Volatile Solubility Experiments on Planetary Melt Analogs and Implications for Rocky Planet Interior-Atmosphere Connections

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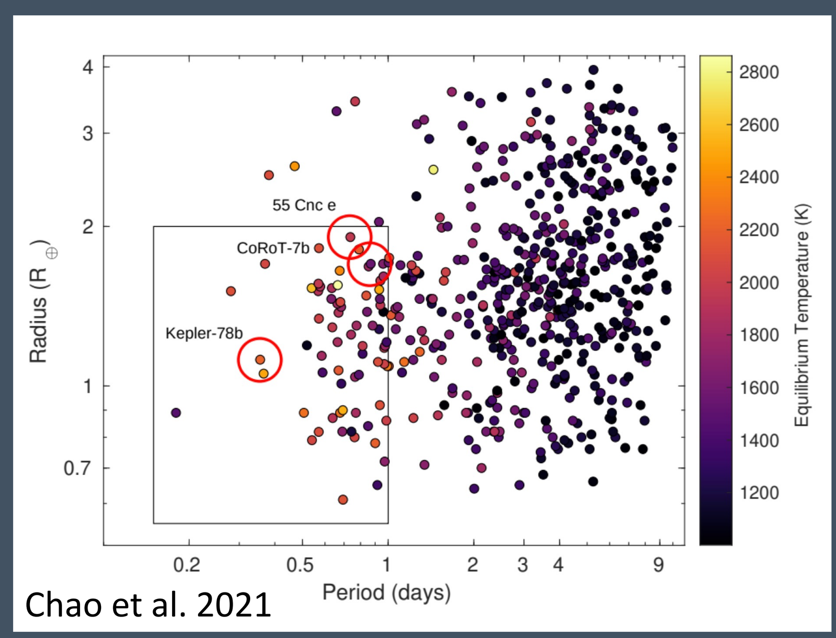
Magma Worlds: Windows into Rocky Exoplanets and the Early Earth

- Magma planets, those with extensive surface lava or global magma oceans, are arguably the most characterizable type of rocky exoplanet for coming decades due to their hot, extended atmospheres, and they may unlock a new avenue for studying the Hadean Earth
- These planets' atmospheres are modulated by solubilities of major gases in magma



Chao et al. 2021

Why Hydrogen?
- Cosmic abundance; significant presence during rocky planet formation if prior to gas disk dissipation
- Solubility for diverse compositions and conditions is unknown

Goal:
Determine H_2 solubility in diverse melt compositions at high temperatures (≥1400 °C) and 1-bar pressure

