Comets - Key Witnesses of the Beginning

Horst Uwe Keller

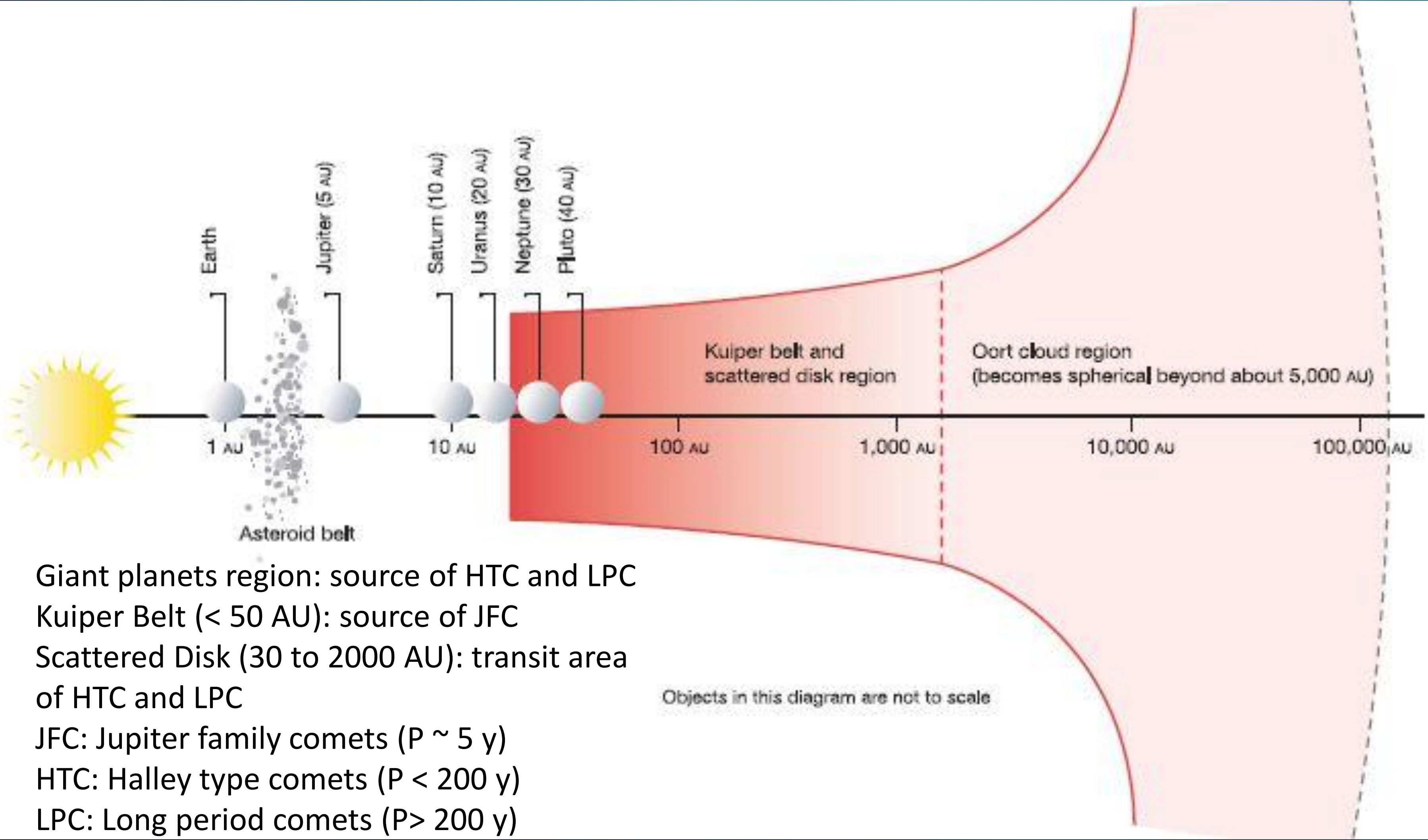
Institute for Geophysics and Extraterrestrial Physics

University Braunschweig

IGEP TU Braunschweig

Institut für Geophysik und extraterrestrische Physik

Bodies in the Solar System



Giant planets region: source of HTC and LPC
Kuiper Belt (< 50 AU): source of JFC
Scattered Disk (30 to 2000 AU): transit area of HTC and LPC
JFC: Jupiter family comets (P ~ 5 y)
HTC: Halley type comets (P < 200 y)
LPC: Long period comets (P> 200 y)

