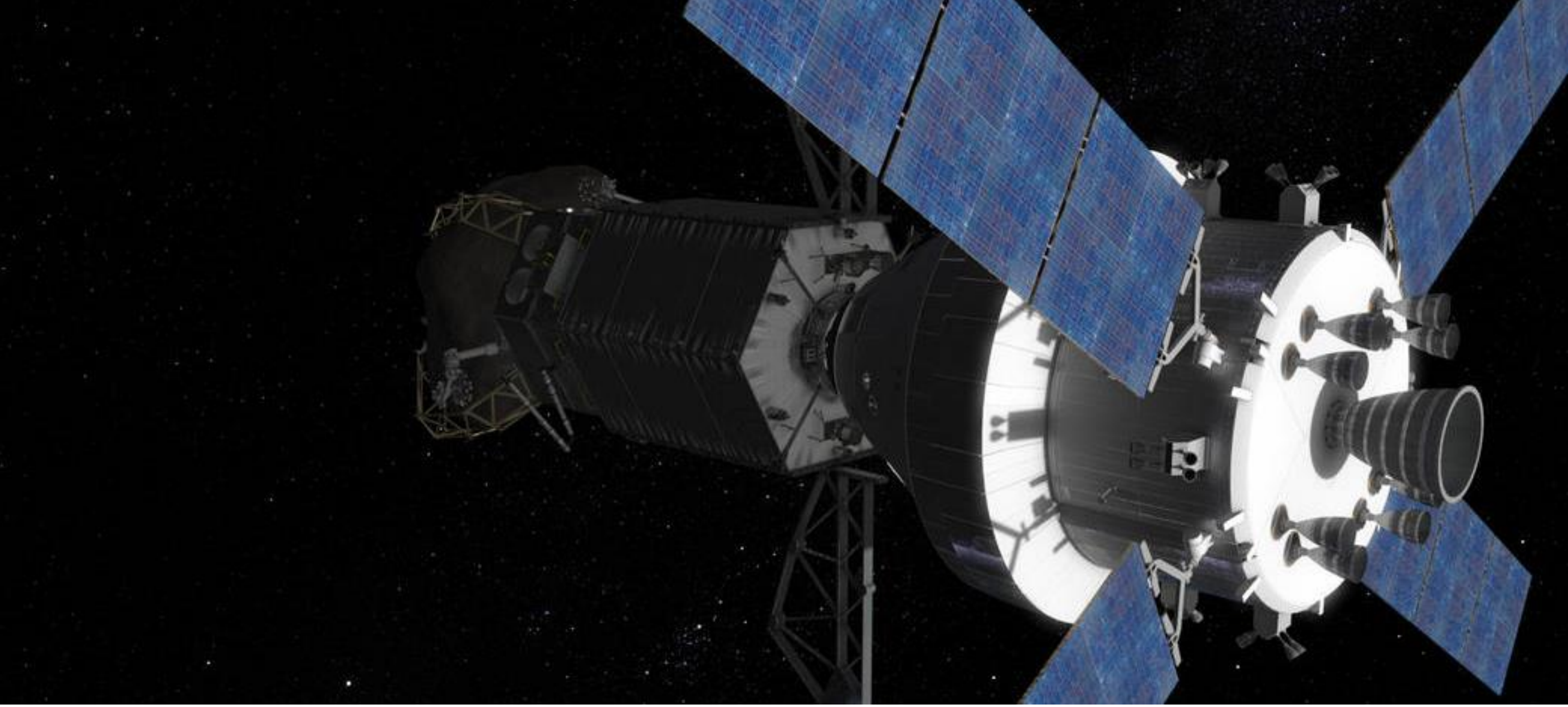

In-Situ Resource Utilization Experiment for the proposed Asteroid Redirect Crewed Mission

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Jet Propulsion Laboratory
California Institute of Technology