1-Bar Solubility Experiments

PLANETARY MELT ANALOG COMPOSITIONS

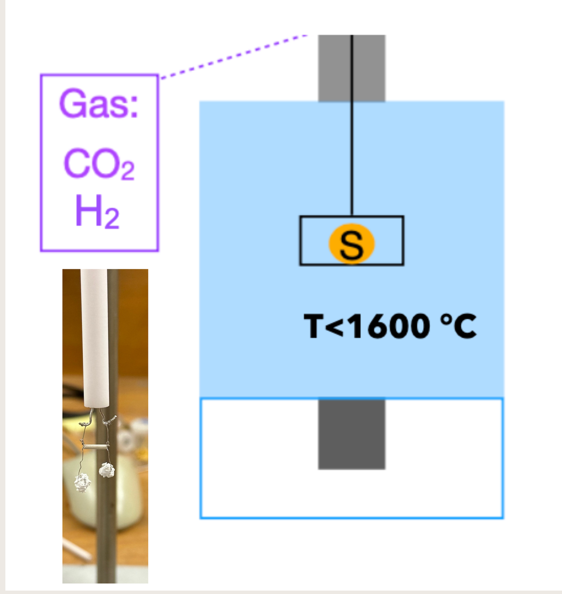
O'Neill & Eggins 2002

Melt	CaO	MgO	Al_2O_3	SiO_2	FeO
AD eutectic	24.1	10.6	15.2	50.1	–
AD+Fo (15%)	20.5	16.9	12.9	49.6	–
AD+En (60%)	15.2	20.6	9.3	54.8	–
AD+Wo (140%)	38.0	4.6	6.6	50.6	–
AD+Qz (50%)	16.2	6.9	10.0	66.8	–
AD eutectic + 10 wt.% FeO	21.7	9.5	13.7	45.1	10.0
AD eutectic + 20 wt.% FeO	19.3	8.5	12.2	40.1	20.0
AD eutectic + 30 wt.% FeO	16.9	7.4	10.6	35.1	30.0

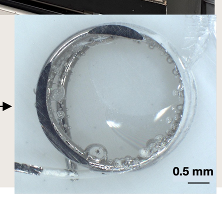
Anorthite-Diopside (AD) Eutectic:
42% Anorthite ($CaAl_2Si_2O_8$) 58% Diopside ($CaMgSi_2O_6$)

More compositions to come soon:
- Synthesizing materials with melting temperatures above 2000 °C using the aerodynamic laser levitation furnace (e.g., peridotite, pyrolite)

1-BAR GAS-MIXING FURNACE



Quenched Sample Post-Experiment
(several mm in diameter)