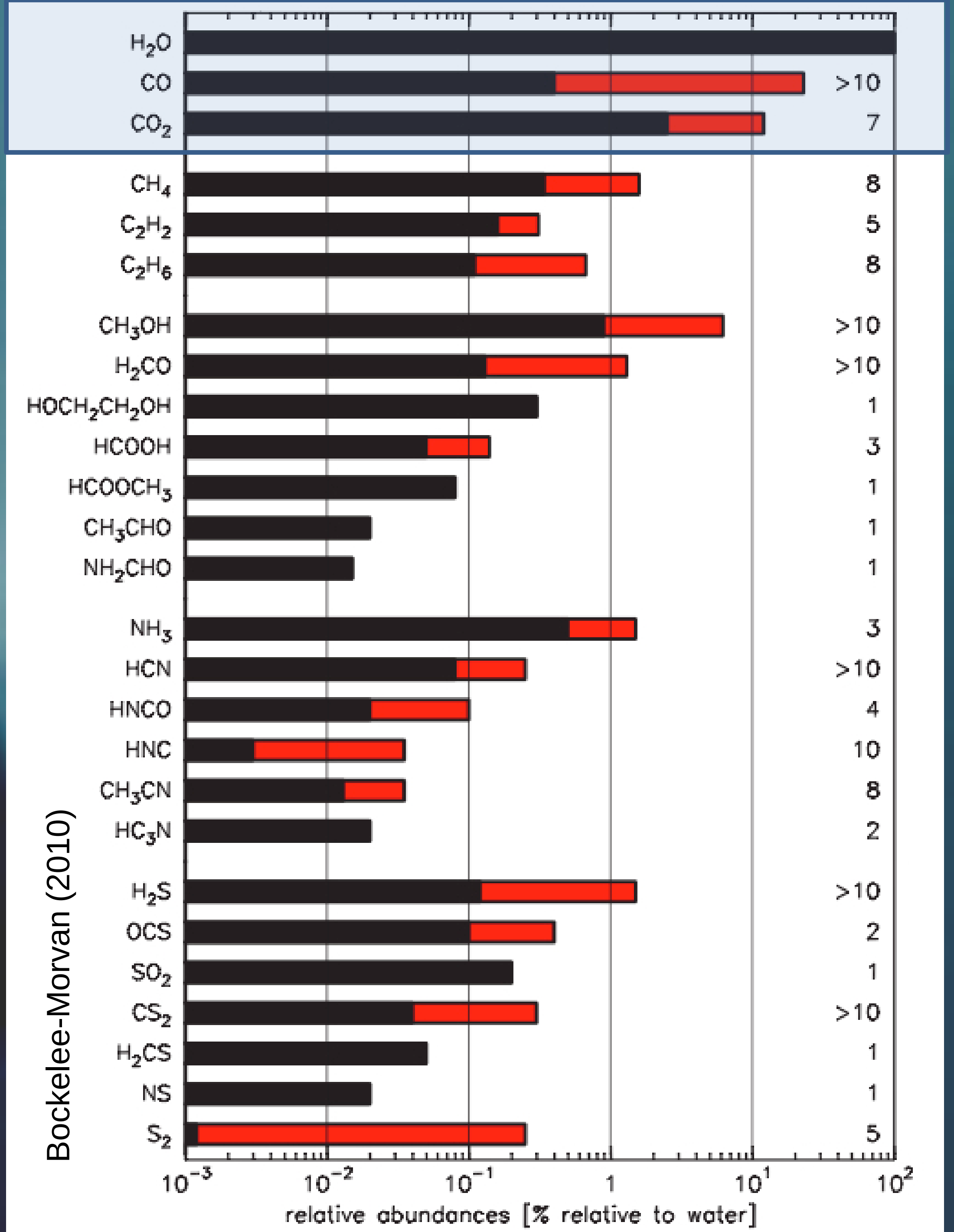
Conventional Concepts

- Comets were formed in the giant planets region (HTC and LPC) and beyond Neptune (JFC) and are stored in the Scatterd Disk (JFC) and Oort Cloud (HTC and LPC)
- Temperature: $T < 50$ K
- Agglomeration of cometesimals with low relative velocities (< 50 m/s)
  - Temperature increase during collision moderate ($\Delta T \approx 10$ K)
  - gravitational heating negligible

