A SURVEY OF CO, CO_2, AND H_2O IN COMETS AND CENTAURS

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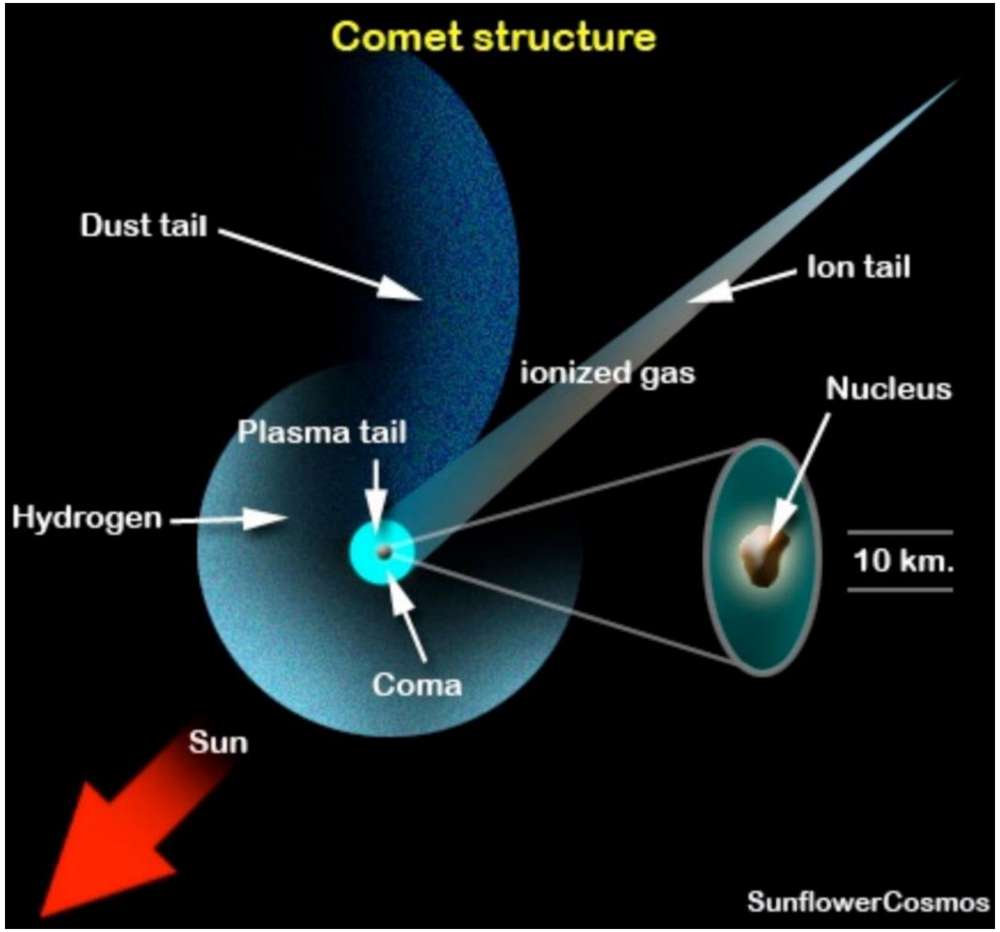
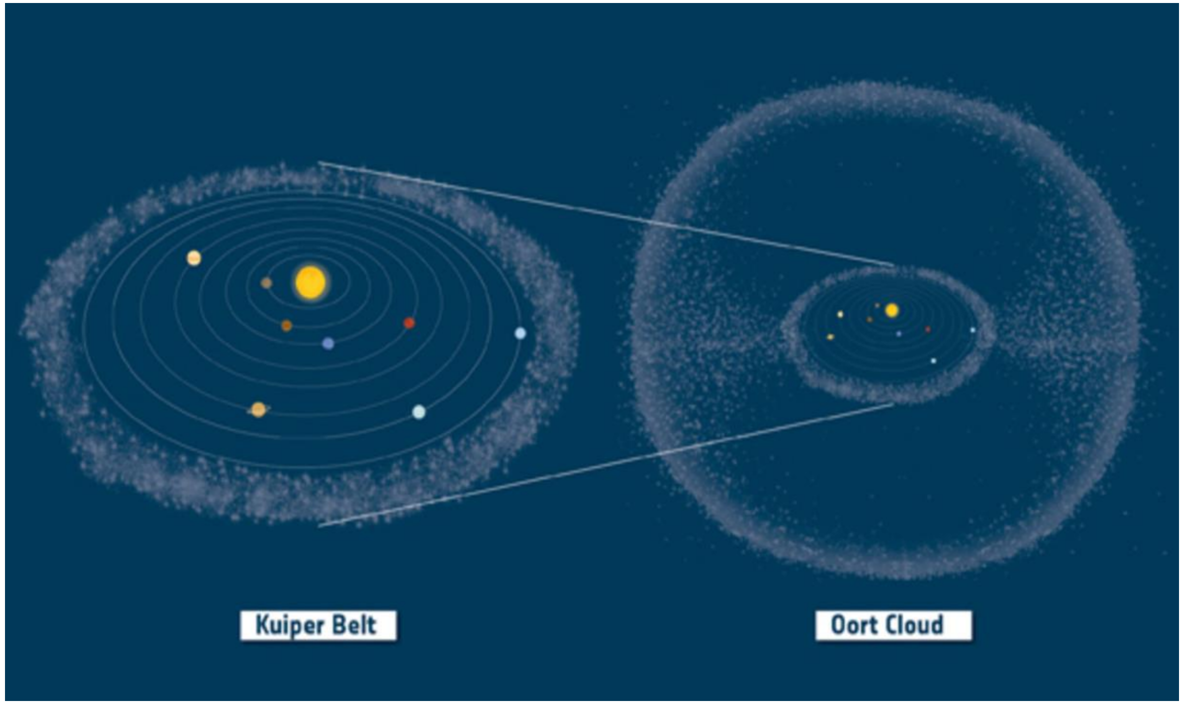
This research is funded by the NSF

