2022.08.23 Space Chemistry Roundtable

Minutes issue date: 2022.09.16 - Venue: UChicago David Rubenstein Forum

Minutes of the Meeting of the Space Chemistry Roundtable held as a separate track of the CME NASA Sustainability Conference
Meeting time: 3:15 – 4:45 pm
Participants and Observers: listed in the Exhibits section of the report include representatives from NASA, CME, ACS Technical Divisions, Axiom Space, Redwire, InnoStudio, Blue Origin, BASF, Air Force Research Laboratory, ProChem, Connell Foley, University of Alberta, Boston University, Intel, Los Alamos National Lab, Sierra Space, NIH NCATS, University of Michigan, Syngenta, SafeRock, NASA HQ - Earth Science Division, University of Minnesota Twin Cities, UChicago, McKinsey, ISS National Laboratory, Argeni, ACS Div. Colloid and Surface Chemistry, Northwestern University, and University of Iowa, among others.

Purpose: Develop a Roadmap for Space Chemistry to Support the Commercialization of Space

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- Ferenc Darvas, PhD, Executive Chairman, InnoStudio
  Building a Roadmap for Space Chemistry Applications
- Jana Stoudemire, Director, In-Space Manufacturing, Axiom Space
  The Developing LEO Economy
- Kenneth Savin, PhD, Chief Scientist, Redwire Space
  Industrial/Commercial Space Chemistry Initiatives

Introduction

This discussion was the first in a series of planned discussions to develop a Space Chemistry Roadmap that will support existing NASA exploration programs - returning the first woman and first person of color to the moon, and future missions to Mars - and the emerging in-space manufacturing markets for advanced materials and biomedical products that are developing in the expanding commercial space economy. Approaches and capabilities that simultaneously foster exploration, commercial, and fundamental research space chemistry needs have the potential to accelerate 1) the development of a robust commercial space economy and 2) NASA exploration goals.

This Roundtable was held as a separate track of the CME NASA Sustainability Conference held on Tuesday August 23, 2022, at the David Rubenstein Forum of the University of Chicago. Presenters and discussion leaders included Jim Green (Senior Advisor, Office of the Chief Scientist, NASA), Ferenc Darvas (Executive Chairman, InnoStudio), Jana Stoudemire (Director, In-Space Manufacturing Axiom Space), and Kenneth Savin (Chief Scientist Redwire Space), The event culminated in the CME STEM Leadership Awards in Academia Reception and Dinner honoring Nobel Laureate Sir Fraser Stoddart, International Institute for Nanotechnology Director Chad Mirkin and University of Chicago President (and Chemist) Paul Alivisatos. The conference followed other CME and NASA activities including the ACS Fall 2022 Fifth Annual CME NASA Symposium "Chemistry for Sustainable Human Space Exploration" and the CME and PMSE ACS Outstanding Global Student & Mentor Awards in Polymer Science & Engineering.

Background

Over the last 20 plus years the International Space Station (ISS) has been continually inhabited by crew members from many nations who have participated in many of the over 3000 experiments that have been conducted in microgravity. Since completion of assembly in the first decade, the ISS U.S. National Laboratory onboard the ISS has produced a decade of results demonstrating the benefits of microgravity not just for discovery, but for the development of new and promising technologies for in-space manufacturing of advanced materials and biomedical products for use on Earth. The ISS remains a critical resource for NASA and its international partners to conduct exploration research, and NASA will continue to utilize the microgravity environment in low-Earth Orbit (LEO) long after the scheduled retirement of the ISS at the end of this decade. NASA's awards for Commercial LEO Destinations (CLDs) in 2020 (Axiom Space) and 2021 (Sierra Space/ Blue Origin, Nanoracks/Voyager, Northrup Grumman) are a key piece of NASA's 2019 strategy for the development of a sustained economy in LEO, enabling private space stations to provide capabilities for continued microgravity research to NASA and future commercial customers. The CLDs currently in development will transition the ISS from a singular government owned and operated facility to multiple commercial platforms enabling access to space for research technology development, manufacturing, and economic benefit for the nation by 2030.

The accessibility of commercial space stations in LEO is near-term. The first commercial module of the Axiom Station, providing crew quarters for private astronauts and state-of-the-art research capabilities, is planned to attach to the ISS in late 2024. A second module supporting crew and research will be added in 2025, and a dedicated research and manufacturing facility is planned for 2026. The final module, a power and thermal tower, will be attached in 2027 providing capabilities that allow the Axiom Station to detach from the ISS as a free-flyer once the ISS is decommissioned at the end of its useful life. Additional commercial space stations from Sierra Space / Blue Origin (Orbital Reef), and Nanoracks / Voyager (Starlab) and Northrup Grumman are anticipated to be deployed as free-flyers by the end of the decade providing additional capacity for activities in LEO.