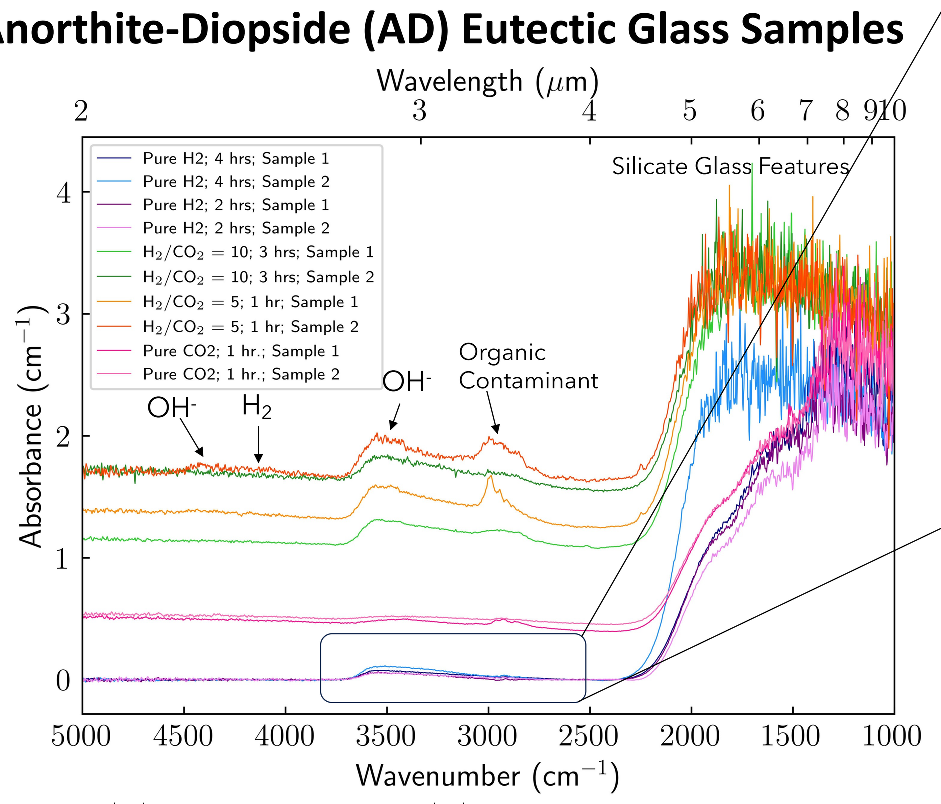


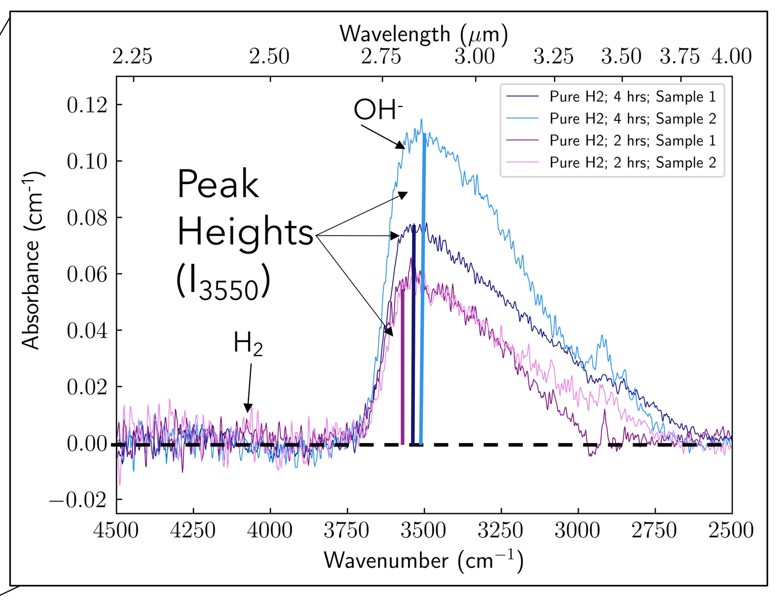
RANGE OF EXPERIMENTAL CONDITIONS

Input H_2/CO_2 Ratio	$f(H_2)$ (bar)	$f(H_2O)$ (bar)	Temperature (°C)	Number of Experiments	Experiment Durations (hrs)
5	0.68	0.16	1400, 1550	5	1-5
10	0.82	8.8E-2	1400	4	1-5
Pure H_2	1	0	1400	8	1-5
Pure CO_2	0	0	1400	2	1-2.5

FTIR Analysis

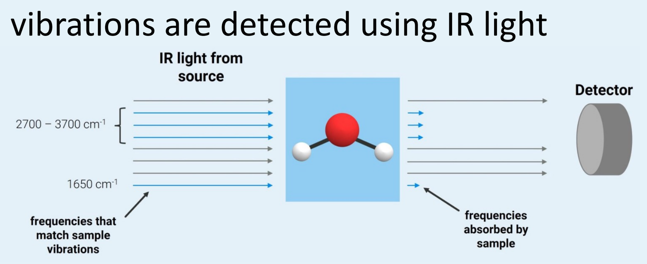
Anorthite-Diopside (AD) Eutectic Glass Samples





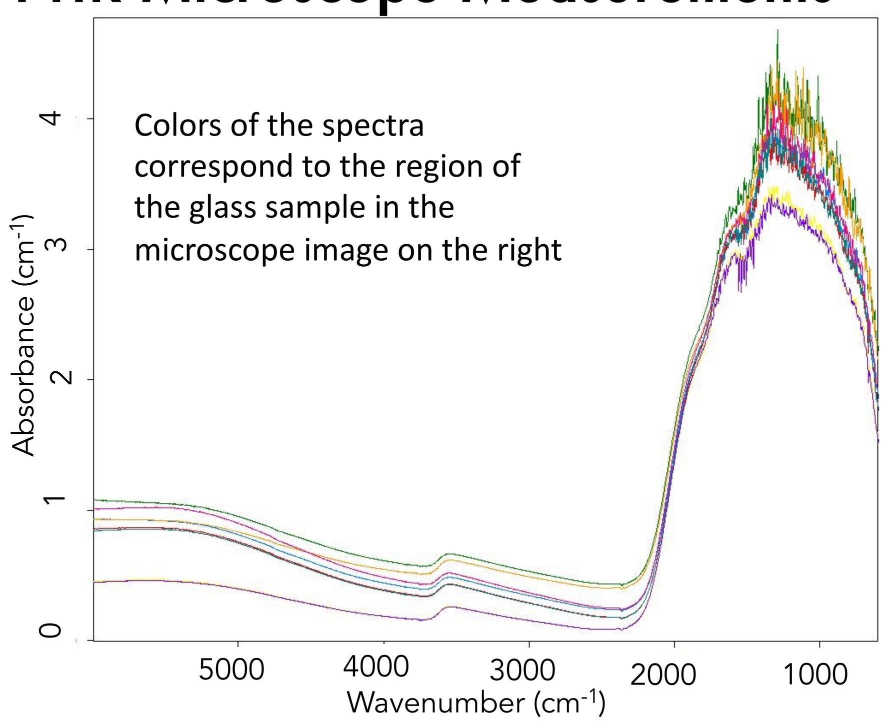
What is FTIR?