GENERAL BACKGROUND





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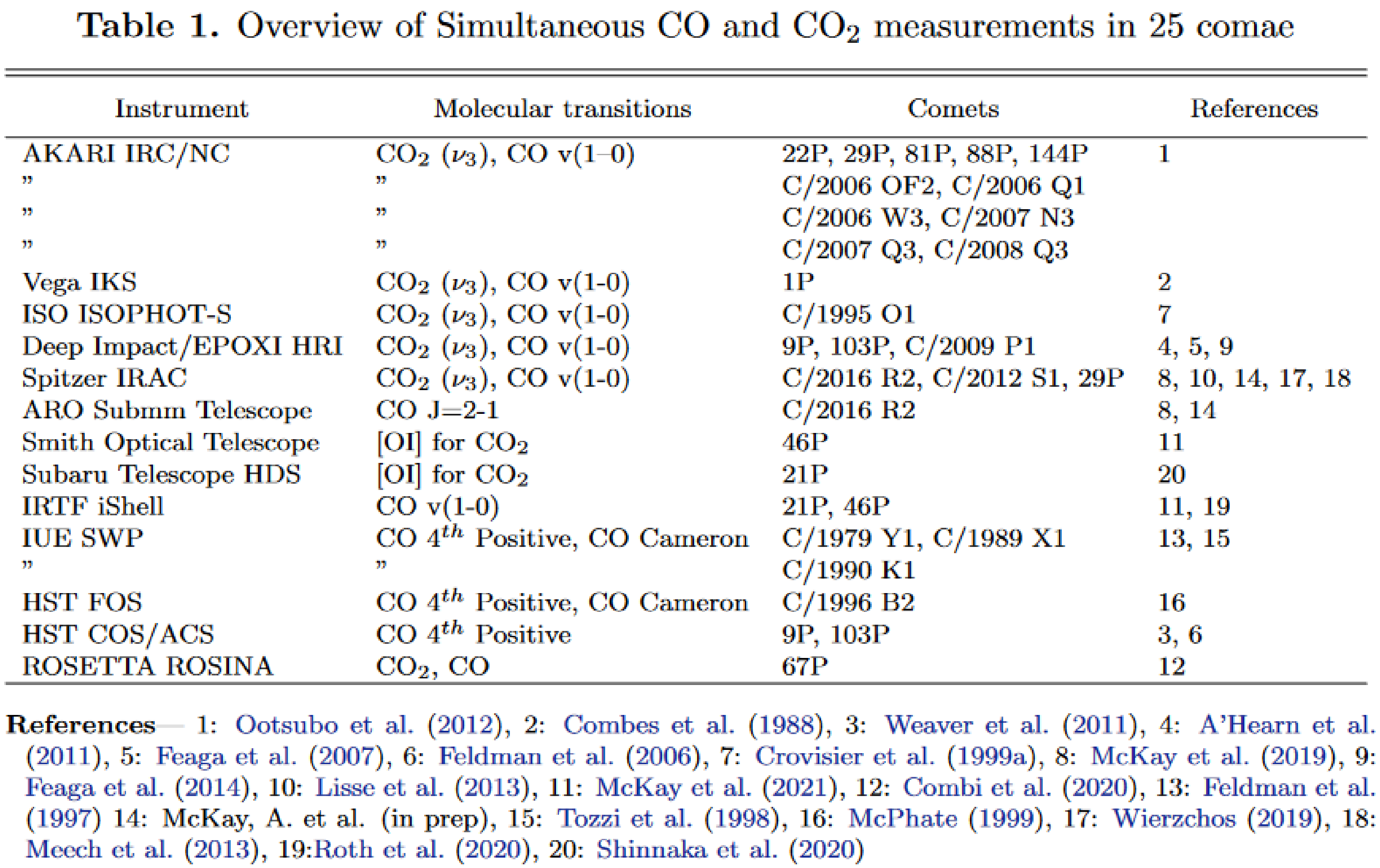

Table 1. Overview of Simultaneous CO and CO_2 measurements in 25 comae

Instrument	Molecular transitions	Comets	References
AKARI IRC/NC	CO_2 (ν_3), CO v(1–0)	22P, 29P, 81P, 88P, 144P	1
”	”	C/2006 OF2, C/2006 Q1	
”	”	C/2006 W3, C/2007 N3	
”	”	C/2007 Q3, C/2008 Q3	
Vega IKS	CO_2 (ν_3), CO v(1-0)	1P	2
ISO ISOPHOT-S	CO_2 (ν_3), CO v(1-0)	C/1995 O1	7
Deep Impact/EPOXI HRI	CO_2 (ν_3), CO v(1-0)	9P, 103P, C/2009 P1	4, 5, 9
Spitzer IRAC	CO_2 (ν_3), CO v(1-0)	C/2016 R2, C/2012 S1, 29P	8, 10, 14, 17, 18
ARO Submm Telescope	CO J=2-1	C/2016 R2	8, 14
Smith Optical Telescope	[OI] for CO_2	46P	11
Subaru Telescope HDS	[OI] for CO_2	21P	20
IRTF iShell	CO v(1-0)	21P, 46P	11, 19
IUE SWP	CO 4^{th} Positive, CO Cameron	C/1979 Y1, C/1989 X1	13, 15
”	”	C/1990 K1	
HST FOS	CO 4^{th} Positive, CO Cameron	C/1996 B2	16
HST COS/ACS	CO 4^{th} Positive	9P, 103P	3, 6
ROSETTA ROSINA	CO_2, CO	67P	12

References— 1: Ootsubo et al. (2012), 2: Combes et al. (1988), 3: Weaver et al. (2011), 4: A’Hearn et al. (2011), 5: Feaga et al. (2007), 6: Feldman et al. (2006), 7: Crovisier et al. (1999a), 8: McKay et al. (2019), 9: Feaga et al. (2014), 10: Lisse et al. (2013), 11: McKay et al. (2021), 12: Combi et al. (2020), 13: Feldman et al. (1997) 14: McKay, A. et al. (in prep), 15: Tozzi et al. (1998), 16: McPhate (1999), 17: Wierzchos (2019), 18: Meech et al. (2013), 19:Roth et al. (2020), 20: Shinnaka et al. (2020)

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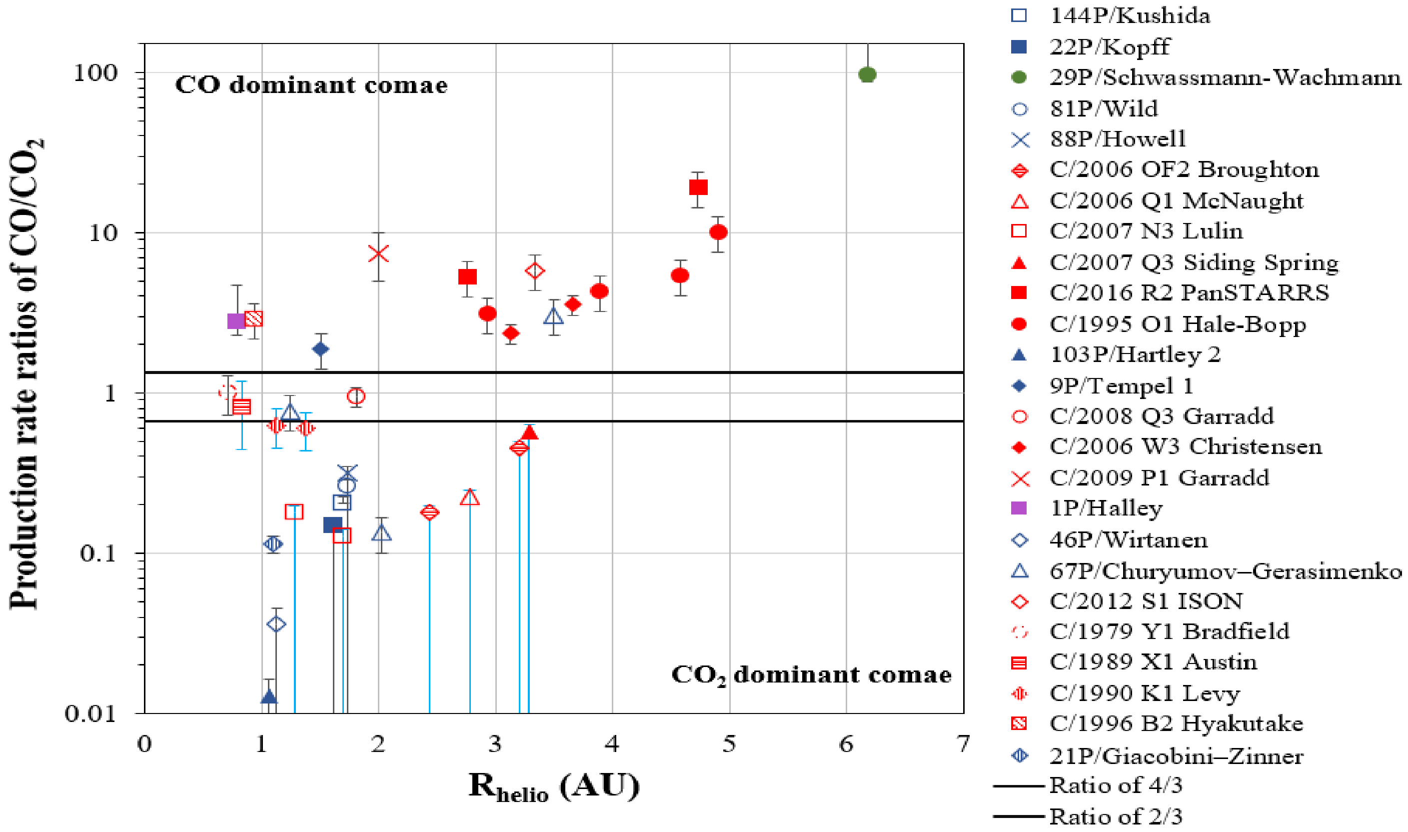
Q_{CO}/Q_{CO_2} VS. HELIOCENTRIC DISTANCE FROM 25 COMETS