Roundtable Discussion

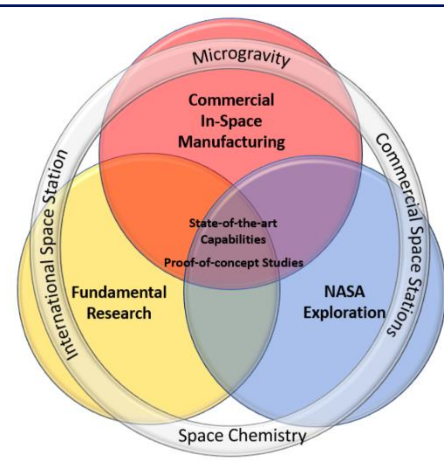
High level considerations for further development of the roadmap focus areas and capabilities are provided in Tables 1 & 2 below.

Table I: Focus Area Considerations:
○ chemistry in space requires a 'mind shift' from traditional thinking ○ different types of methods and approaches from those used today are potentially options in microgravity ○ start with what fundamental questions can we ask/answer ○ not all types of chemistry in space are relevant; define which benefit from microgravity ○ opportunities to leverage the vacuum of space and other aspects of the external environment on chemical reactions and processes ○ potential areas to explore; polymers, crystals, nanomaterials, MOFs, ring opening/closing reactions, quantum chemistry, thin-films, optical fiber, CO2 conversion, many other areas to be defined ○ low volume high value products that support economic/financial case for commercial markets ○ identify a minimal set of materials to be produced for commercial product proof-of-concept studies

Table 2: Capabilities Considerations:
○ capabilities required depend on type of chemistry to be conducted in space; establish standardized in-space chemistry capabilities suitable for research and production ○ transport of reagents to ISS vs. making feedstocks available on orbit to facilitate a variety of types of chemistry and production of multiple products ○ pluripotent materials (example plastics) already in use that may serve as starting feedstocks for production of multiple products required for chemistry in space ○ universal delivery systems incorporating robotics and automation ○ transition from analog methods to 'digitized' chemistry in space ○ microreactors and flow reactors contained in modular systems accommodating reduced upmass/downmass (reagents only on ascent and return) ○ analytical methods that provide opportunities for characterization on orbit (mass spectrometry, RAMAN, IR, FIR, etc.); facilitate iterative experiments in a single mission and can be used for manufacturing in-line process controls ○ remote control of on orbit operations (command uplink) and near-real time data downlink ○ ability to conduct simulations, including using quantum computing, AI/ML and other high-throughput methods, for discovery and synthesis of chemicals needed to facilitate multiple reaction types; quantum sensing also discussed in the context of standards development ○ incorporation/development of standards for chemistry in space (e.g., IUPAC standards – international community to define standards for space chemistry; SPB screening transformed ability to screen biology – similar concept for space chemistry?)

Proof-of-Concept Studies

In defining proof-of-concept studies, participants discussed the balance between focus on exploration and commercialization goals. Identifying areas where alignment between exploration, fundamental, and commercial goals exist will be a significant focus of future discussions. The existing ISS provides a platform to conduct proof-of-concept studies that can inform continued development of capabilities for future commercial space stations that support both exploration and commercialization goals in LEO. The commercial space stations in development provide near term, and future, unique opportunities for conducting space chemistry given upgraded designs, configurations, and state-of-the-art capabilities that will be available.



Conceptual Focus for a Space Chemistry Roadmap

For commercial applications, clear definition of economic value will also be an important consideration. Examples provided include pharmaceutical products using crystalline formulations. Currently of the top 100 products with markets exceeding $1B, the majority are crystalline structures that can be made and sold on Earth. However, approximately 50% of these successful drugs have a formulation issue that could potentially be addressed in microgravity, resulting in new process or product intellectual property (IP) that has significant value to pharma companies.

Information from the Center for Advancement of Science in Space (CASIS – ISS National Laboratory) partnership with NSF for studies on combustion in microgravity was also shared. Research on ISS has identified the existence of cool flames, i.e., re-ignition of flames at lower temperatures created when fuel and oxidizers don't mix prior to reacting in the absence of convection in microgravity. These conditions, that are nearly impossible to produce on Earth, provide a unique opportunity for studying combustion that may lead to cleaner burning and more efficient engines. Graphene aerogel research on ISS evaluating production of homogenous layers (less stratification) with more isotropic properties in microgravity was also discussed. Work on ISS evaluating ZBLAN fiber and pre-form production has also been conducted.

Current technology on ISS for CO_2 capture and conversion using the Sabatier reactor (a 100-year-old method) may also benefit from new methods and approaches that can solve challenges on Earth and for exploration. Compact devices already exist terrestrially that can produce methane and other products from conversion reactions that may be useful for space chemistry applications.

Further discussion of additional work conducted on ISS for commercial and exploration space chemistry will be discussed at future upcoming meetings.

Roadmap Development

Current plans discussed included informational webinars and virtual discussions conducted quarterly to develop a roadmap for space chemistry over the next year, with a goal of presenting the Space Chemistry Roadmap at the next CME NASA conference in conjunction with the ACS Fall Meeting in San Francisco (Harnessing the Power of Data, August 13-17, 2023). Along with the participants and observers from this initial roundtable discussion we plan to invite additional industry participants to participate. We plan to also continue to develop and announce future strategic Advisory Board membership.