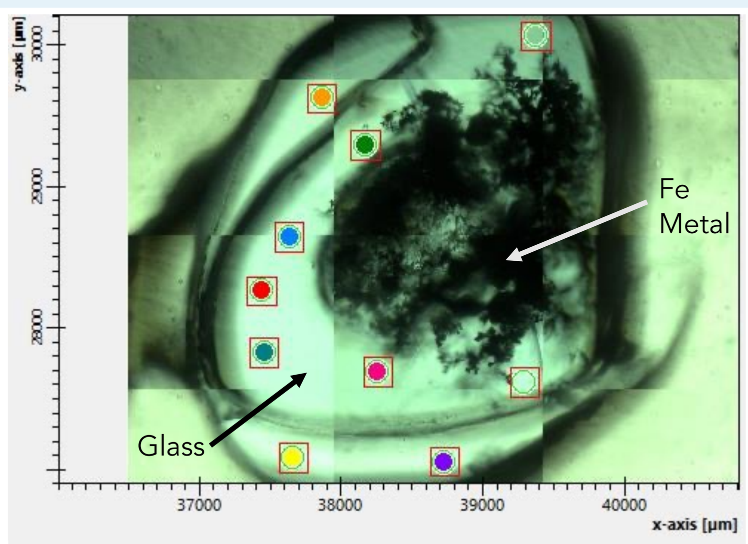
- Fourier-Transform Infrared Spectroscopy: chemical analysis technique where molecular vibrations are detected using IR light



Key Spectral Features from Samples:
- OH^- stretching band at 3550 cm^{-1}
- No detection of molecular H_2 absorption peak at ~4130 cm^{-1}

FTIR Microscope Measurements





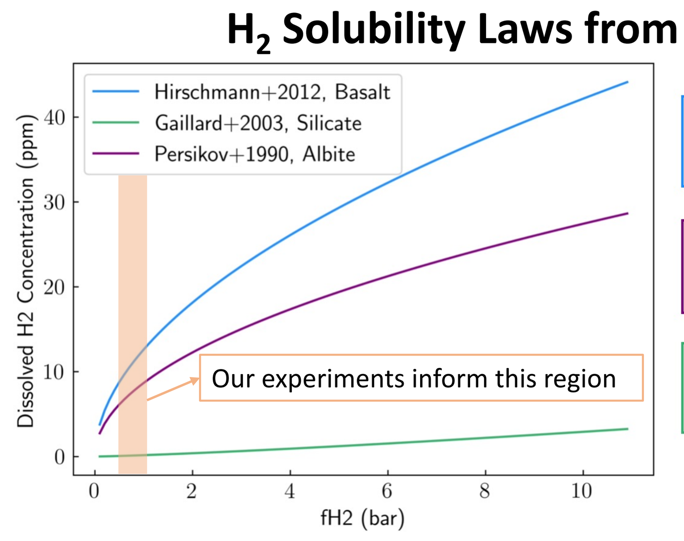
AD Eutectic + 20 wt. % FeO Quenched Sample

FTIR Microscope Advantages:
- Measure IR spectra at multiple points across the sample
- Better correction for epoxy resin (organic contaminant)