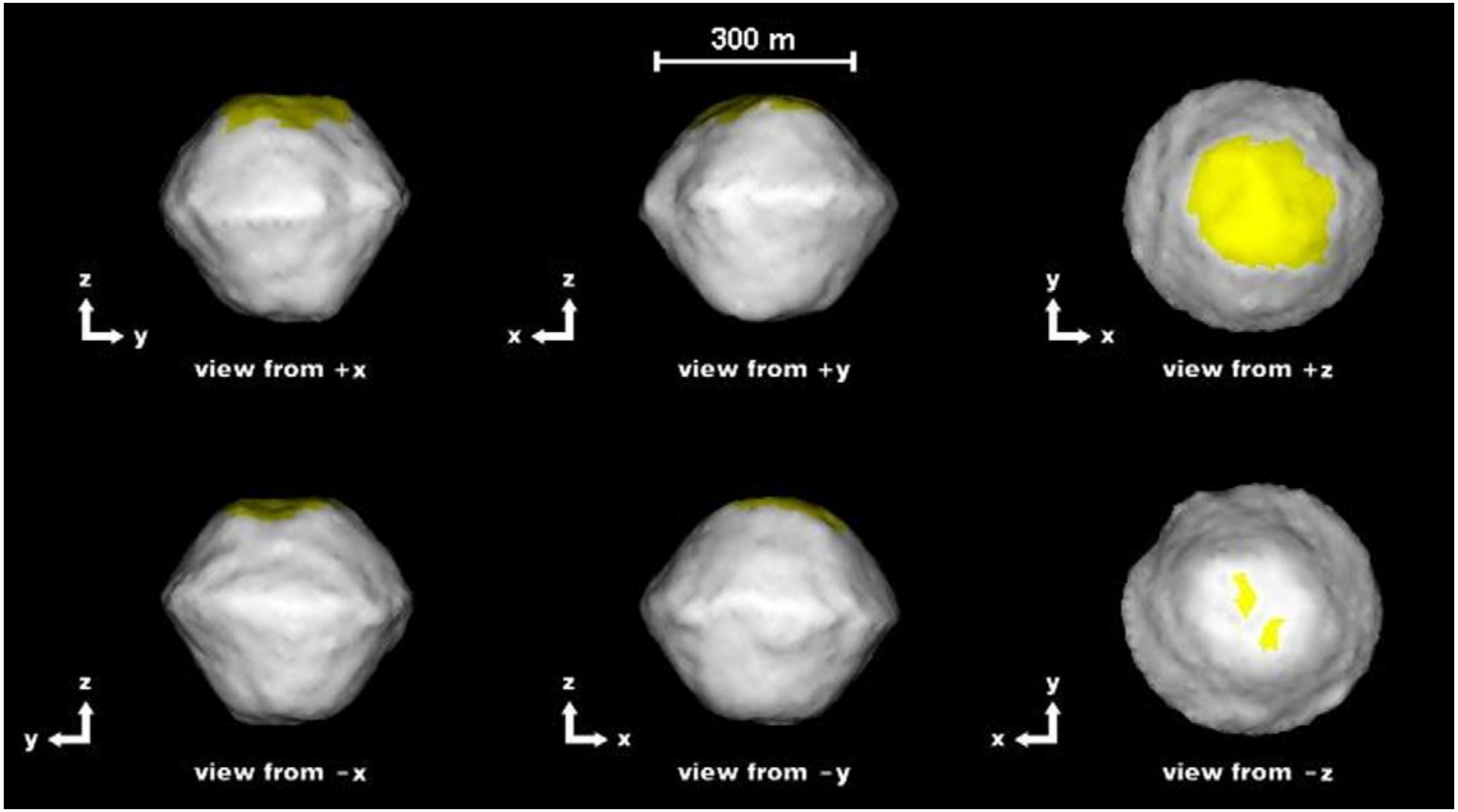
September 29, 2015

Jet Propulsion Laboratory
California Institute of Technology

Johnson Space Center
Astromaterials Research and Exploration Science

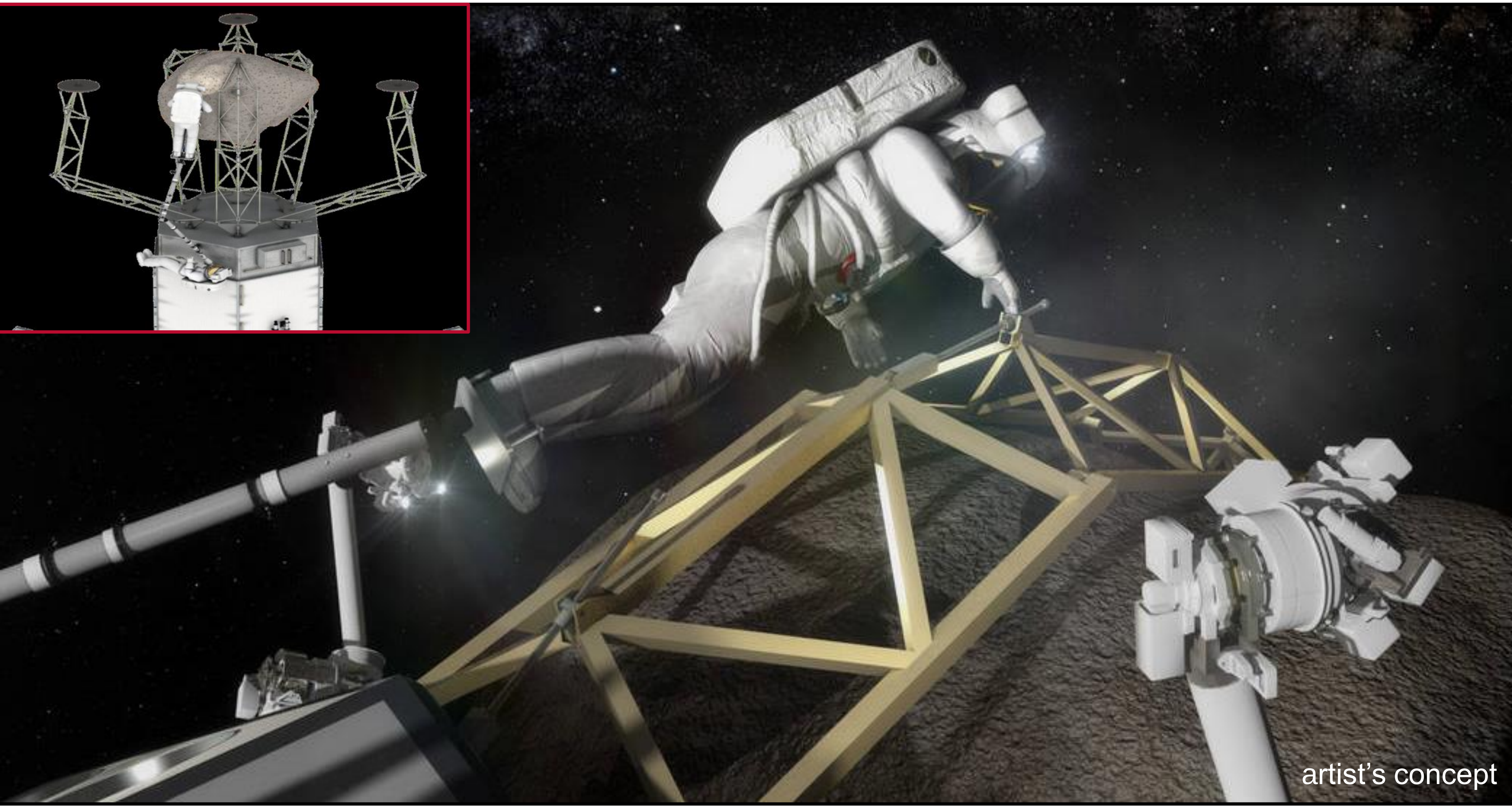
Prime candidate for Asteroid Redirect Mission

Asteroid *2008 EV5*, C-type



M. W. Busch, S. J. Ostro, L. A. M. Benner, M. Brozovic, J. D. Giorgini, J. S. Jao, D. J. Scheeres, C. Magri, M. C. Nolan E. S. Howell, P. A. Taylor, J. L. Margot, and W. Brisken, "Radar observations and the shape of near-Earth ASTEROID 2008 EV5", *Icarus* **212** (2011) 649-660.

proposed Asteroid Redirect Crewed Mission



Asteroid In-Situ Resource Utilization (ISRU)

- Current launch costs are $10,000/kg to LEO and $ 30,000/kg to Earth escape.
- Asteroid Redirect Robotic Vehicle (ARRV) would be designed to use 10 tons of propellant to retrieve a 1000-ton asteroid.
- If we could extract 250 tons of volatiles from the asteroid, then the recurring cost (i.e. to refuel the ARRV in LEO) per kg of in-situ volatiles would be only $400/kg

D. Mazanek, R. Merrill, J. Brophy, R. Mueller, "Asteroid Redirect Mission concept: A bold approach for utilizing space resources", *65th International Astronautical Congress*, IAC-14-D3.1.8. 2014.

Composition of C-type asteroids

Volatile yield measured by Court & Sephton (2014)

Yields of carbon dioxide, water and sulphur dioxide produced upon pyrolysis of the samples, as measured in ppm per degree Celsius.