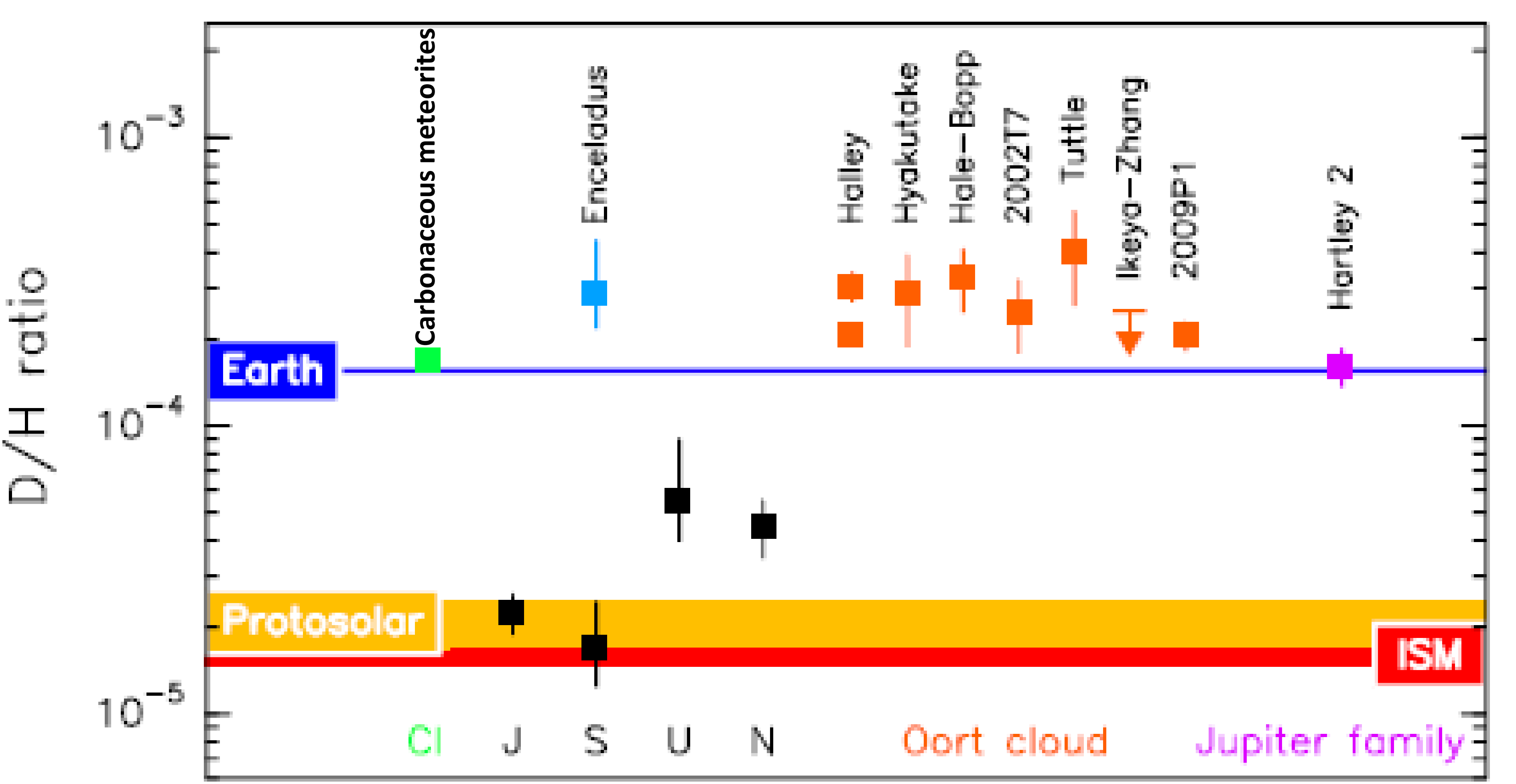
Composition of Comets

- Comets formed beyond the water “snow line”
- Little heating during formation
- Little change over the age of the solar system
- High content of volatiles (H_2O) and complex compounds
- Similarity to interstellar medium
- Seemingly pristine but also refractory material (Star Dust)

- Where were comets (JFC, HTC, LPC) formed?
- Do their compositions (here HDO, CO_2, CO) vary with type?



