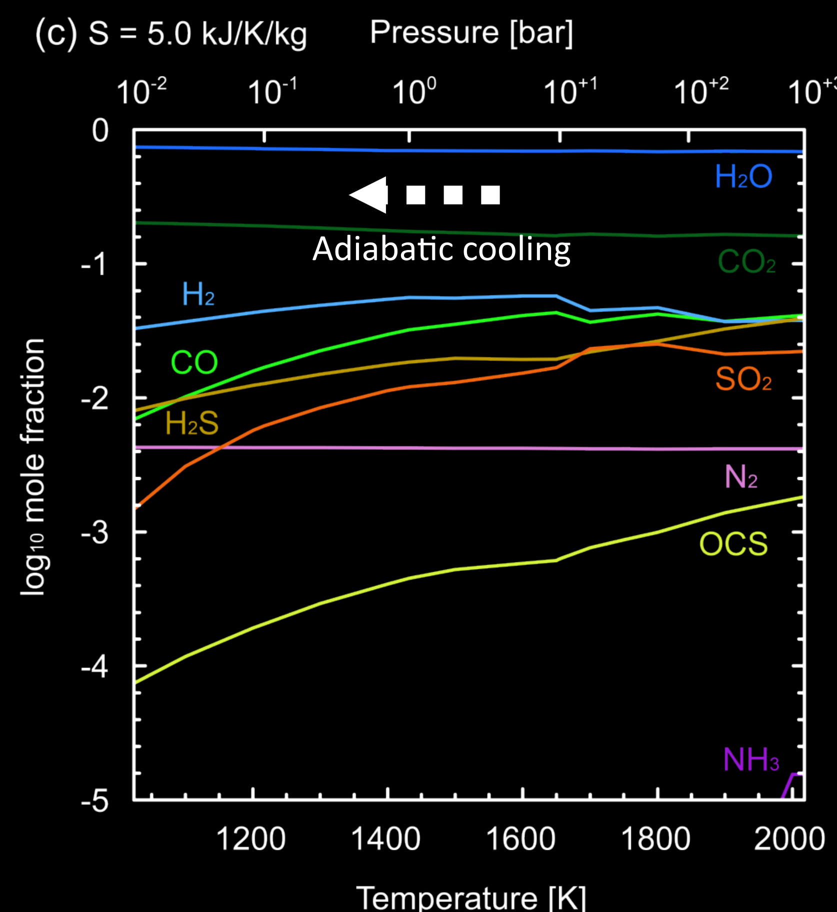
The molecular composition of CI-chondrite vapor

- **Mars impacts and Earth ocean impacts**



- ■ 1000 ppm ~ % of CH_4; CH_4 > CO

- **Earth land impacts and Venus impacts**



- ■ No appreciable CH_4; CO+H_2

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(Kuwahara and Sugita 2015 *Icarus, 257,* 290–301)

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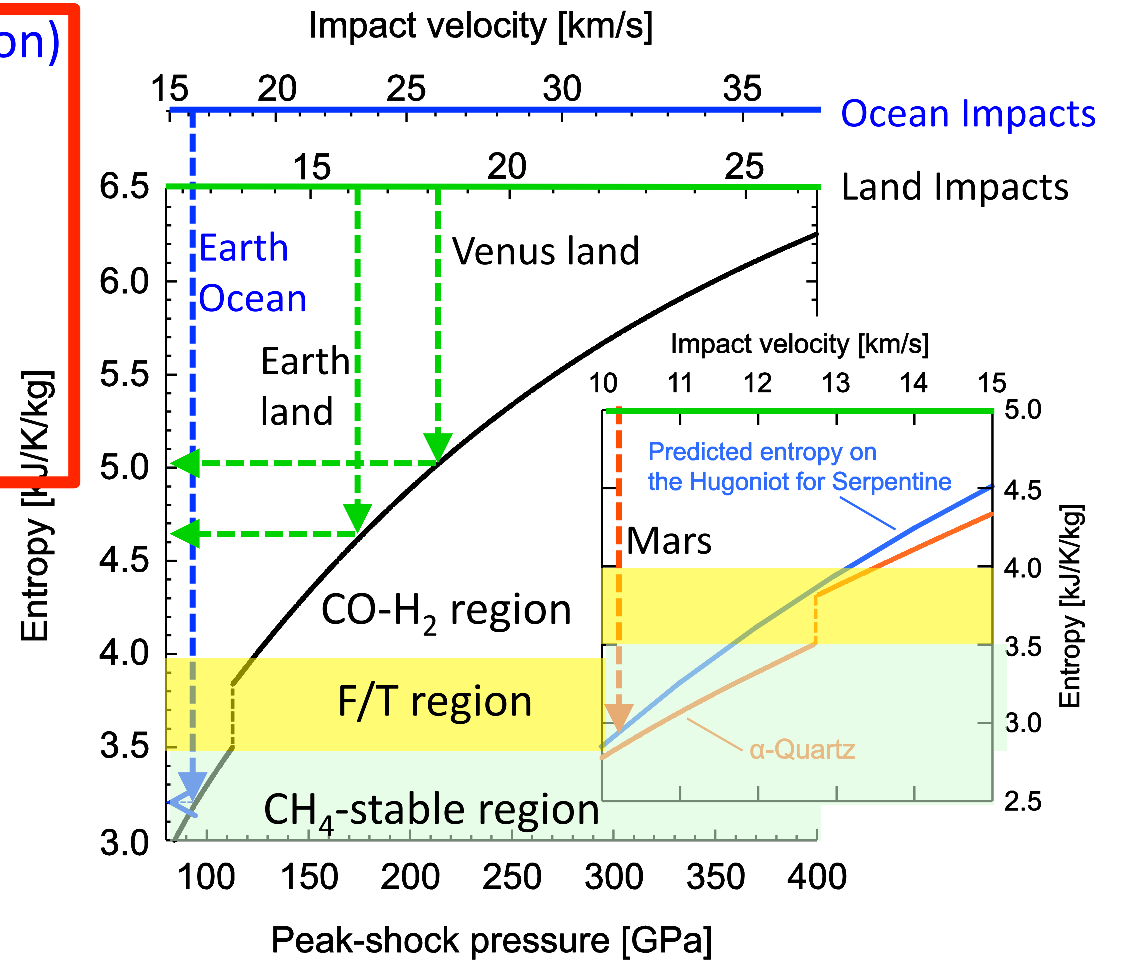
   (Raymond+, 2013 *Icarus*)