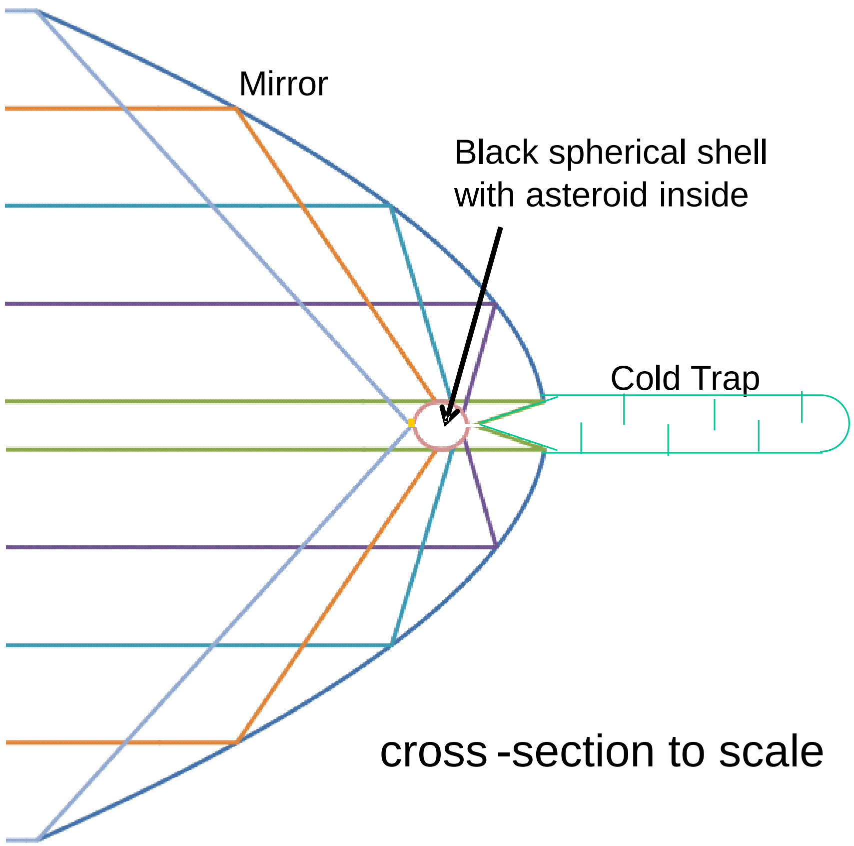
Temp. (°C)		Yield (ppm $°C^{-1}$)																	
		Orgueil CI1			ALH 88045 CM1			Cold Bokkeveld CM2			Murchison CM2			Mokoia CV3			Mean of Org., CB and Murch.[1]		
		H_2O	CO_2	SO_2	H_2O	CO_2	SO_2	H_2O	CO_2	SO_2	H_2O	CO_2	SO_2	H_2O	CO_2	SO_2	H_2O	CO_2	SO_2
250		230.5	0.2	0.0	87.4	1.9	0.0	317.7	2.9	0.0	67.3	2.1	0.0	7.6	0.2	0.0	205.2	1.7	0.0
300		147.3	7.9	14.2	38.7	4.5	0.0	203.9	12.1	9.8	45.8	4.5	0.0	0.0	2.1	0.0	132.3	8.2	8.0
400		151.1	26.5	76.0	53.2	8.4	0.0	156.5	30.7	40.5	74.7	14.3	0.0	4.9	6.6	0.0	127.5	23.9	38.8
500		90.4	53.6	26.5	95.1	23.0	0.0	103.4	51.2	11.7	116.6	31.9	0.6	0.7	10.3	1.7	103.5	45.6	12.9
600		83.4	83.5	98.6	173.9	33.1	1.4	95.3	79.5	92.2	160.2	46.2	12.1	0.0	7.8	29.6	113.0	69.7	67.7
700		95.6	113.8	114.1	226.5	45.0	9.3	92.4	97.9	96.3	158.8	63.7	56.0	0.0	8.4	39.6	115.6	91.8	88.8
800		138.0	124.6	60.8	252.3	57.5	14.7	132.0	122.1	58.8	126.9	64.0	63.1	0.0	14.6	38.5	132.3	103.6	60.9
900		106.4	205.9	32.4	112.4	87.0	17.6	85.4	134.4	42.9	73.5	81.8	44.0	n/a	n/a	n/a[2]	88.4	140.7	39.8
1000		16.8	113.6	37.1	14.9	79.5	28.6	24.9	113.2	41.2	27.9	76.9	34.5	0.0	20.8	3.9	23.2	101.2	37.6
Yield (wt.%)	250 °C	5.8	0.0	0.0	2.2	0.0	0.0	7.9	0.1	0.0	1.7	0.1	0.0	0.2	0.0	0.0	5.1	0.0	0.0
	⩾300 °C	7.6	7.3	4.5	9.5	3.4	0.7	7.9	6.4	3.9	7.6	3.8	2.1	0.1	0.7	1.1	7.7	5.8	3.5
	Total	13.3	7.3	4.5	11.7	3.4	0.7	15.9	6.4	3.9	9.3	3.9	2.1	0.2	0.7	1.1	12.8	5.8	3.5

[1] Org. = Orgueil, CB = Cold Bokkeveld and Murch. = Murchison; ALH 88045 and Mokoia are excluded from this mean because of their terrestrial alteration and thermal metamorphism, respectively.

[2] Data not available because of instrumental error. These data have a margin of uncertainty about ±5%, relating to errors in sample measurement and purity.