D/H ratio in the water of comets



Bockelee-Morvan et al. (2012)

influence of time and location on isotopic abundance distribution

Giants
R < 20 AU

Kuiper belt
R > 30 AU

D/H in LPC vs. JFC

- **Generally assumed that D/H ratio increases with heliocentric distance**
- **Herschel JFC observation (**Hartogh et al. (2011)**):**
  - **JFC were not formed further from the sun than LPC (contradiction to classical view)**

  or

  - **Assumption of D/H dependence on r_h is wrong**
- **Herschel C/2009 P1 (Garradd) observation (**Bocklee-Morvan et al. (2012)**):**
  - **Single archetypal D/H value for LPC not anymore tenable (also reavaluated 1P/Halley results)**

LPC and JFC may originate from overlapping regions

CO and CO_2

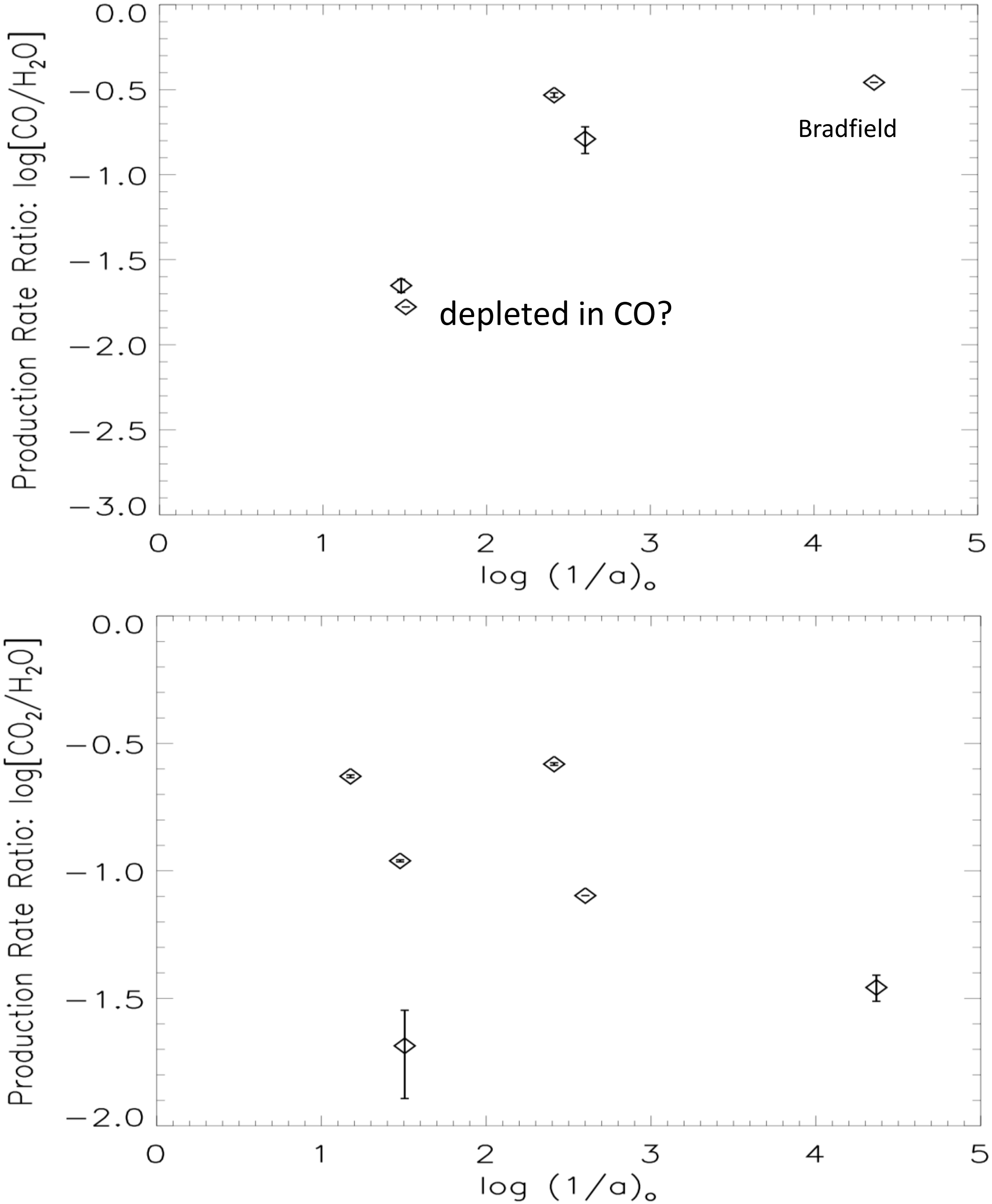
- CO and CO_2 most abundant molecules
- Hardly any CO_2 in gas phase (sublimation from icy grains)
  - Formation on grains from CO (combining with OH)
- CO_2 formed by destruction of CO (ice)
- Hence temperature in the protoplanetary disk has to be low (< 30 K). Trapping of CO by water at higher T possible