A high level overview of proposed timeline and goals for the Space Chemistry Roadmap development is provided below. Informational meetings will be conducted during the remainder of 2022 to develop a comprehensive overview of completed, planned, and future space chemistry research and development (including existing capabilities) on ISS. This will help to identify gaps and inform future direction. Additionally, we will engage with subject matter experts conducting leading-edge research for insight on the types of chemistry to consider for inclusion in the Space Chemistry Roadmap.

Proposed Space Chemistry Roadmap Development Timeline

Summary

The insights shared in this initial discussion have provided a strong foundation for the continued Space Chemistry Roadmap development. The feedback and willingness to work together from all who have participated is appreciated. Collaboration from all stakeholders ensures the development of a roadmap that has value for all. Special thanks to the organizers of the CME NASA conference for their support of this initial, and future, meetings.

Proposed Next Meetings & Webinars (2022 / 2023)

Informational Webinars (2022)

- Overview of Space Chemistry Research Conducted or Planned on ISS
- Commercial Applications* - Ken Savin (Redwire), Ryan Reeves (CASIS, ISSNL), Kevin Engelbert, Commercial Portfolio Manager for In-Space Production Applications (InSPA) NASA Johnson Space Center
- NASA Exploration* - Jim Green (formerly NASA), Jack Kaye (NASA HQ Earth Sciences Division, Kirt Costello (ISS Chief Scientist and ISS Research Integration Office Deputy Manager)

Quarterly Meetings (**2023** dates TBD)

- Q1 2023 – Focus Areas & Capabilities
- Q2 2023 – Proof-of-Concept Studies
- Q3 2023 – Finalize Draft Roadmap Sections
- Draft Space Chemistry Roadmap Presentation - CME NASA conference in conjunction with the ACS Fall Meeting in San Francisco (Harnessing the Power of Data, August 13-17, 2023).

Suggested additional informational webinar speakers*

- Sir Fraser Stoddart, Northwestern University – Chemistry Away from Equilibrium
- Stuart Rowan, University of Chicago – Pluripotent Plastics
- Kathryn Beers, NIST -
- Chad Mirkin, Northwestern University – Nanomaterial Megalibraries

*Additional topic areas and speakers to be identified

Exhibits

Agenda, Speakers,
Participants & Observers

Exhibit A

PME

NASA STEM
SUSTAINABILITY

UChicago

August 23 PM: UChicago
Space Chemistry Roundtable Agenda

Separate Track at the CME NASA Sustainability Conference

In-Space Chemistry Roundtable			
Register for Schedule Updates, Speaker Bios, Room Assignments: www.CME-STEM.org			
8/23 - Afternoon Track at the UChicago Rubenstein Forum			
3:00 PM	Move from Main Auditorium to the Roundtable Room		
3:05 PM	George Rodriguez	CME	Welcome
3:06 PM	James Green	NASA	Introduction
3:10 PM	Ferenc Darvas	InnoStudio	Building a Roadmap for Space Chemistry Applications
3:15 PM	James Green	NASA	NASA Space Chemistry Exploration Needs
3:20 PM	Jana Stoudemire	Axiom Space	The Developing LEO Economy
3:25 PM	Kenneth Savin	RedWire	Industrial/Commercial Space Chemistry Initiatives
3:35 PM	Lead: Jana Stoudemire, Ferenc Darvas	Axiom Space, InnoStudio	Roundtable Discussion
3:35 PM	Panel		Discussion of relevant focus areas and impactful POCs
3:45 PM	Panel		Necessary capabilities to support in-space chemistry
3:55 PM	Panel		Use of the ISS and obrital platforms for development
4:10 PM	Panel		Collaboration amongst government, academia, and industry
4:20 PM	Lead: Kenneth Savin	RedWire	Summary and Next Steps
4:34 PM	Steve Barnett	CME	Adjourn
4:35 PM	Go to Auditorium of the Sustainability Conference		