- Comae beyond 3.5 au produce more CO than CO_2.
- Eight of the nine JFCs had CO_2-dominated comae.
- At first, OCCs appear evenly split, but dynamically new OCCs tend to produce more CO_2 than CO. →

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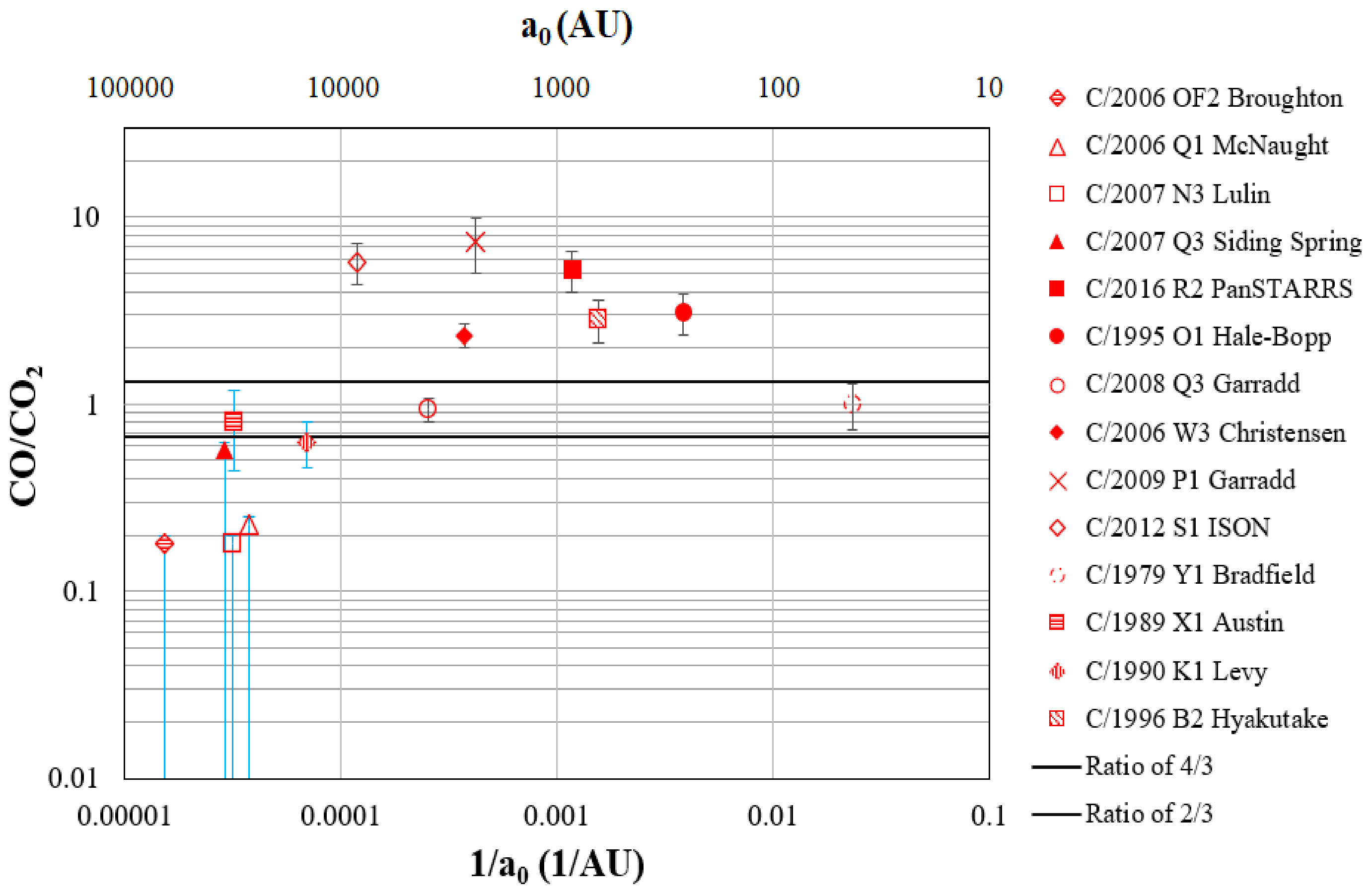
Q_{CO}/Q_{CO_2} VS. DYNAMICAL AGE



- **QCO/QCO2 ratio in 14 comae increases with dynamical age,** which is inconsistent with models dynamically new comets should outgas more CO than CO_2.
- Result may be explained by galactic cosmic ray processing of outer layers which leads to CO-depletion with respect to CO_2. The CO-depleted layer is eroded during the first perihelion passages and reveals fresh stores of CO at deeper levels (Gronoff et al. 2020; Maggiolo et al. 2020).
- **Comets that have already been in the inner solar system already may produce more pristine material than dynamically new comets.**