Mechanisms for H_2 Dissolution

- Hydrogen can dissolve as molecular H_2, OH^- and H_2O
- Our findings show that at 1 bar gaseous H_2 dissolves into anorthite-diopside-eutectic melt as OH^- not molecular H_2
  - Consistent with experiments from Gaillard+2003 and Newcombe+2017
  - Hirschmann+2012 find that at higher pressures H_2 dissolves as both H_2 and OH^-

H_2 Solubility Laws from Prior Studies



$$[H_2](ppm) = 10^{(0.524*\log_{10}(f_{H_2})+1.101}$$

$$H_2(ppm) = 8.67\sqrt{f_{H_2}}$$

$$[H_2](ppm) = 0.163 f_{H_2}^{1.252}$$

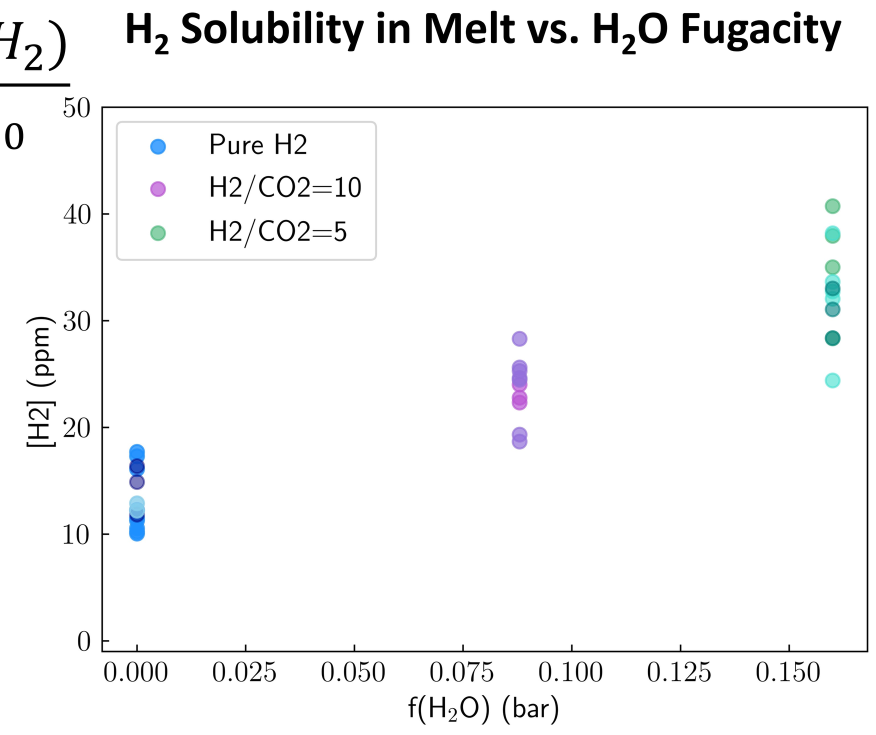
Determining Dissolved $[H_2]$ in Planetary Melts

Beer-Lambert Law:

$$[H_2]_{(ppm)} = 10^6 \frac{I_{3550} M(H_2)}{d \rho \epsilon_{3550}}$$

- I_{3550}: Absorption peak height at 3550 cm^{-1}
- $M(H_2)$: Molar mass of H_2
- d: Sample thickness (m)
- ρ: Glass density at glass transition temperature for anorthite-diopside eutectic (2743 kg/m³)
- ϵ_{3550}: Molar absorption cross section for 3550 cm^{-1} band