Exhibit B

PME

CME
NASA STEM
SUSTAINABILITY

UChicago

Space Chemistry Roundtable

Speakers Shaping the Roadmap to the Space Economy

Jim Green
NASA
Senior Advisor and former Chief Scientist

Ferenc Darvas
InnoStudio, SpaceMedChem
Executive Chairman

Jana Stoudmire
Axiom Space
Director, In-Space Manufacturing

Ken Savin
RedWire
Chief Scientist

Exhibit C

Roundtable Participants & Observers**

First Name:	Last Name:	Company:	ACS Technical Division	Participant / Observer
Jesus	Alcazar	J&J	NONE	Observer
Rigoberto	Advincula	Oak Ridge National Laboratory	NONE	Participant
Christopher	Allison	Redwire Space	NONE	Observer
Luke	Baldwin	Air Force Research Laboratory	NONE	Participant
Viktor	Balema	ProChem Inc.	None	Participant
Steve	Barnett	Connell Foley	NONE	Participant
Chyree	Batton	SC Johnson	NONE	Observer
Tigist	Batu	University of Alberta	BIOL	Observer
Aaron	Beeler	Boston University	NONE	Participant
Aaron	Bishop	Quantum Security Alliance	NONE	Observer
Ferenc	Darvas*	InnoStudio	NONE	Participant
Madushanka	Dissanayake	Intel Corporation	BMGT	Observer
Partha	Dutta	United Semiconductors	NONE	Observer
Amanda	Evans	Los Alamos National Lab	NONE	Observer
Robert	Garmise	BMS	NONE	Observer
Marc	Giulianotti	Sierra Space	NONE	Participant
Alex	Godfrey	NIH NCATS	NONE	Participant
Theodore	Goodson	University of Michigan	PHYS	Observer
James	Green*	NASA	NONE	Participant
Frank	Gupton	VCU	NONE	Observer
Volker	Hessel	University of Adelaide	NONE	Observer
Bernhard	Hufenbach	ESA	NONE	Observer
Heidi	Irrig	Syngenta	AGRO	Observer
Richard	Jones	InnoStudio	NONE	Observer
Shah	Karim	SafeRock	NONE	Observer
Jack	Kaye	NASA HQ – Earth Science Division	PHYS	Participant
Hira	Khalid	Univer. of Minnesota Twin Cities	NONE	Observer
Benjamin	Knudsen	BASF	NONE	Observer
Qinghuang	Lin	ASML	PMSE	Observer
Joshua	Macey	U Chicago	NONE	Observer

First Name:	Last Name:	Company:	ACS Technica l Division	Participant / Observer
Jon	McClain	McKinsey	NONE	Observer
Hans	Mumm	Victory Systems	NONE	Observer
Tim	Noel	University of Amsterdam	NONE	Observer
Reno	Novak	ProChem	NONE	Observer
Divya	Panchanatha n	Axiom Space	NONE	Observer
Ryan	Reeves	ISS National Laboratory	NONE	Participant
Paul	Reichert	Merck	NONE	Observer
Aaron	Rodgers	Redwire Space	NONE	Observer
George	Rodriguez	Argeni	NONE	Participant
Marina	Ruths	ACS Div. Colloid and Surface Chemistry	COLL	Observer
Tara	Ruttley	Blue Origin	NONE	Participant
Naohiro	Sato	JAMMS	NONE	Observer
Kenneth	Savin*	Redwire Space	NONE	Participant
Keeper	Sharkey	ODE L3C	NONE	Observer
CK	Singla	Flawless Photonics	NONE	Observer
Bo	Song	Northwestern University	NONE	Observer
Jana	Stoudemire*	Axiom Space	NONE	Participant
Michael	Vestel	Flawless Photonics	NONE	Observer
Jonathan	Volk	Sierra Space	NONE	Observer
Jun	Wang	University of Iowa	NONE	Observer
Liz	Warren	Blue Origin	NONE	Observer
Brian	Warrington	University of Cambridge	NONE	Observer
Jeff	Williams	Exum Instruments	NONE	Participant
Brian	Warrington	University of Cambridge	NONE	Observer

*Presenter/Discussion Lead
** Participated virtually or invited and interested in participating in future discussions

Appendix
(Presentations)

Jim Green, PhD, Senior Advisor, Office of the Chief Scientist
NASA Space Chemistry Exploration Needs

Ferenc Darvas, PhD, Executive Chairman, InnoStudio
Building a Roadmap for Space Chemistry Applications

Jana Stoudemire, Director, In-Space Manufacturing, Axiom Space
The Developing LEO Economy

Kenneth Savin, PhD, Chief Scientist, Redwire Space
Industrial/Commercial Space Chemistry Initiatives