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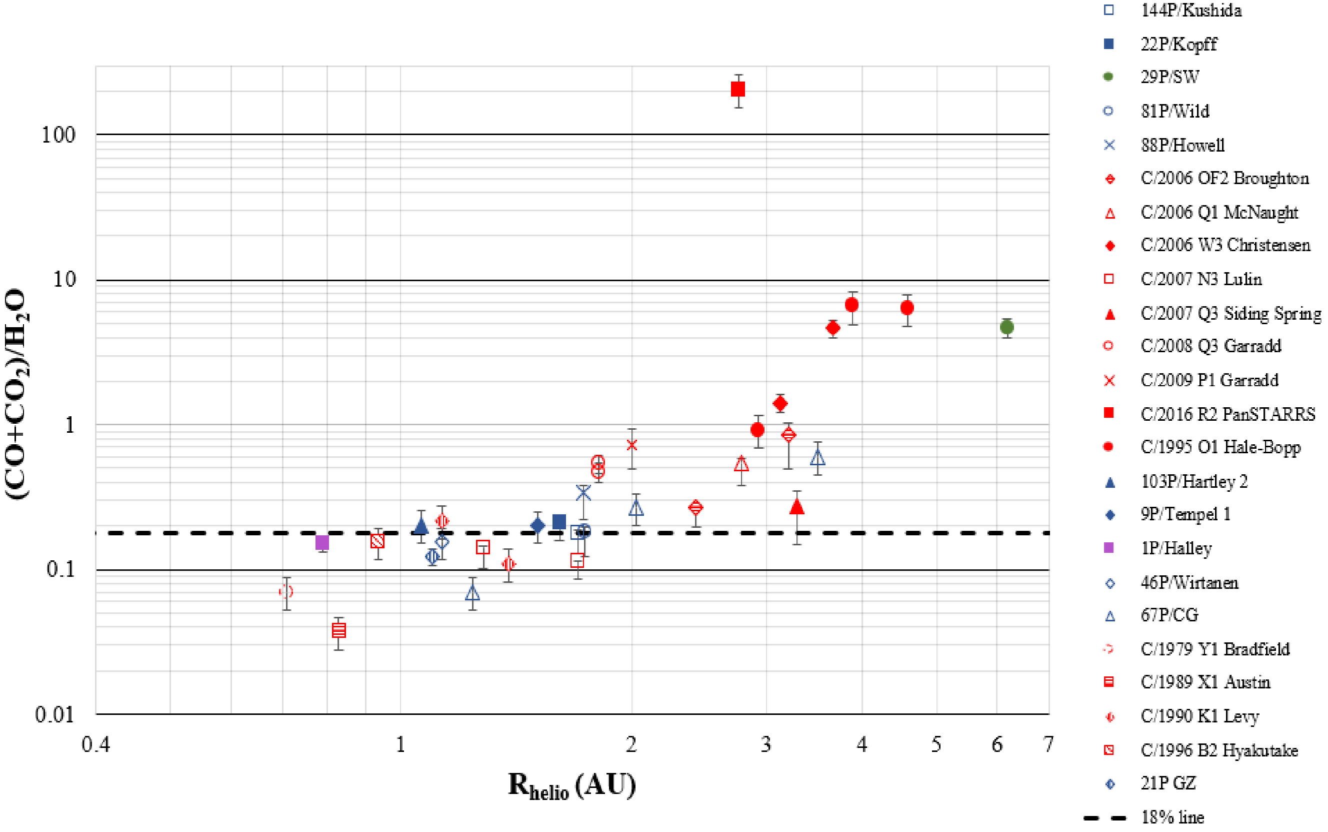
$(Q_{CO}+Q_{CO_2})/Q_{H_2O}$ VS. HELIOCENTRIC DISTANCE



- The median production rate ratios of **$(Q_{CO}+Q_{CO_2})/Q_{H_2O}$ for all comets within 2.5 au is 18 ± 4%.**
- The total amounts of CO and CO_2 produced within 2.5 au may be conserved for most comets and represents ~ 20% of the total volatile component, as proposed by (A'Hearn 2012, Lisse 2021). **Thus, comets may retain a strong amount of their natal composition.**

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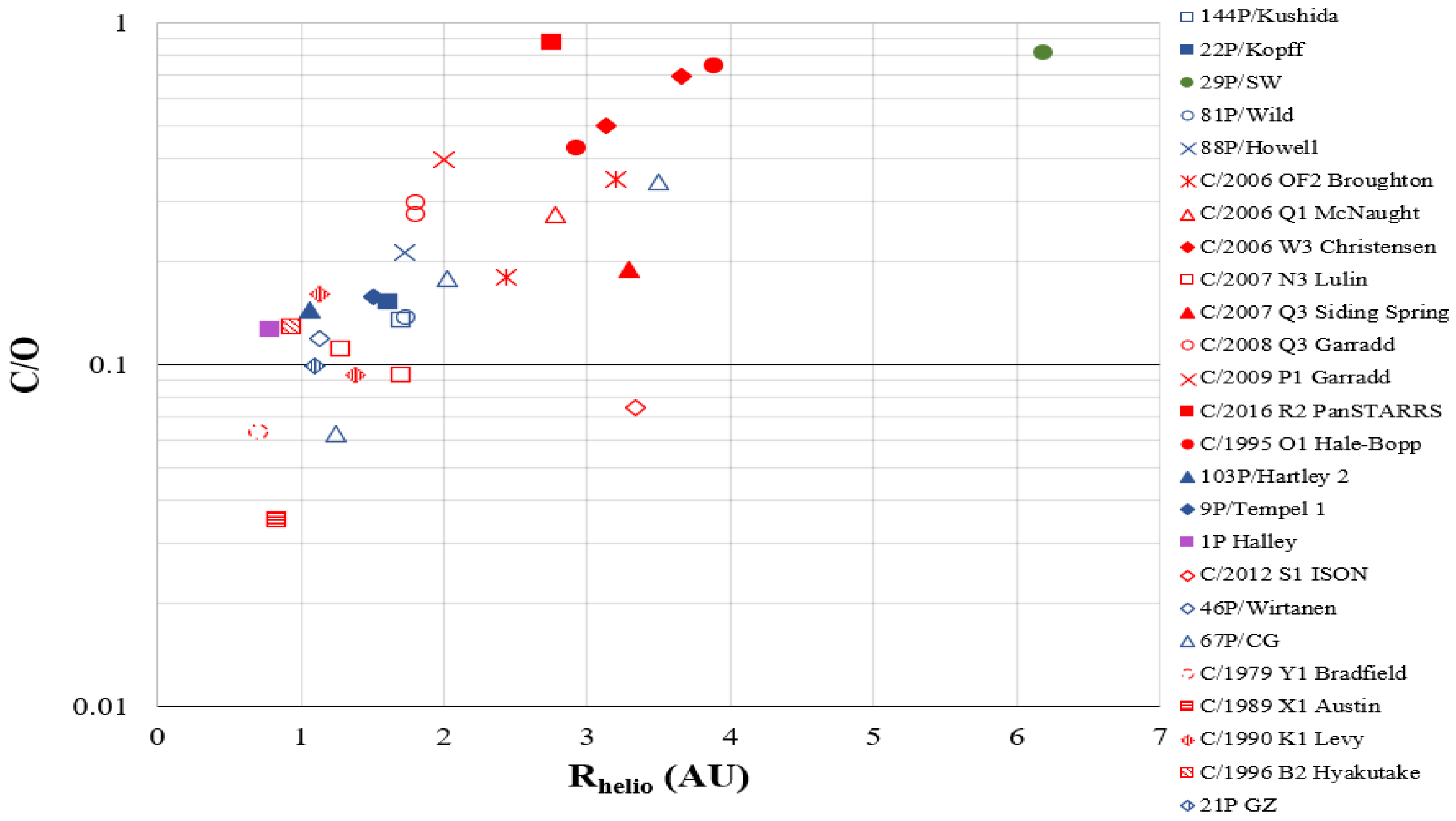
C/O VS HELIOCENTRIC DISTANCE



- C/O = Carbon to Oxygen ratio based on the top Carbon bearing molecules (CO, CO_2) and the Oxygen bearing molecules (CO, CO_2,H_2O)
- $C/O_{average}$ ~15%
  C/O_{median} ~13%
- **These low C/O ratios are consistent with most comets forming within the CO snow line** (Oberg et al. 2011, Seligman et al. 2022).