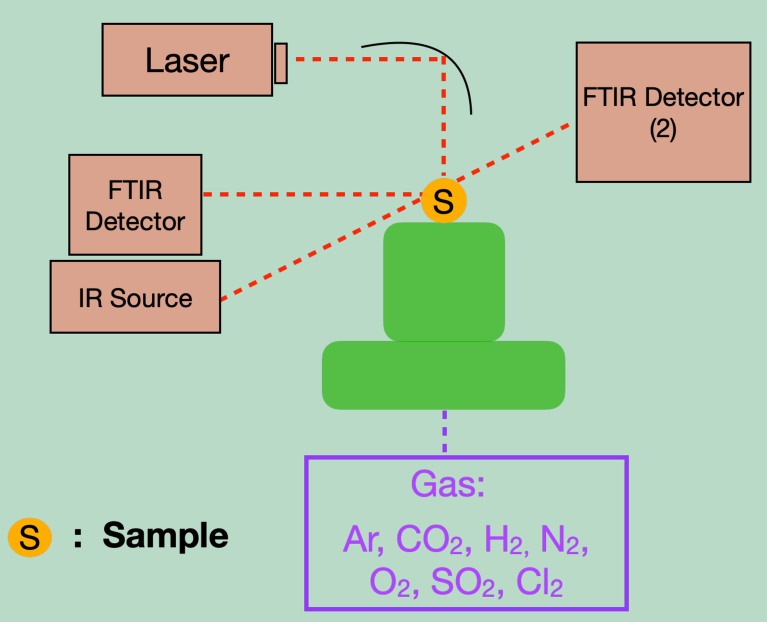
H_2 Solubility in Melt vs. H_2O Fugacity



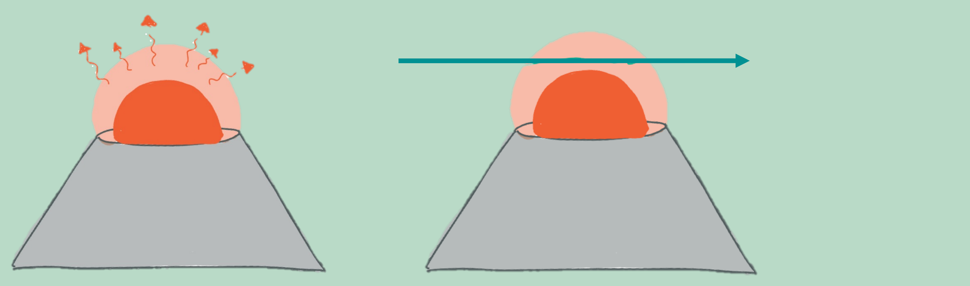
RESULTS:
H_2 Solubility ↑ as H_2O fugacity ↑
No strong dependence on temperature or iron content in melt (based on preliminary measurements, but more to come!)

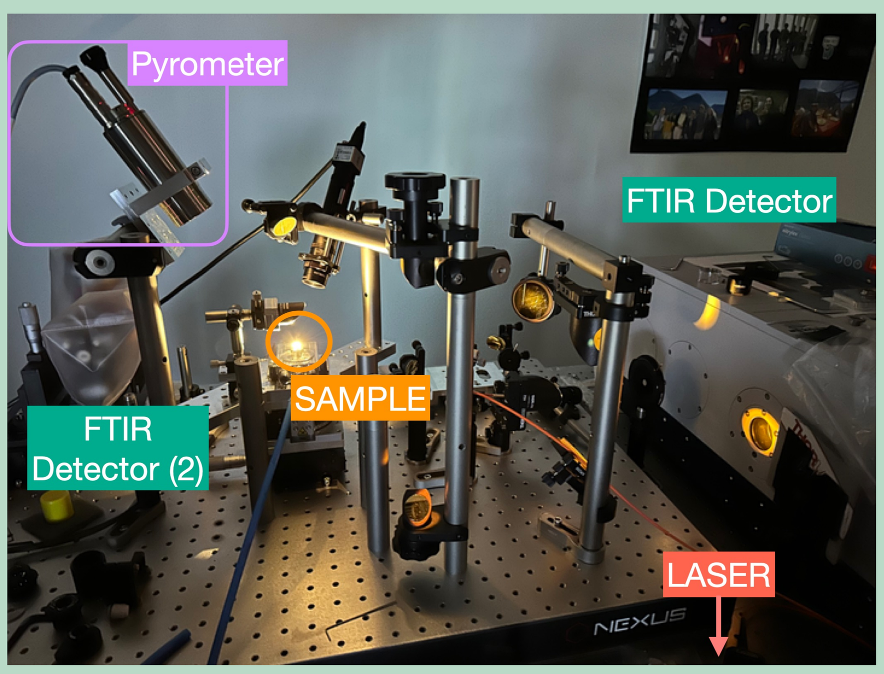
Aerodynamic Laser Levitation Furnace + FTIR