R.W. Court, M.A. Sephton / Geochimica et Cosmochimica Acta 145 (2014) 175–205

How to cook an asteroid: oven

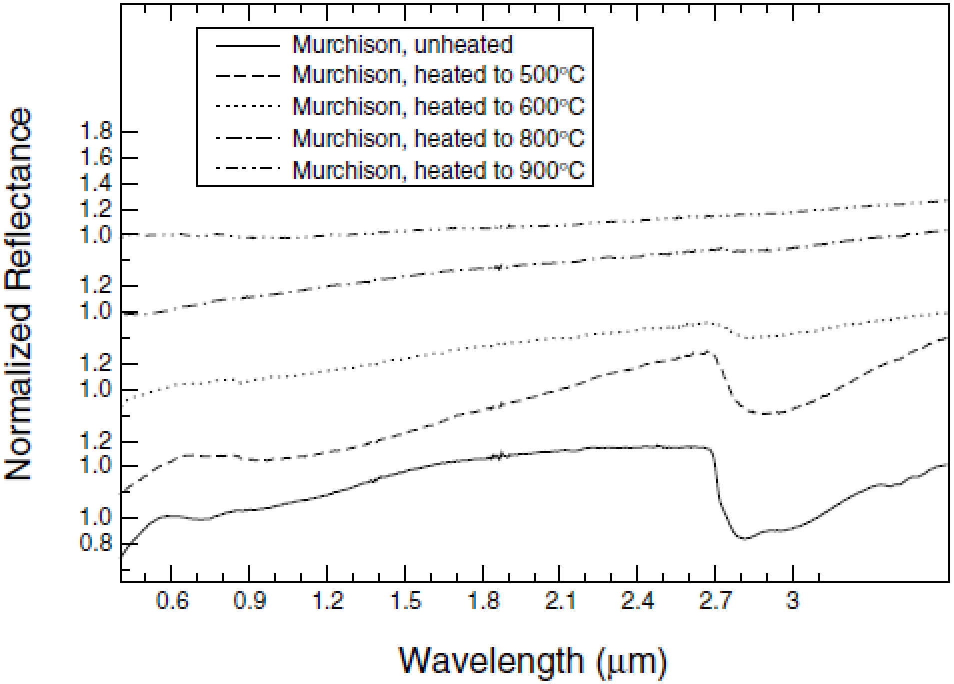


cross -section to scale

- Mirror concentrates sunlight uniformly over a sealed black sphere containing ~5 m volatile-rich asteroid.
- The black sphere heats up to ~1100 K and "cooks” volatiles (mostly H_2O) out of the asteroid.
- Hot volatile gases pass through a hole in the black sphere into a long cold-trap in the shadow of mirror that radiates into space to condense volatiles.
- Baffles in the cold-trap create graded-temperature zones for separation of volatile species.

How to cook an asteroid: temperature

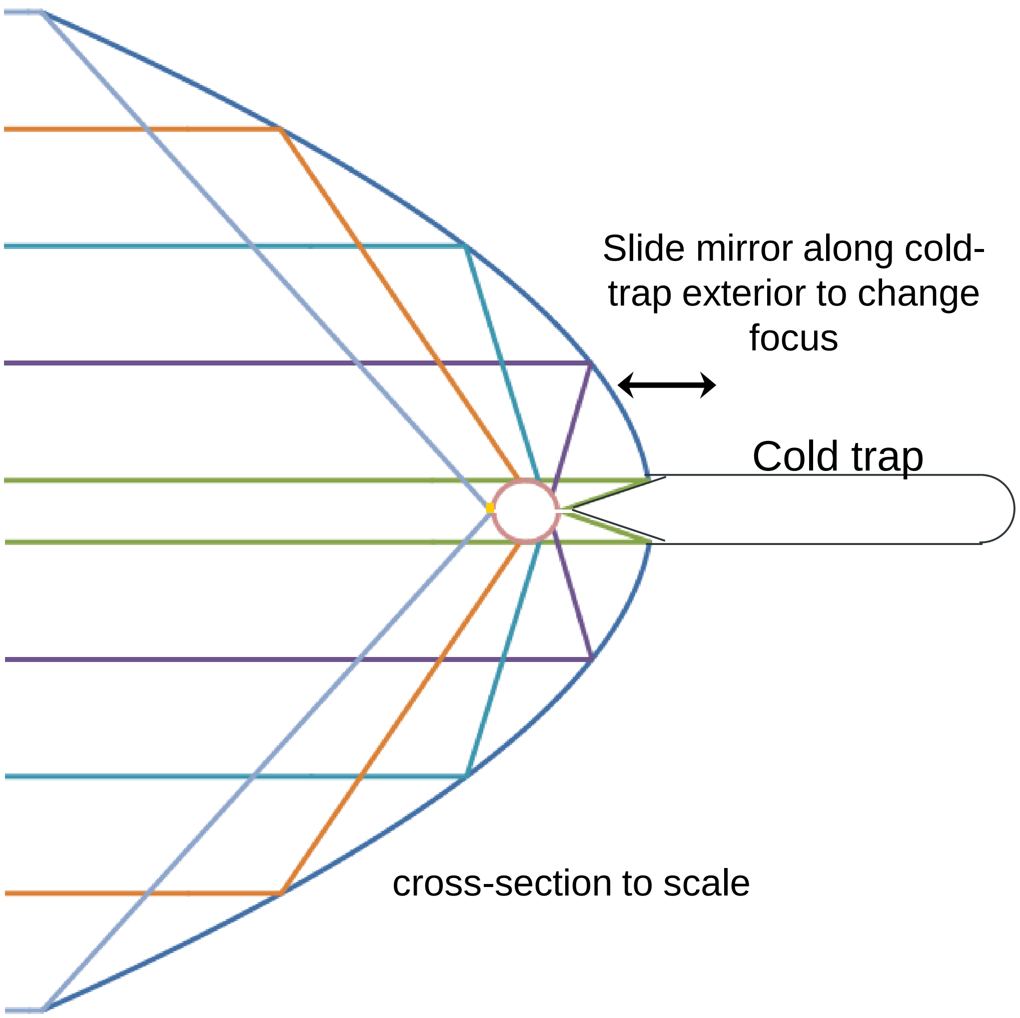
- Spectrum of CM meteorite Murchison, taken after heating to different temperatures (data from Hiroi et al. 1996.
- Suggests that 800^{o}-900^{o}C is sufficient to drive off not only adsorbed water but also water incorporated into the crystal structure.