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CONCLUSIONS

- JFCs tend to produce more CO_2 than CO, possibly due to increased heating in inner solar system, but we need more measurements beyond 3.5 au.
- **Surprisingly, Dynamically New comets tend to produce more CO_2 while Dynamically Older OCCs produce more CO. This trend may be explained by a model that includes long-term galactic cosmic rays processing of outer layers that are eroded during first pass through inner solar system.**
- When independent measurements are not possible for both CO and CO_2 in an active comet beyond 3.5 au, assume that the dominant outgassing volatile is CO.
- The median production rate ratios of **$(Q_{CO}+Q_{CO_2})/Q_{H_2O}$ for all comets within 2.5 au is 18 ± 4%, consistent with models predicting that comets retain a strong amount of their natal composition**.
- **The C/O_{median} ~13% value is consistent with most comets forming within the CO snow line.**

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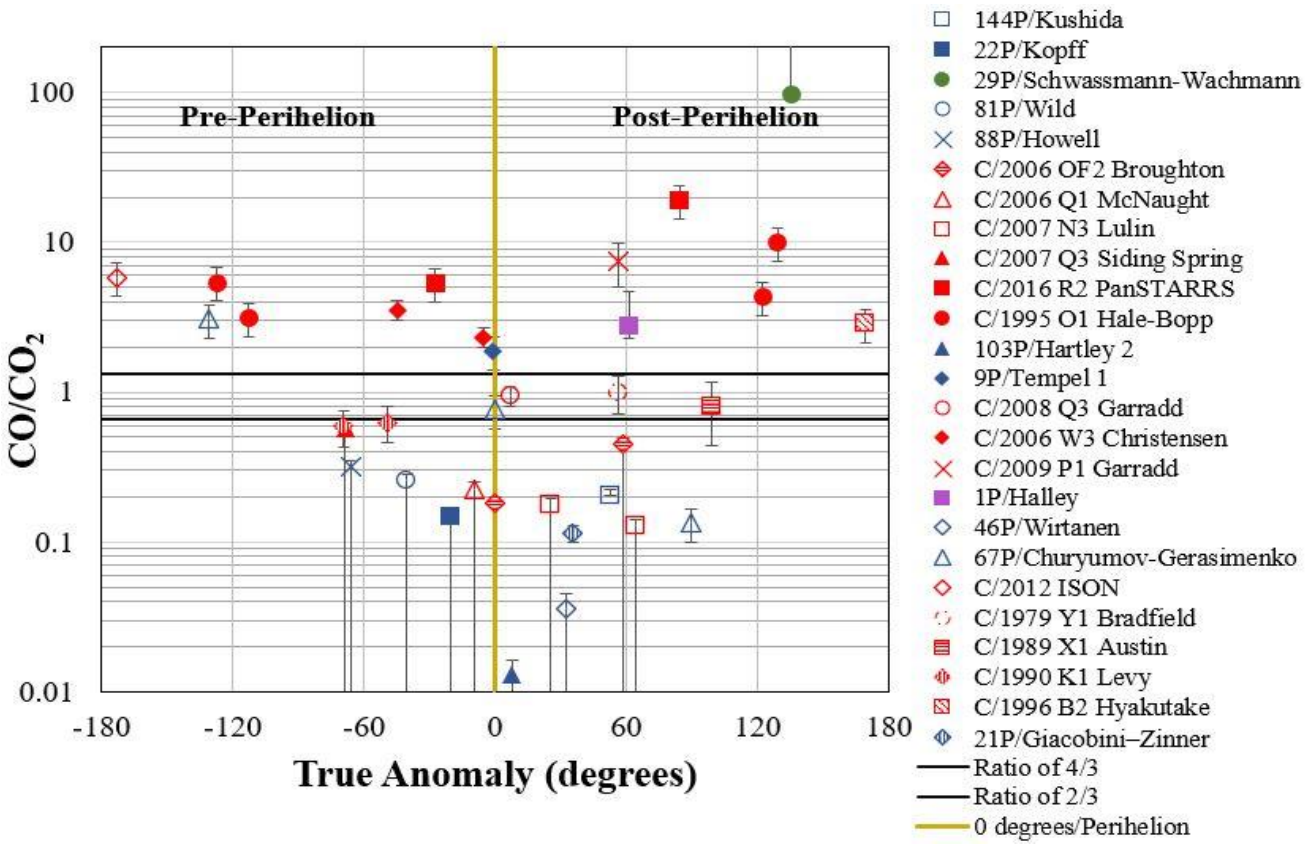
BACK-UP SLIDES

CO/CO$_2$ VS. TRUE ANOMALY



- Pre- and post-perihelion comets are spread among the three regions.
- From detections we see that post-perihelion data is more spread out.
- Including upper and lower limits we see that the post perihelion data is still more spread out (since 29P could be a higher CO/CO$_2$).

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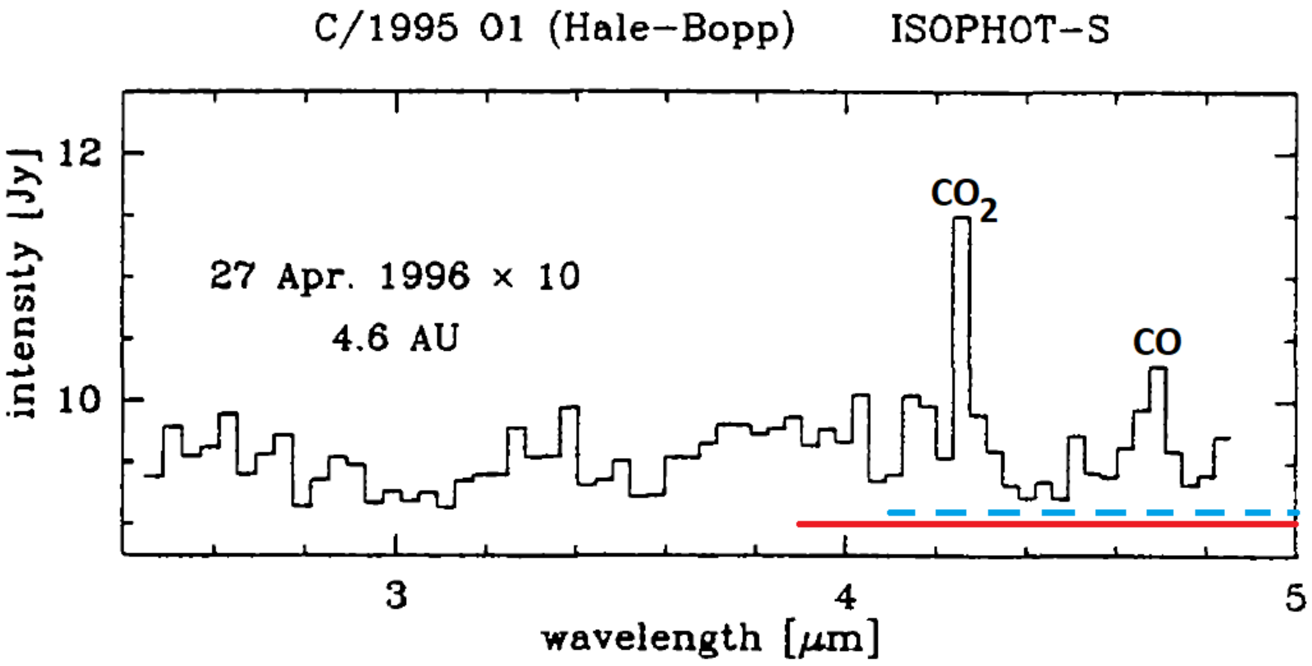
BACKGROUND ON CO_2



- CO_2 difficult to get, mainly because of Earth's atmosphere and the lack of a permanent dipole moment.
- Space-based spectroscopy is ideal for CO_2 measurements, but rare.
- Optimize the existing NEOWISE and Spitzer 4.5 um images and indirect measurements of CO_2.