Snow lines and T in early protoplanetary disk

- Snow lines moved during the first 10^6y following e. g. the models of Dodson-Robinson et al. (2009):
- H_2O from 5 to 2 AU
- CO from 12 to 8 AU
- CO_2 in between

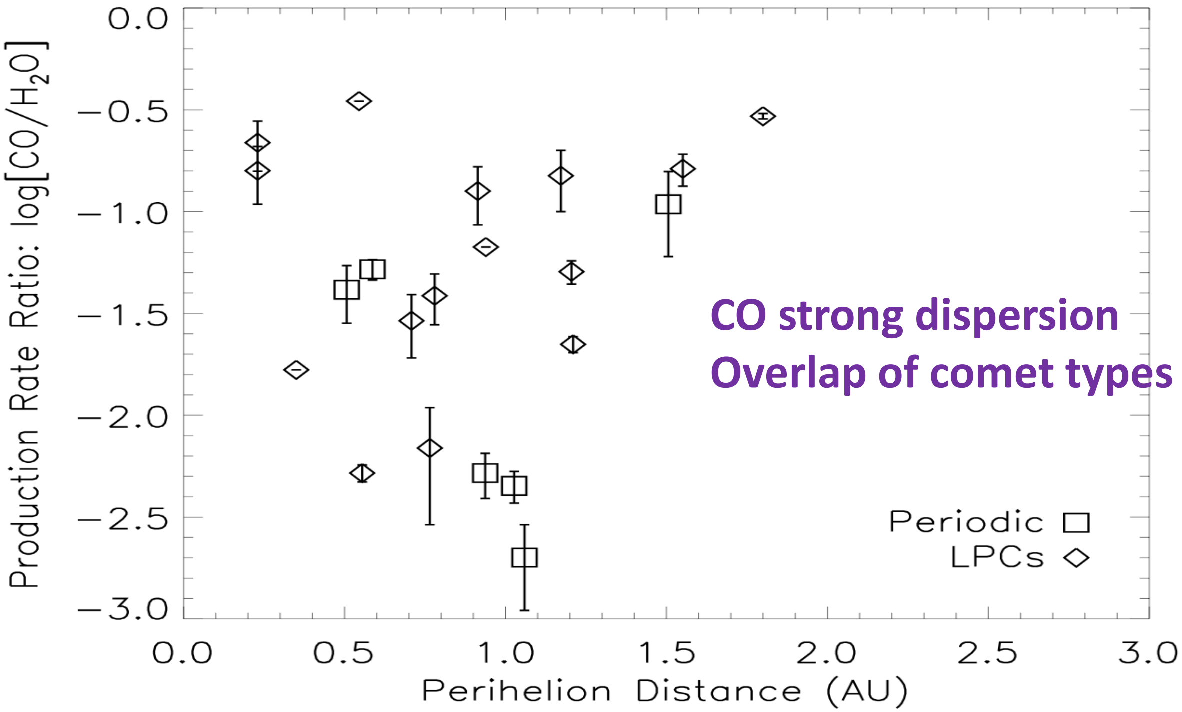
Production rates

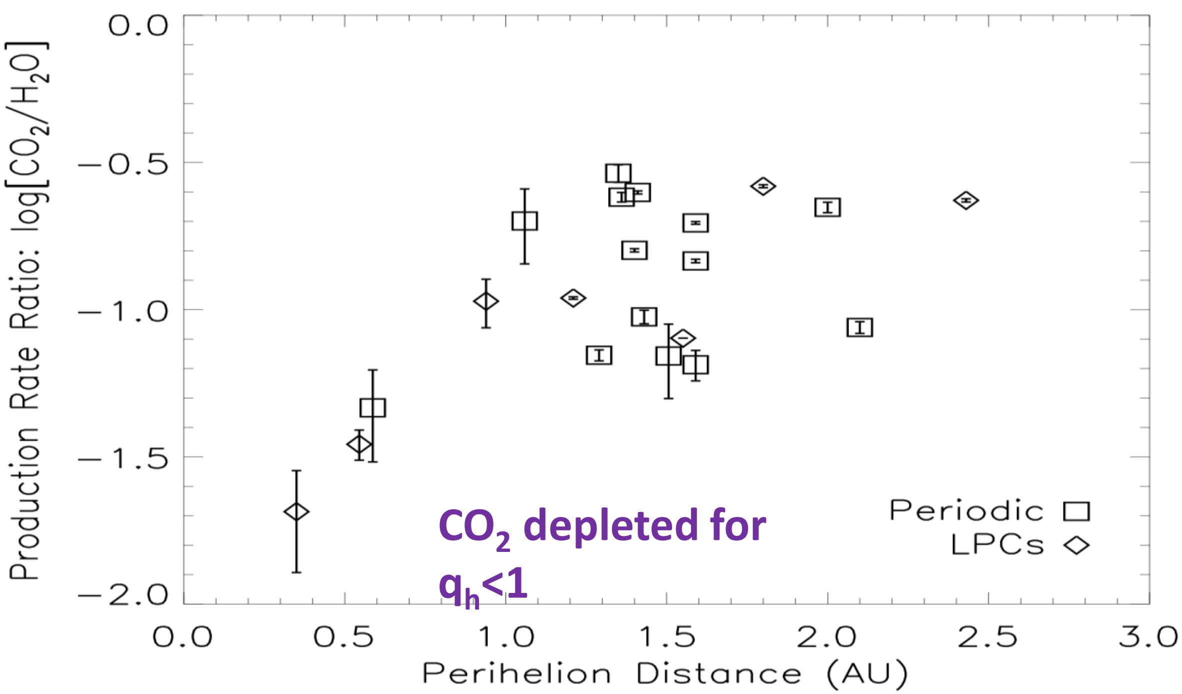
- Abundances and ratios of H_2O, CO_2, and CO should tell about the formation regions of comets
- Unfortunately CO (mainly in UV) and CO_2 (IR) are difficult to observe simultaneously