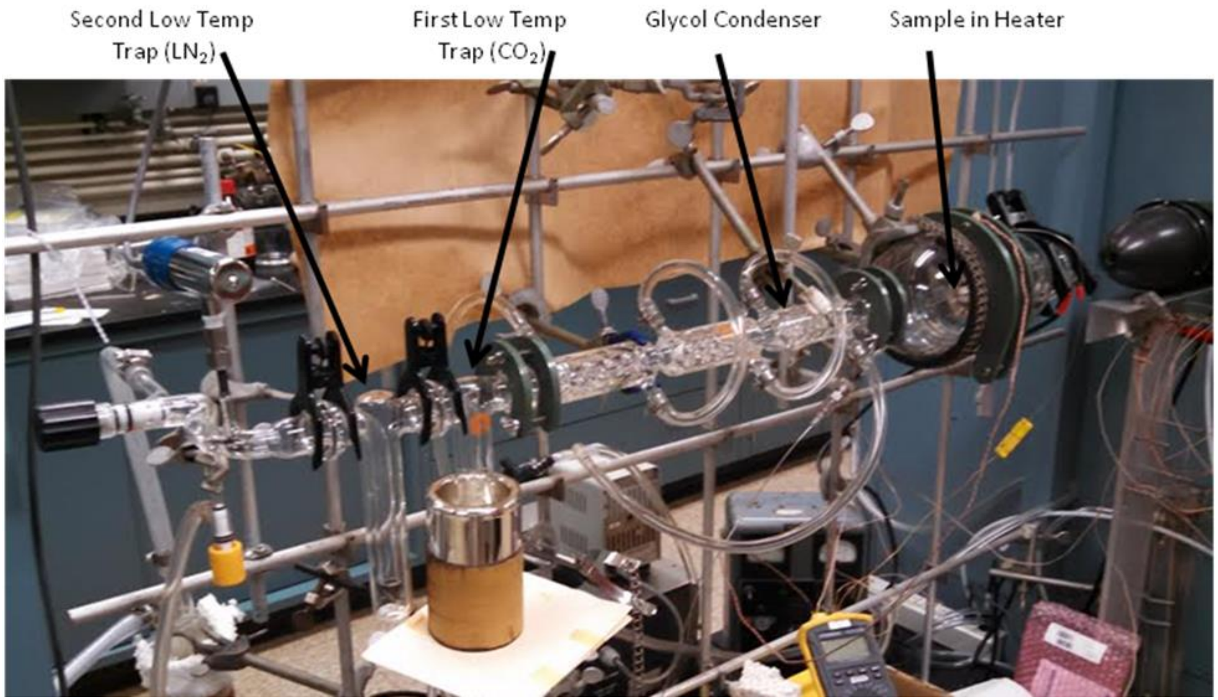
From Rivkin, A.S., Howell, E.S., Vilas, F., Lebofsky, L.A., *Hydrated Minerals on Asteroids The Astronomical Record,* Asteroids III, p 236-:253

How to cook an asteroid: process

- Rotate mirror away from sun and "split open" black sphere to insert asteroid.
- Rotate back towards sun and slowly "insert" sphere from back towards focus, modulating motion based on gas pressure in cold trap.
- ~100 ton, 5 m diameter asteroid (or split of a larger asteroid) can be de-volatilized with all volatiles condensed in ‘fractionation column’ within a few days.