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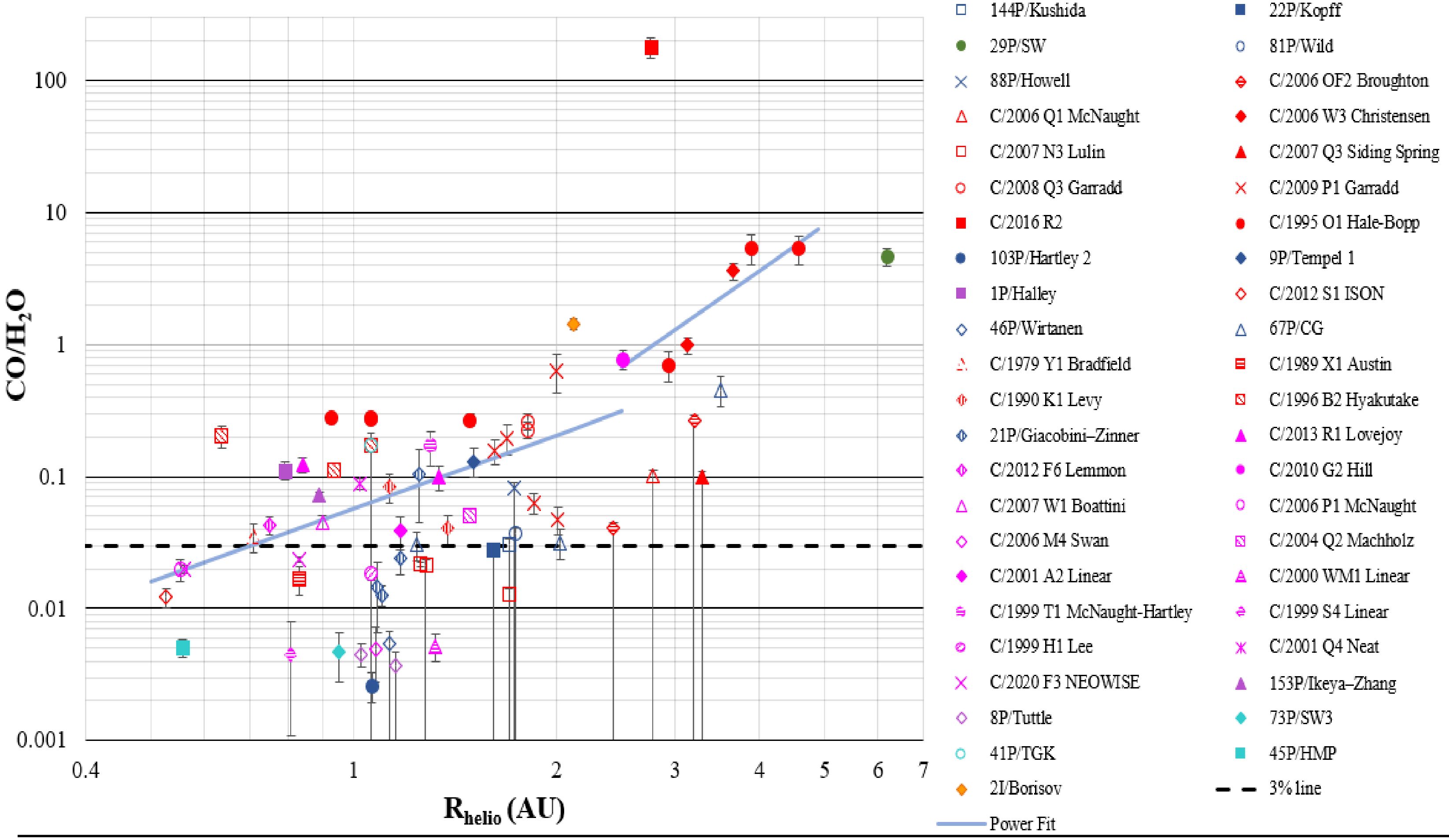
Q_{CO}/Q_{H_2O} VS. HELIOCENTRIC DISTANCE



- For comets within 2.5 au, $Q_{CO}/Q_{H_2O} = 3 \pm 1\%$, (median) with a range from 0.3% to 26%.
- The production rate ratio for CO may change slope at ~ 2.5-3.0 au, where water ice sublimation noticeably changes its efficiency.

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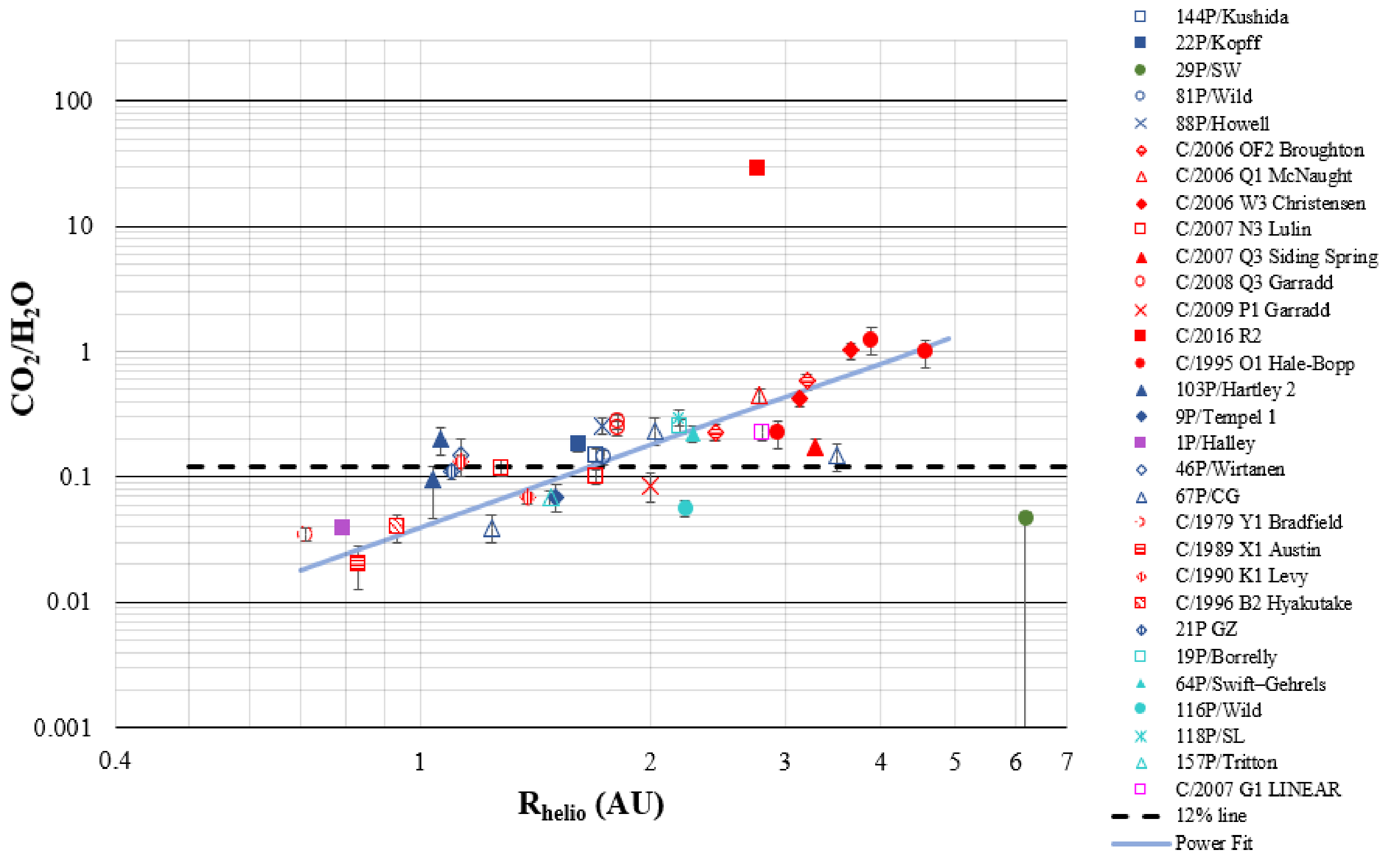
Q_{CO_2}/Q_{H_2O} VS. HELIOCENTRIC DISTANCE