In-Space Chemistry Roundtable

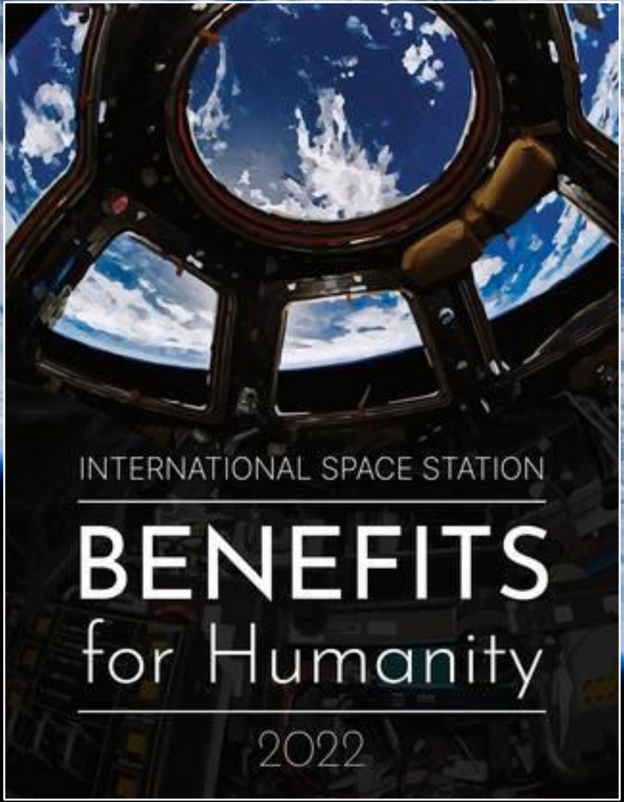
NASA Space Chemistry Exploration Needs

James Green
Senior Advisor
Office of the Chief Scientist

August 23 2022

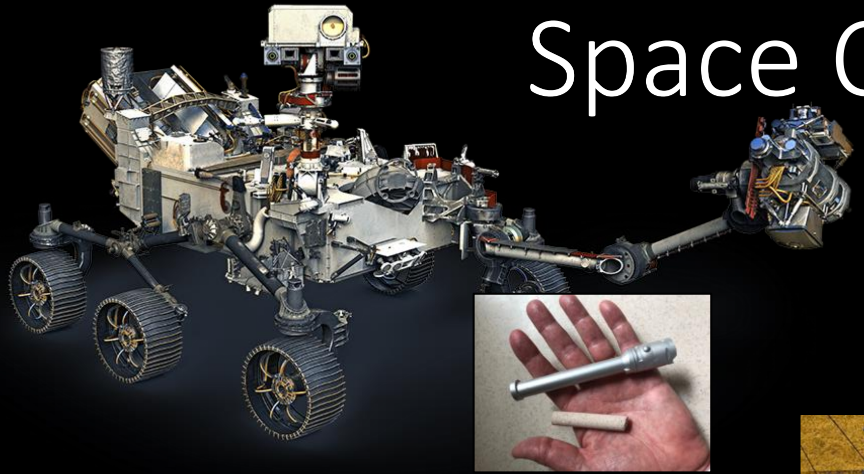
Space Chemistry in Low Earth Orbit

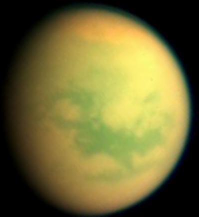
- NASA's work with commercial industry will help ensure an uninterrupted, continuous human presence and capabilities in microgravity
  - The ISS evolved from an outpost in LEO into a highly capable microgravity laboratory
  - Results are compounding, new benefits are materializing, and the third decade is building on this previous work
  - Extending ISS operations through 2030 will enable another decade of research advancement and create a seamless transition of capabilities in LEO to one or more commercially owned and operated space stations in the late 2020s.

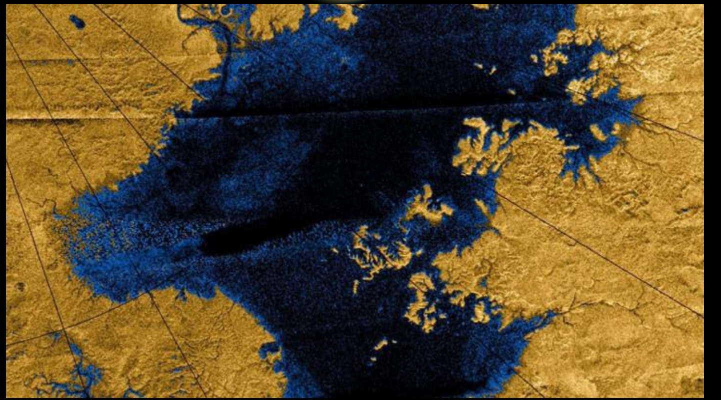


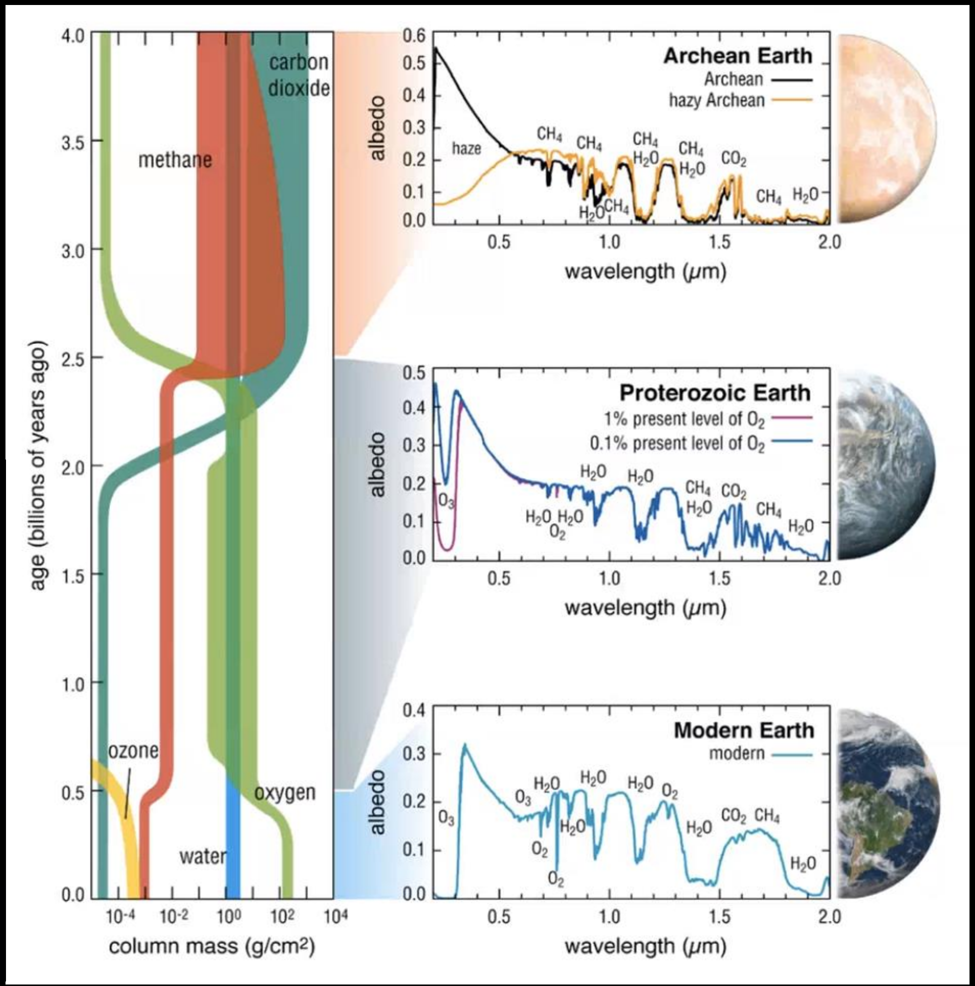
https://www.nasa.gov/mission_pages/station/research/news/benefits-2022-book