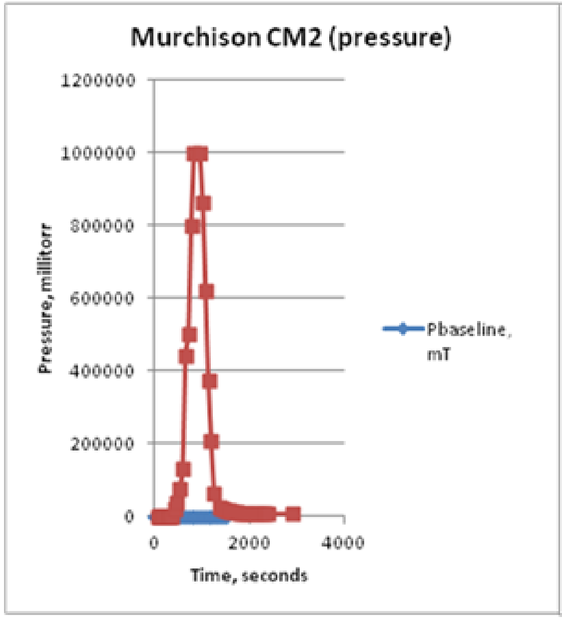


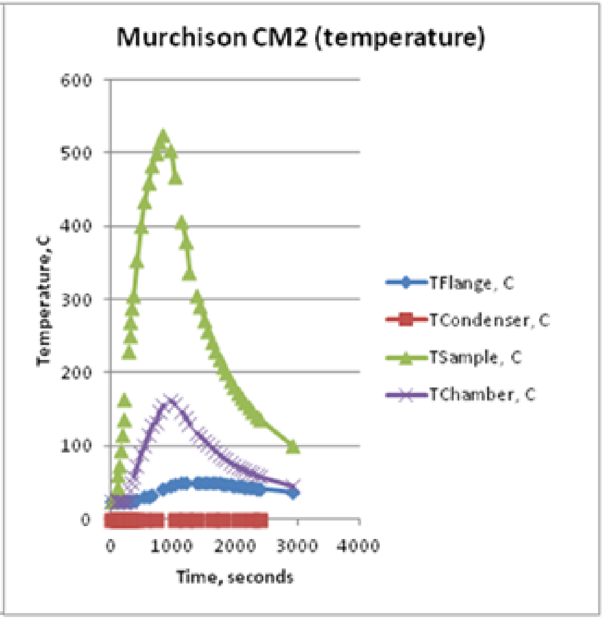
Laboratory experiments: apparatus



Sample materials: a) alumina foam, b) kaolinite clay, c) Murchison CM2 in alumina

Laboratory experiments: results





Murchison CM2 LN_2 Trap (#1)

Species	1st Run	2nd Run	3rd Run	Ave
N_2	11.78	12.04	12.02	11.95
O_2	0.163	0.159	0.164	0.16
Ar	0.0811	0.0745	0.0731	0.08
CO_2	86.08	85.96	86.01	86.02
H_2O	0.511	0.434	0.418	0.45
H_2	0.495	0.474	0.471	0.48
SO_2	0.294	0.287	0.283	0.29
HC	0.589	0.573	0.565	0.58

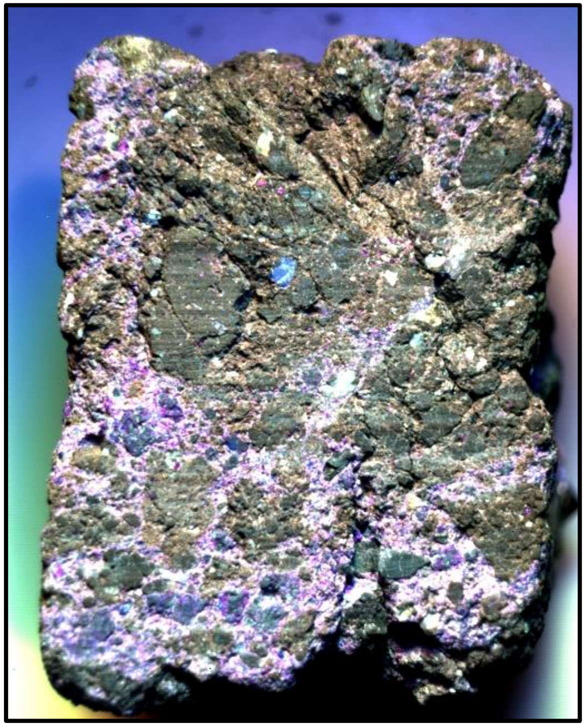
Murchison CM2 CO_2 Trap (#2)

Species	1st Run	2nd Run	3rd Run	Ave
N_2	26.11	25.47	25.56	25.71
O_2	4.39	4.26	4.27	4.31
Ar	0.718	0.688	0.653	0.69
CO_2	49.35	50.55	50.61	50.17
H_2O	1.4	1.42	1.38	1.40
H_2	2.52	2.58	2.22	2.44
SO_2	10.74	10.44	10.47	10.55
Benzene	0.329	0.304		0.32
HC (sum)	4.458	4.291	4.288	4.35