- The CO_2/H_2O median ratio is higher, 12 ± 2% with a range from 2% to 30%.
- For all comets from 0.7 to 4.6 au, **CO_2/H_2O shows a much tighter correlation (less scatter) with respect to heliocentric distance than does CO/H_2O.**
- The production of CO_2 and CO might have significantly different mechanisms over this range.
- CO_2 may be more intimately tied to water production than CO.

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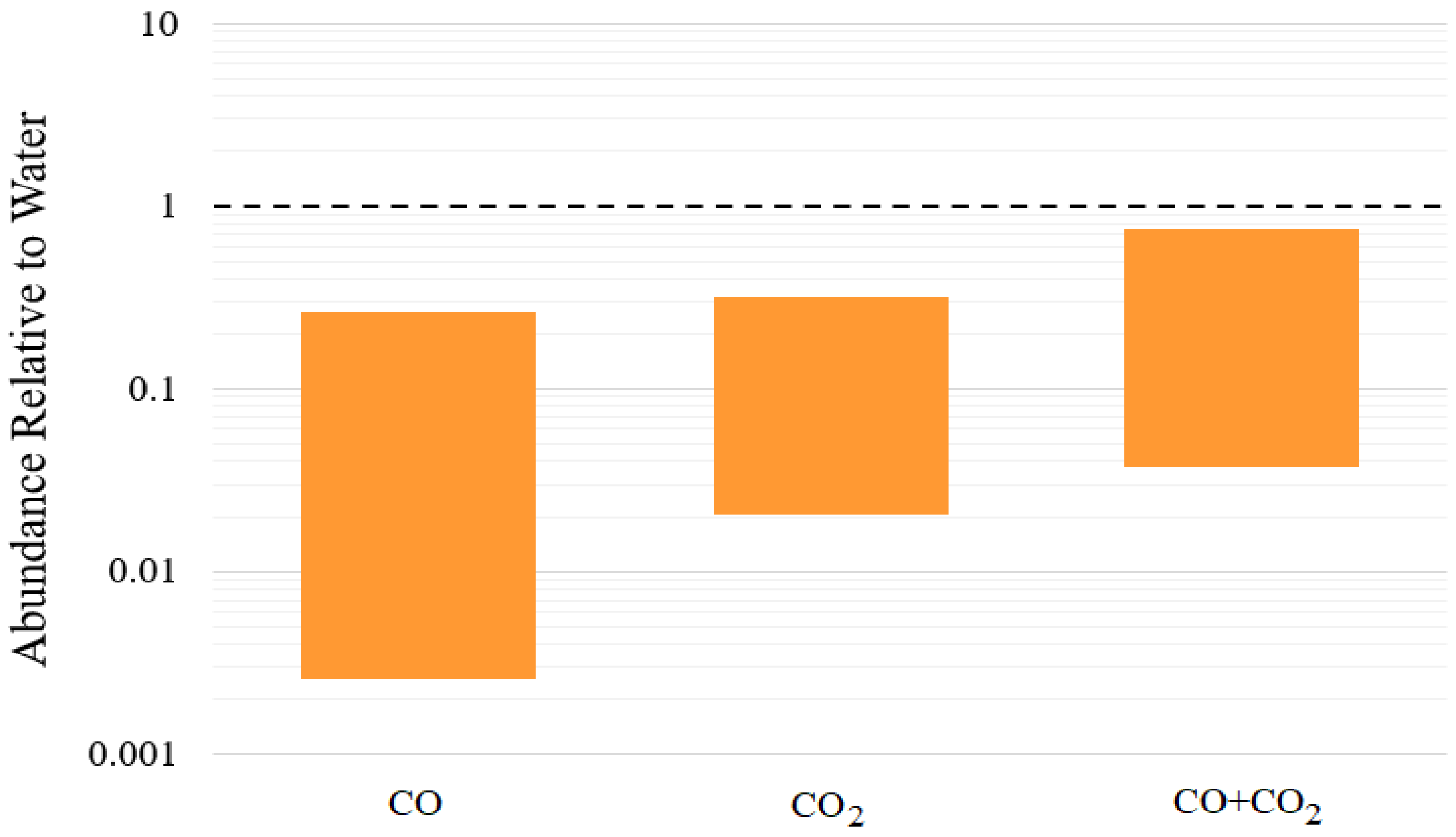
SUMMARY OF ABUNDANCE RATIOS W.R.T. H_2O



- There are fewer CO_2 measurements than CO which could be one of the reasons we see a larger range of abundance ratios for CO/H_2O.
- The smaller range for CO_2/H_2O could also be explained by the closer relationship of CO_2 with H_2O.