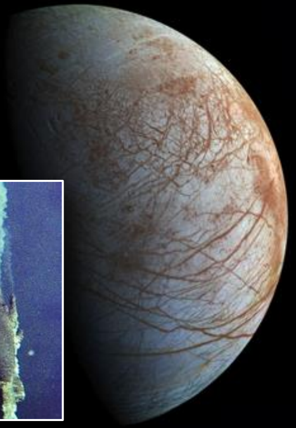
Space Chemistry Beyond LEO











Working together

- NASA wants to foster growth of the commercial space economy and address future space exploration goals
  - One approach is to create a dialog with the commercial sector that develops a future roadmap for low-Earth orbit (LEO) space chemistry applications.
- NASA needs your inputs on focus areas such as:
  - Proof-of-concept (POC) studies
  - Capabilities required to support in-space manufacturing application development
  - Timing/collaboration for missions to the International Space Station
- Layout the plan for the roundtable and publish the results of this workshop as a preliminary roadmap for "Space Chemistry in Low-Earth Orbit and Beyond."

Building a Roadmap for Space Chemistry Applications

Ferenc Darvas,
InnoStudio, Inc., Budapest, Hungary

Space Chemistry - an Emerging Field

- Performing chemistry in space is different of chemistry on Earth: Microgravitation, Radiation, High vacuum, extremely low or high temperature*

•First results of Space Chemistry going back to the sixties (Salyut 6, MIR, and the Space Shuttle).These are still mostly unknown or released recently: A. Pavláth's results with O2 generation from C-suboxide from 1966,published in 2017, at the ACS Space Chemistry Symposium. Mattiodaet al. first reported photostability results of organic compounds on orbit in 2012

- One of the earliest chemical reactions investigated on the ISS was about the combustion of fuels by Williams et al. in 2017

•Troubles with mixing in conventional batch reactions in microgravity. Flow chemistry helps in solving them. Space chemistry got an impulse by the fast development of flow chemistry around 2010.

•Publications on industrial applications started by early 2010's.

•Initiatives for pre-competitive consortia going back to 2015, with support from flow chemistry and microfluidics communities (Flow Chemistry Society, IMRET Community). Scientific events started by ACS and NASA (2017).

*Jones,R.,Darvas,F.,&Janáky,Cs.(2017)."Newspaceforchemicaldiscoveries."NatureReviews|Chemistry,Vol.1.,Art.no.005:,pp1-3.

How to Build a Roadmap for Space Chemistry Applications?

Start to today with an overview discussion….

Focus Areas for Consideration

- Pharma and associated life science industries: formulation, synthesis, medchem/agrochem Associated life science industries: agrochemicals, cosmetics, natural products
- Material sciences, incl. polymers, nanoparticles and aerogels
- CO_2 processing
- Perhaps: propellant synthesis in Space?
- Others?

Necessary Capabilities for In-Space Chemistry

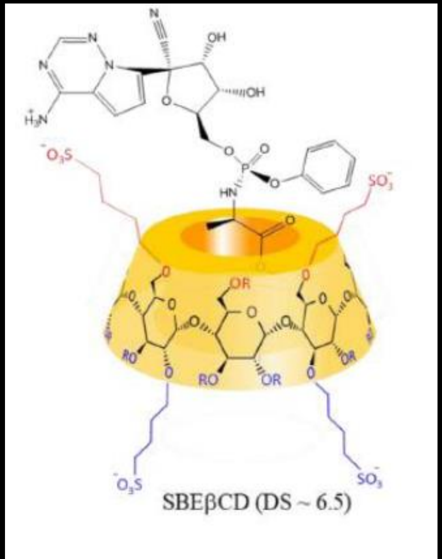
- Individual synthesis (small molecules)
- Production scale systems (MIT)
- Multi-purpose Flow Synthesizer (gas reactions)
- Laboratory environment and reagents – containment / safety in space