- Compilation of production rates of H_2O (OH), CO_2, and CO of 30 comets at $r_h < 2.5$ AU
- Triggered by AKARI observations (Ootsubo et al. 2012)
- Strong caveat: still small statistics



Production of CO and CO_2, as a fraction of production of H_2O, shown as a function of original reciprocal semi-major axis for LPCs. The initial, reciprocal, semi-major axis has units of 10^{-6} AU^{-1}. Comets arriving for the first time from the Oort cloud appear to the left at values < 2

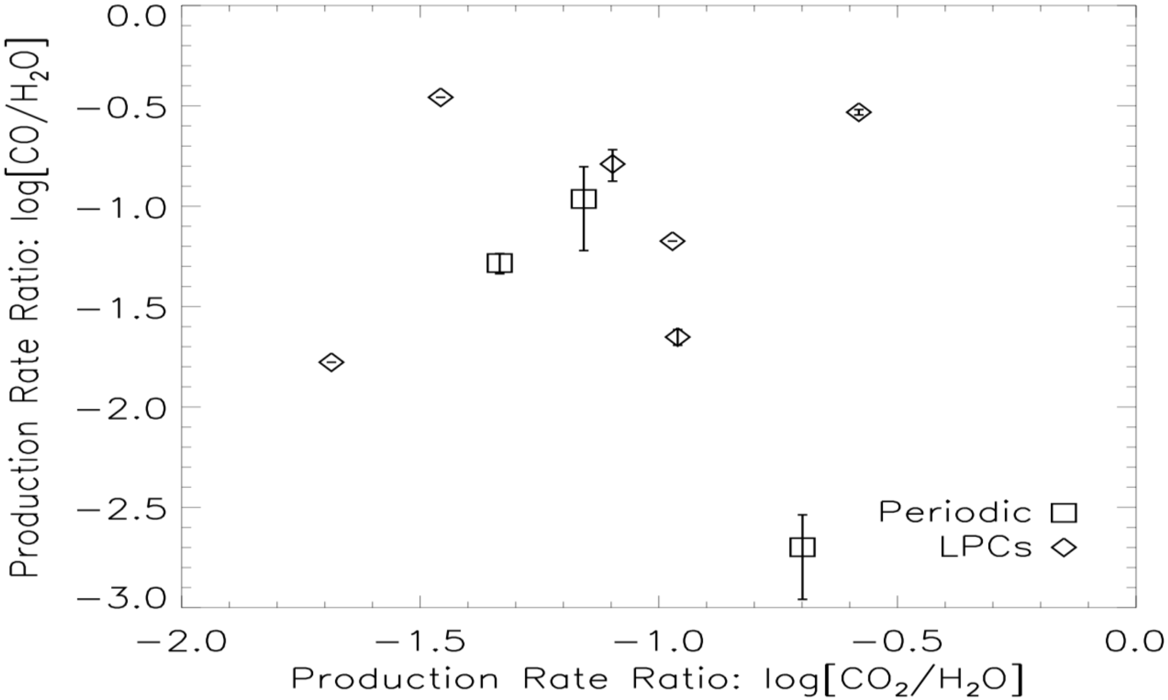
No evolutionary effects within the poor statistics