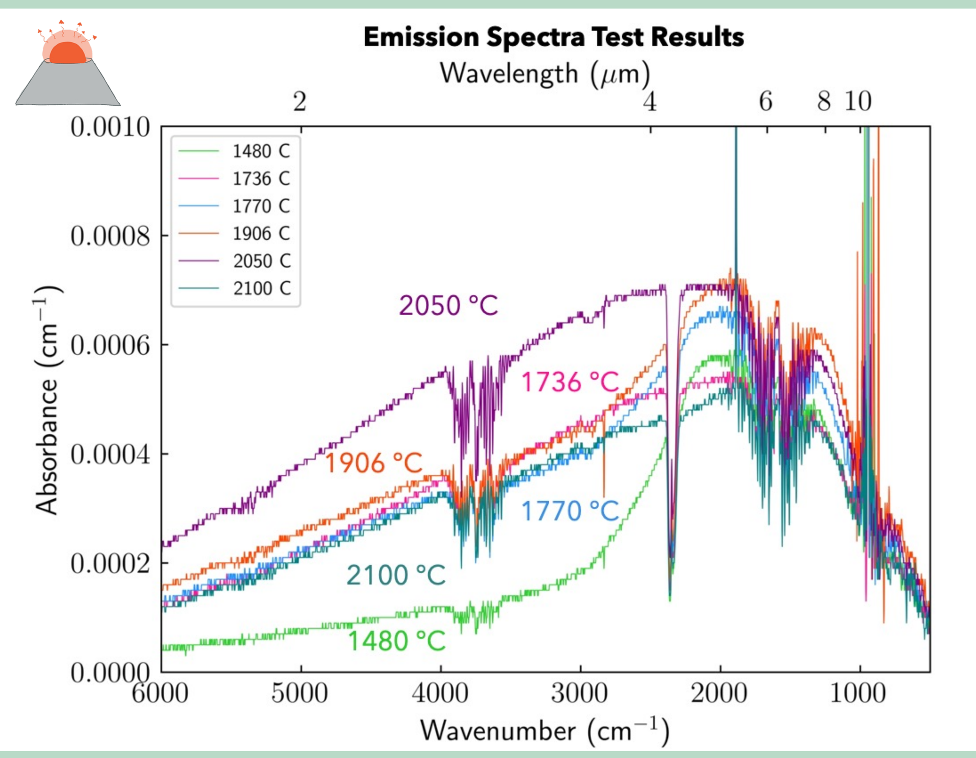
Novel Instrument to Measure Volatile Solubilities, Outgassing Compositions, and Melt Emissivity



- Temperature: 1450 – 2500 °C and even higher
- Pressure: 1 bar
- In-situ spectroscopy measurements in emission and transmission