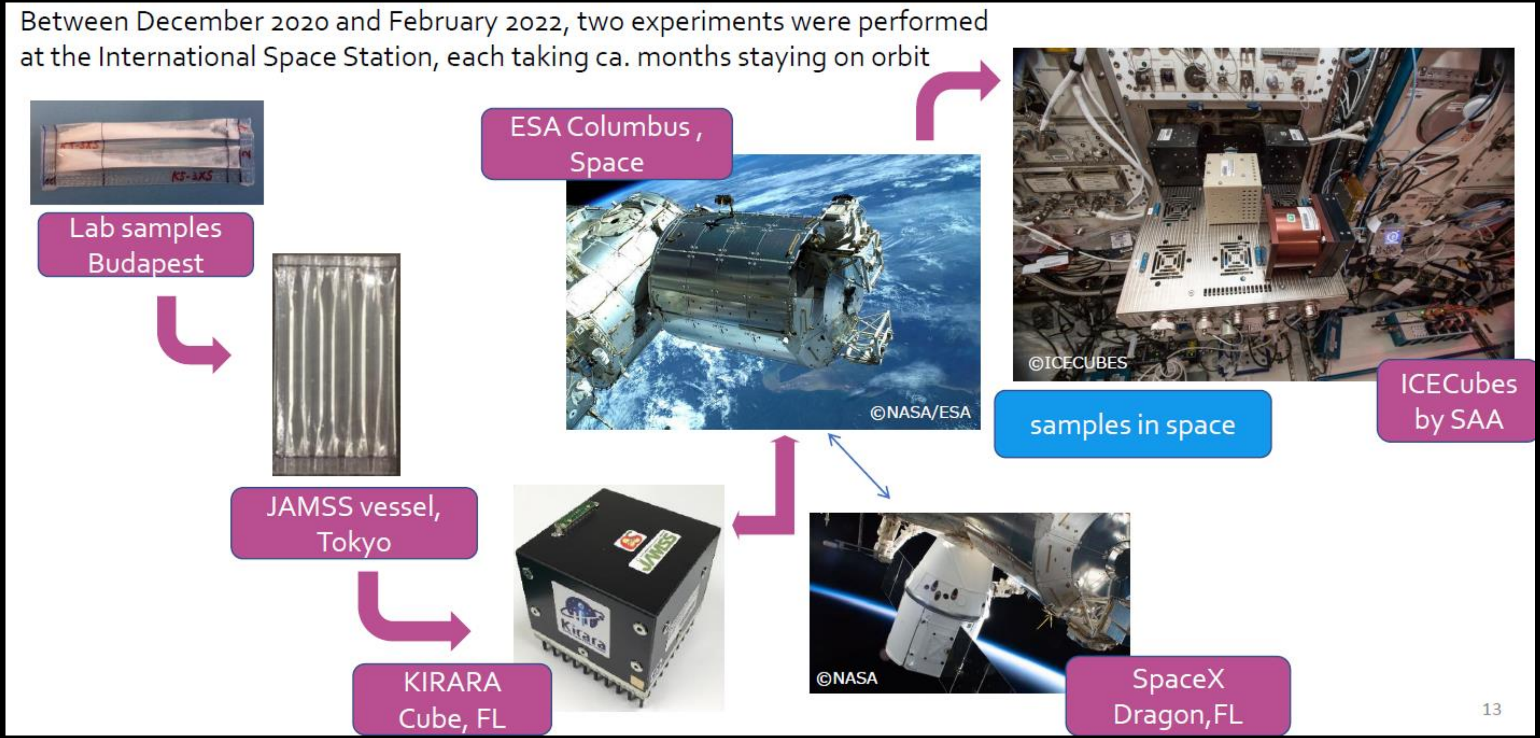
How to Build a Roadmap for Space Chemistry Applications?

Start to today with an overview discussion....

ISS and Orbital Platforms

- ISS available today and future commercial platforms in development
  - Remdesivir case study on ISS





How to Build a Roadmap for Space Chemistry Applications?

Start to today with an overview discussion....

Collaborations among the main player groups - a must for optimizing the available resources

A possible model: pre-competitive consortia **(governmental, industrial, and academic)**

Pre-competitive: **no one can solve a game changer problem alone**, a collaborative strategy brings significant advantages relative to competition.

Successful examples from the pharma industry: Technology Enabled Compound Library (7 industrial members, US-Eu-Japan), GRID consortium (EU academic and industrial + Russian academic members), EMIL Consortium (Japan, US industrial-academic members)

Space industry: SpaceFlow(later SpaceChem) consortium, SpaceMedchemconsortium (Remdesivir research: Eu-Japan members)

Humanity's Next Chapter

AXIOM SPACE

Jana Stoudemire
Director, In-Space Manufacturing
In-Space Solutions
jana@axiomspace.com

Enabling New Market Sectors In Low Earth Orbit (LEO)

In-Space Production of Advanced Materials and Biomedical Products that Benefit Life on Earth and Support Continued Exploration

Increased human presence in space

Surge in demand for launch & return services

Reduction of launch costs enabling business opportunities

The world’s first commercial space station; maintaining a permanent presence in LEO beyond the ISS