2) Impact velocity (LHB)
   - Mars: 13 km/s (*S*=~4 kJ/K/kg)
   - Earth: 20 km/s
     - Ocean (*S*=~4.1 kJ/K/kg)
     - Land (*S*=~5.3 kJ/K/kg)
   - Venus: 26 km/s (*S*=~5.8 kJ/K/kg)

   (Minton and Malhotra, 2010, *Icarus*)



- **There are three different regions for CH_4 stabilities.**
- **Elevated impact velocity during LHB reduces a chance of CH_4 formation.**

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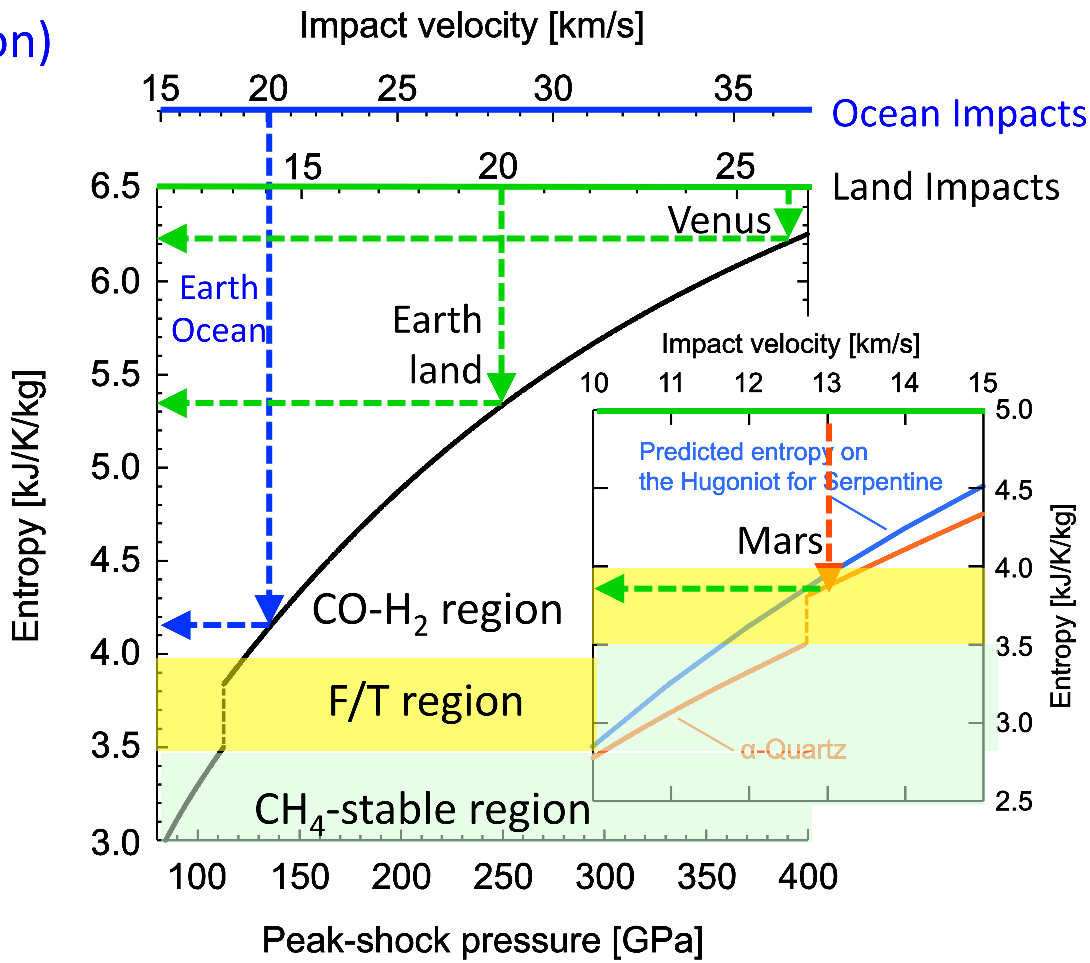

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Summary on impact-generated atmospheres

- Volatiles from meteoritic impacts after magma ocean solidification may have been a major source for early terristrial atmospheres.
- Volatile-rich impacts in the terminal phase of accretion on Mars and Earth ocean would have formed a CH_4-rich vapor plumes.