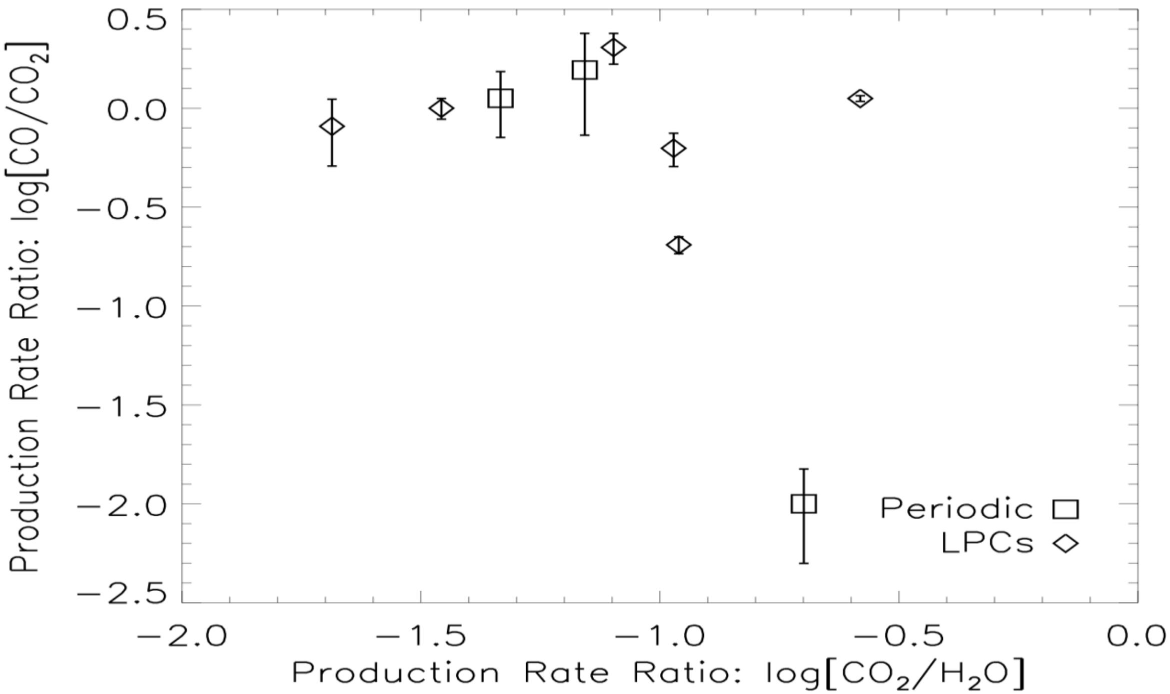




Production of CO and CO_2, as a fraction of production of H_2O, shown as a function of perihelion distance. Different symbols indicate periodic (including both JFCs and HTCs) and non-periodic comets