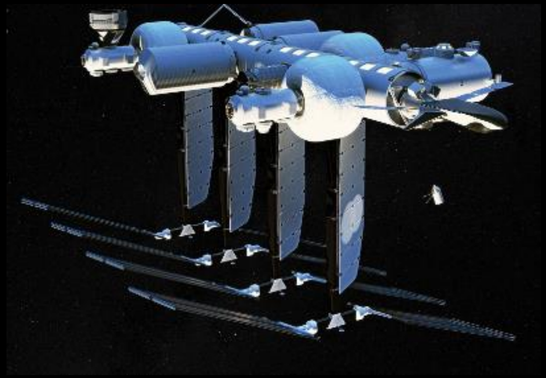
Expanding NASA Support for Commercial LEO Destinations

In early 2020, NASA awarded exclusive rights to Axiom to attach its own module to a docking port on the ISS; the first step to building the station of the future.

Axiom Station
Credit: Axiom Space

In December 2021, NASA provided three Commercial LEO Destinations awards for future free-flying space stations that are anticipated to be operational in 2028

Starlab (Nanoracks, Voyager Space, Lockheed Martin)
Credit: Nanoracks ($160M)



Orbital Reef (Blue Origin, Sierra Space, Boeing, Redwire)
Credit: Blue Origin ($130M)

HALO Concept
Credit: Northrup Grumman ($125.6M)

AXIOM SPACE

The Assembly Sequence: 2024-2029


09/2024 | First Module


05/2025 | Second Module

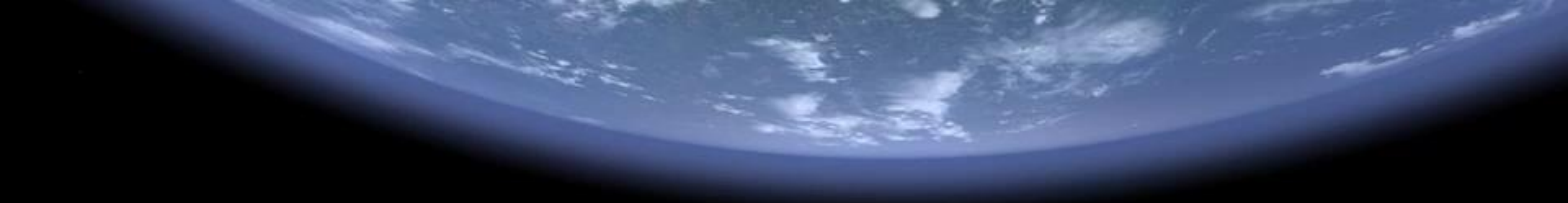

09/2026 Research & Manufacturing


12/2027 Power Tower

The first module of Axiom Station is well under development

Axiom’s first module has passed its Preliminary Design Review (PDR) and will be undergoing its Critical Design Review this summer

AXIOM SPACE



Chemistry In Space
Emerging Commercial Opportunities

We do chemistry in space when we want to:

Advance Exploration Goals

a) Providing products that enable mission success

Production of food, pharmaceuticals or products for life support systems

b) Utilize space based resources to make useful materials

The production of building materials for use on other planetary bodies or space platforms (make it, don't take it…) like concrete.

Identify Commercial Applications

a) Do something that is difficult or impossible to do on earth?

Make alloys that would separate during the smelting process terrestrially

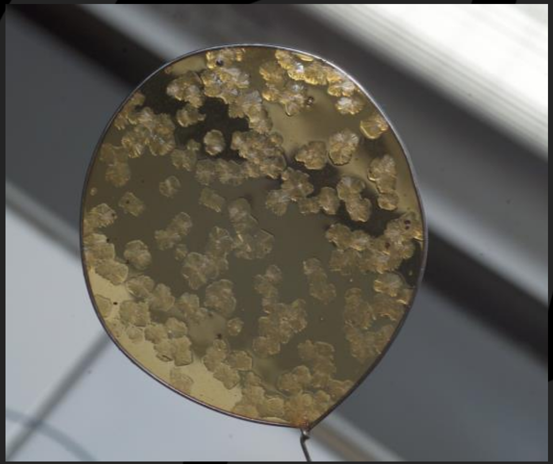
b) To understand some effect that is hidden by the force of gravity?

Pure diffusion controlled processes

c) Get a result that is different than what we see on earth

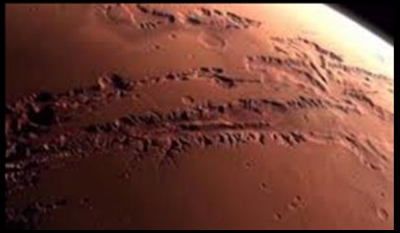
Growing crystals to generate new forms

Commercial Applications Being Explored for Space Chemistry



Crystal production in microgravity generally leads to larger, more ordered crystals and improve uniformity

Phase interactions change the outcomes of chemical processes



Make it, don’t take it.

Round Table Discussion Topics:

- What - Focus areas and why (exploration/commercial)
- How - Capabilities (standards, tools, on-orbit analytics)
- When – Target timeframe to complete proof-of-concept
- Next Steps – defining the roadmap (how, who, when)

CME STEM

AXIOM SPACE

Thank You

REDWIRE

INNOSTUDIO