⇩

- If volatile-rich chondrites were dominant impactors during the terminal phase of accretion (e.g., late veneer), early terrestrial planets may have CH_4-rich (100's ppm ~ %) atmospheres.
  - Important implications for organic supply to prebiotic Earth and wet and warm Mars in its early history.

- No catalyst is needed for CH_4 formation.
- Low impact velocities and high volatile content are the key!

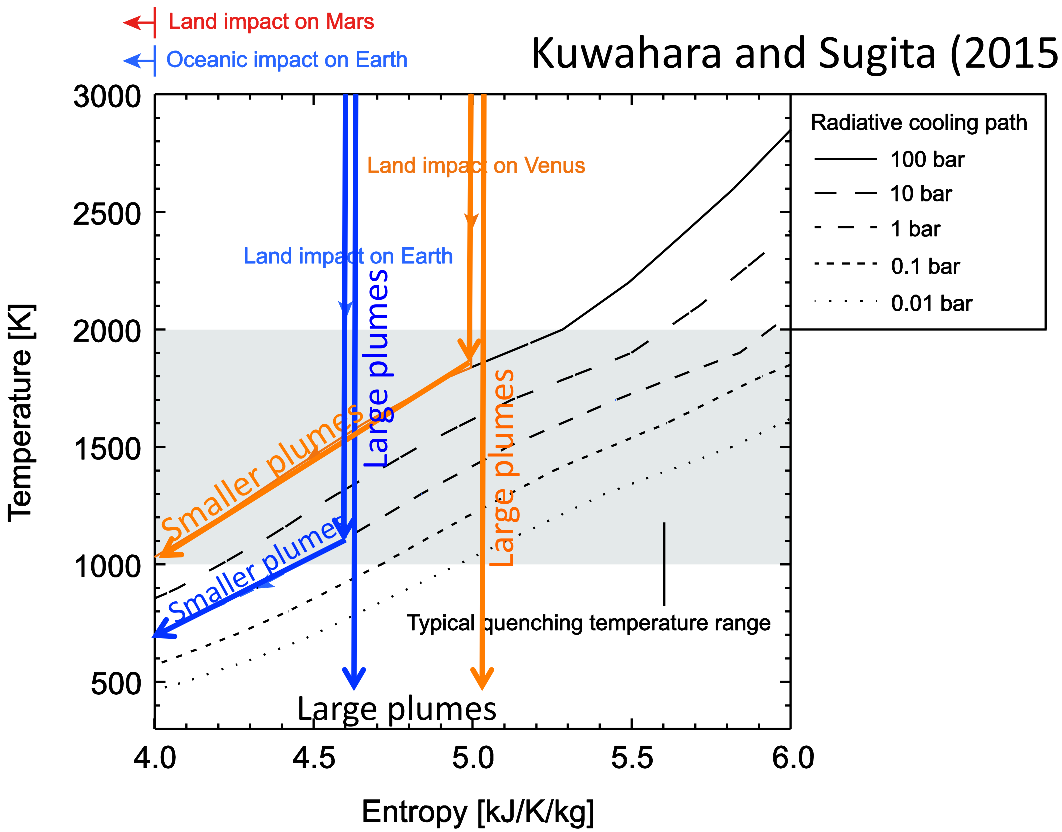
⇨ The composition and dynamical history of asteroids are the key.

⇨ Needs for asteroid observations and explorations.

Transition from adiabatic cooling to radiative cooling

- Vapor cools along an isentrope until it reaches the ambient pressure.
- Impact vapor may cool at an constant pressure via radiation.
  - Transition from isentrope to isobaric curve.
  - P-T diagrams by Hashimoto+(2007), Schaefer&Fegley (2010) would work.
  - Isobaric cooling stabilize CH_4, but actual CH_4 formation may require catalysts.
- However, vapor plumes larger than atmospheric scale height may penetrate through the atmosphere without reaching pressure equilibrium.

Kuwahara and Sugita (2015) *Icarus, 257,* 290–301



Implications for Exoplanets

- Expoplanets within a habitable zone would receive similar strength of stellar radiation.
  - Star luminosity varies with mass.
    - $L \propto M^{a}$, a = 2.6 – 4.5 (Salaris and Cassisi, 2005)
  - Habitable zone distance: $r \propto M^{a/2} = M^{1.3-2.2}$
  - Typical impact velocity for habitable planets would be lower for higher mass stars.
    - $v_{impact} \propto v_{Kepler} \propto M^{-(a-2)/4} = M^{-0.15 - -0.63}$
    - Greater chances of CH_4 forming impacts around high-mass stars, (e.g., A, B type), than low-mass stars (e.g., M type).