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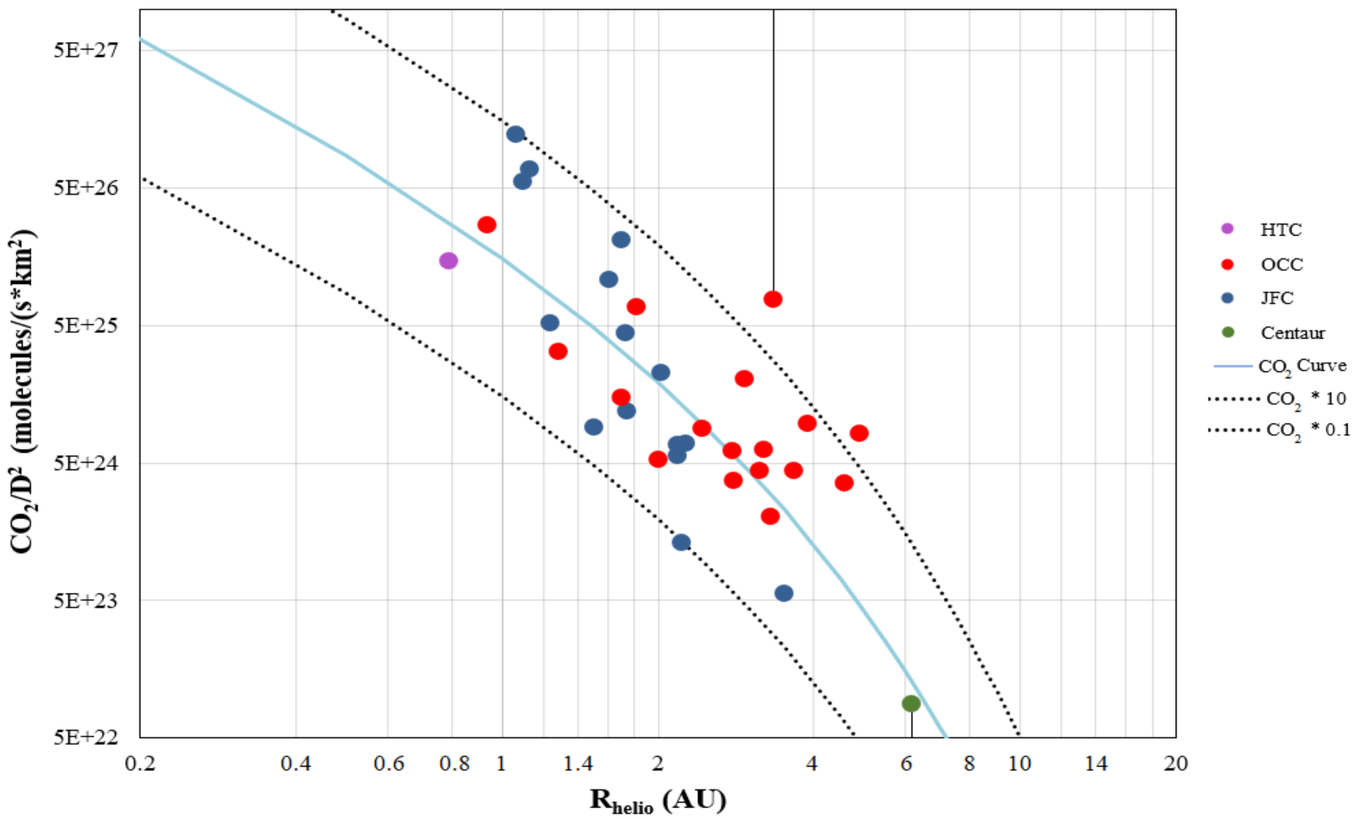
QCO_2/D^2 VS HELIOCENTRIC DISTANCE



- JFCs seem to be more affected by heliocentric distance, since we see the decline of the QCO_2 per surface area as heliocentric distance increases.
- The lack of CO_2 measurements available for Centaurs and HTCs is clearly seen (again).

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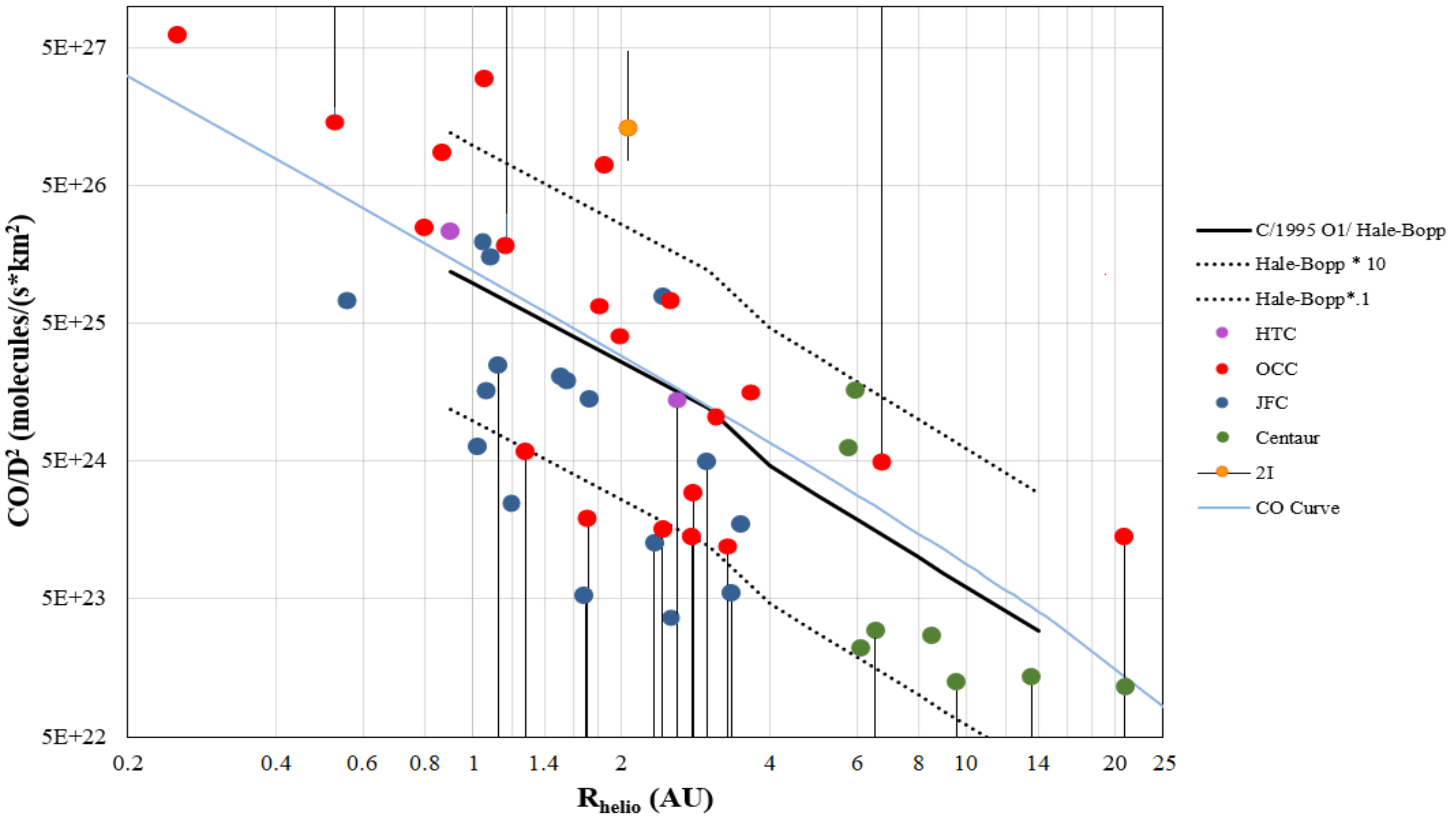
CO/D² VS HELIOCENTRIC DISTANCE



- From 1 au to 2 au, most OCCs produce significantly more CO per surface area than JFCs.
- Most JFCs and Centaurs tend to produce less CO per surface area than Hale-Bopp, and the CO Curve (sublimation curve for an object with a diameter ~32km).

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CARBON DEPLETION VS CO OR CO_2 DOMINANCE

	Carbon Depleted	Carbon Typical
CO dominant	1979 Y1	1P, 9P, C/1979 Y1, and C/1989 X1 1P, 9P, C/1989 X1, C/1995 O1, and C/1996 B2
CO_2 dominant	21P, 67P, and 81P 21P, and 81P	22P, 46P, 88P, 103P, and C/1990 K1 22P, 67P, 88P, 144P, and C/1990 K1

- There's no apparent connection between CO or CO_2 dominance and whether a comet is carbon depleted or carbon typical.
- Following the definitions by A'Hearn et al. 1995 (in blue), and Cochran et al. 2012 (in red).