CO and CO_2 uncorrelated with dynamical comet family

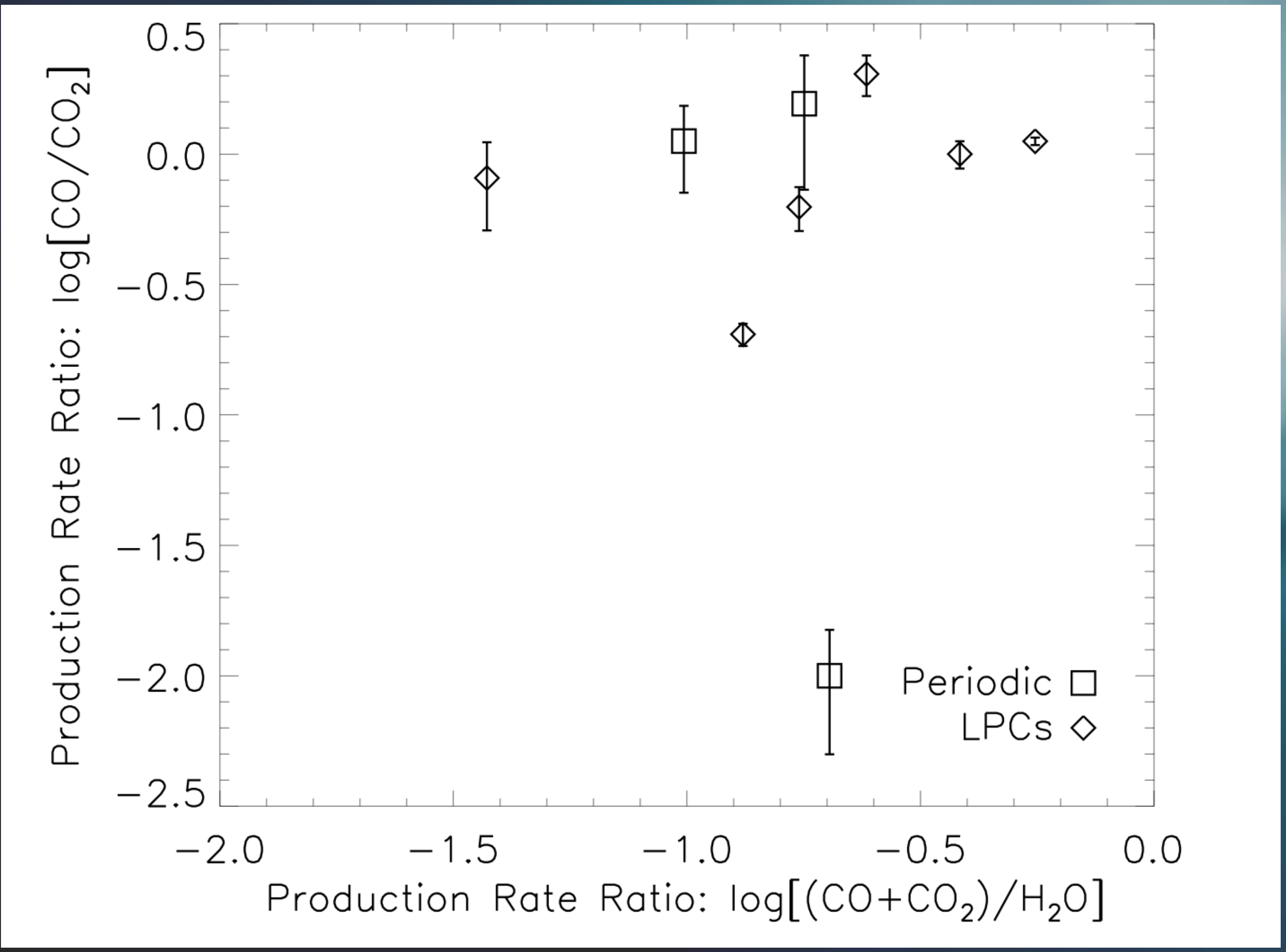




Relative abundance of CO as a function of relative abundance of CO_2

Ratio of CO/CO_2 as a function of relative abundance of CO_2

No correlation is seen in either plot
No correlation with dynamical family



Ratio of abundances, CO/CO_2, as a function of total inorganic carbon (assumed entirely to be CO plus CO_2)

CO/CO_2 uncorrelated with dynamical comet family
CO/CO_2 ratio less variable than CO or CO_2

Suggestions and Conclusions

- The dominant variable controlling CO and CO_2 fractional abundances is the total inorganic carbon in ices, with the conversion of CO to CO_2 reaching an equilibrium state in the protoplanetary disk
- This is consistent with variable condensation of CO followed by conversion to an equilibrium with CO_2
- Comets formed near the snow line of CO, possibly straddling it, around 8 to 12 AU and beyond (depending on the protoplanetary model)

Summary and Conclusions

- D/H ratio varies in comets (also within LPC)
- D/H ratio of JFC does not fit conventional models of separate regions of formation
- H_2O, CO_2, and CO show a wide range of abundances in all types of comets
- JFC, HTC, and LPC formed between the CO_2 and CO snow lines
- This explains the wide range of abundances relative to water and simultaneously a much smaller range of CO/CO_2 abundances

A'Hearn et al. (2012) ApJ: Cometary Volatiles and the Origin of Comets