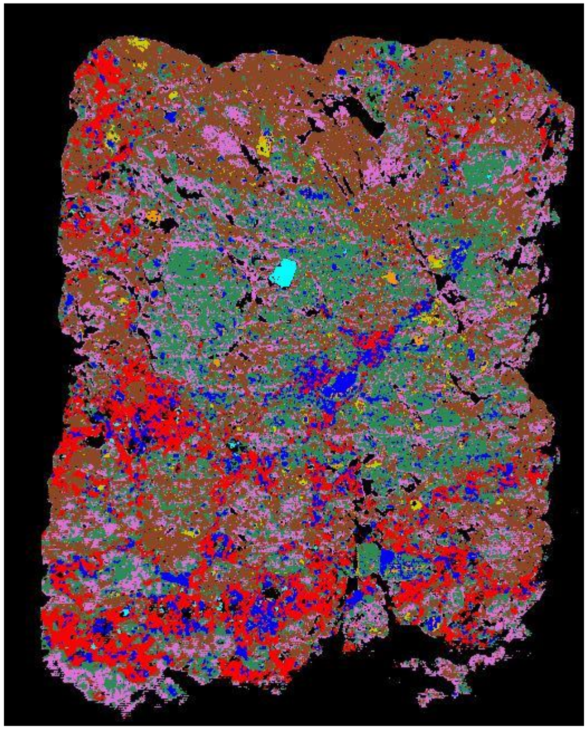
Multispectral imagery reveals mineralogical diversity

Apollo sample 14321,88 (lunar breccia); 3 x 4 cm

Natural-color (470, 525, 630 nm)



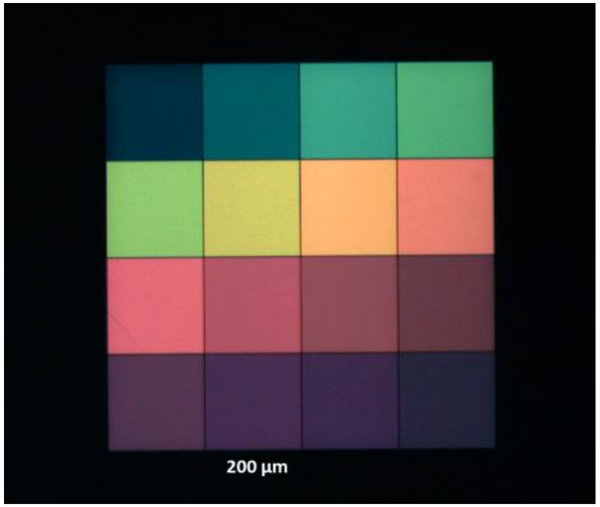
False-color IR (735, 905,1200 nm)

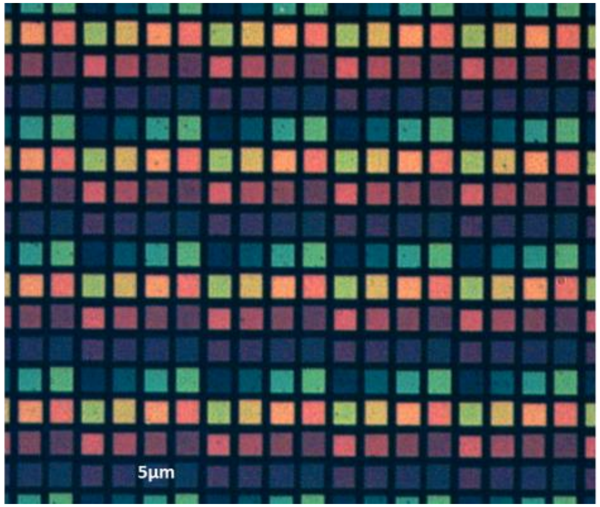


Mineral map derived from multiple wavelengths

J. I. Nuñez, J. D. Farmer, R. G. Sellar, C. C. Allen, "Exploring the Moon at the Microscale," *Annual Meeting of the America Geophysical Union* (2009).

Color filter array for multispectral video camera





- Visible/infrared color filter arrays enable a video camera with 4, 9 or 16 colors/bands
- Fabricated at JPL using electron-beam etching.

Subscale ISRU experiment for ARCM

1. Video from suit-mounted multispectral IR camera would be used by mission control to guide sampling during EVAs.
2. At end of EVA 1, crew deposit a sample in a 1:75 scale version of the solar extractor.
3. Experiment would run (outside Orion) for up to one day between EVA's.
4. Crew would retrieve container with collected volatiles on EVA-2.

Photo credit: S. Sipila, Z. Scoville, J. Bowie, and J. Buffington "EVA Asteroid Exploration and Sample Collection Capability", *AIAA SpaceOps* 2014, abstract 1605. 2014