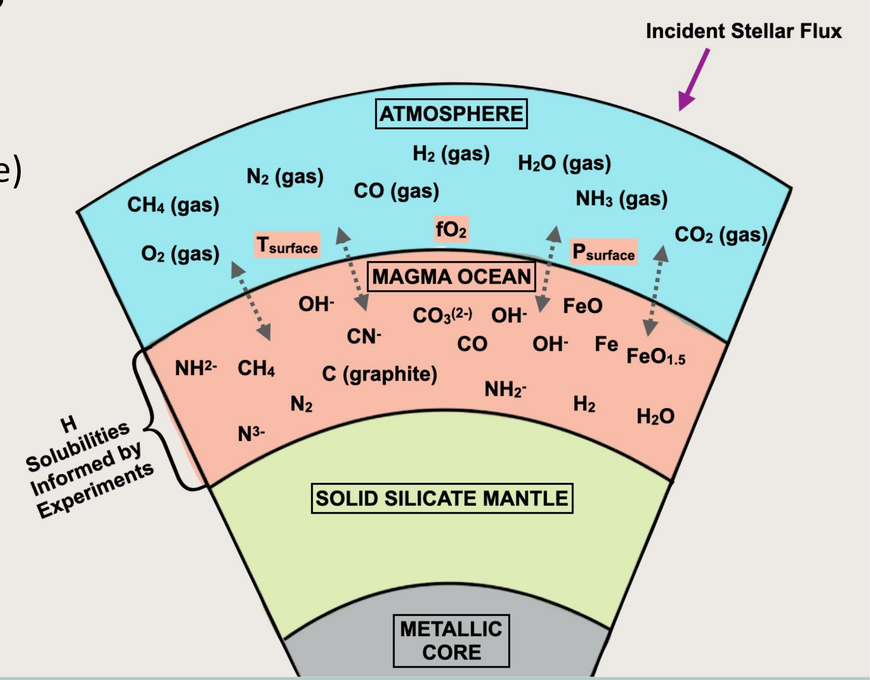


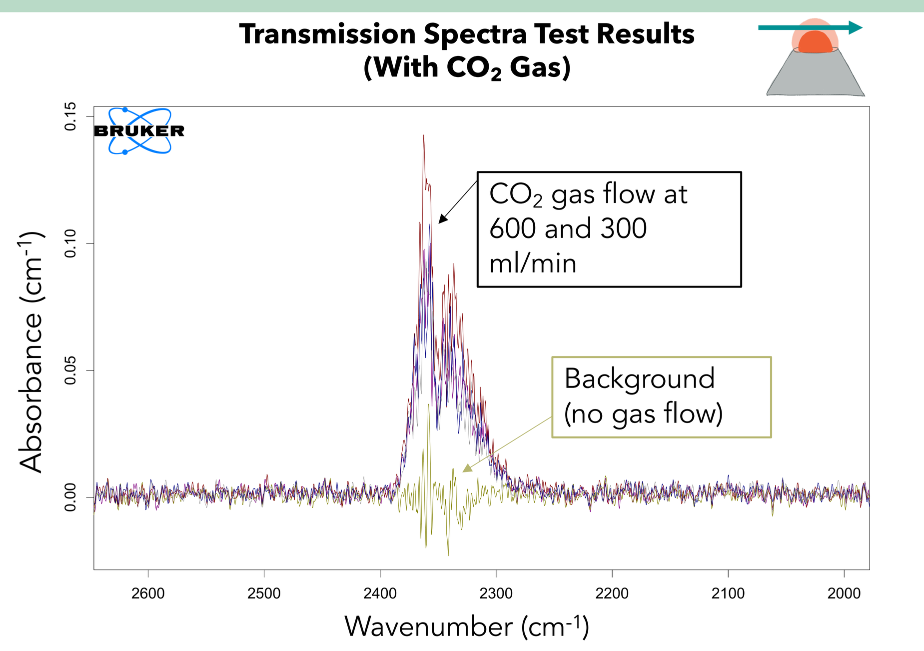


Implications for Rocky Planets

- Our experiments demonstrate that at 1 bar the concentration of dissolved H_2 (in the form of OH^-) is larger (i.e., several times up to an order of magnitude) than some prior studies suggest
- For rocky planets that accrete nebular gas, hydrogen solubility influences a planet's volatile retainment, atmospheric composition, and habitability potential (e.g., Young et al. 2023)
- Models of magma exoplanets should include the effect of volatile solubilities (e.g., H_2, H_2O, CO, CO_2, CH_4, N_2, NH_3, SO, SO_2) on a planet's atmospheric composition **(See Dan Bower's Poster No. 855!)**

Magma Planet Model Schematic





Questions? Want to get in touch?

Send me an email! **mthompson@carnegiescience.edu**

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