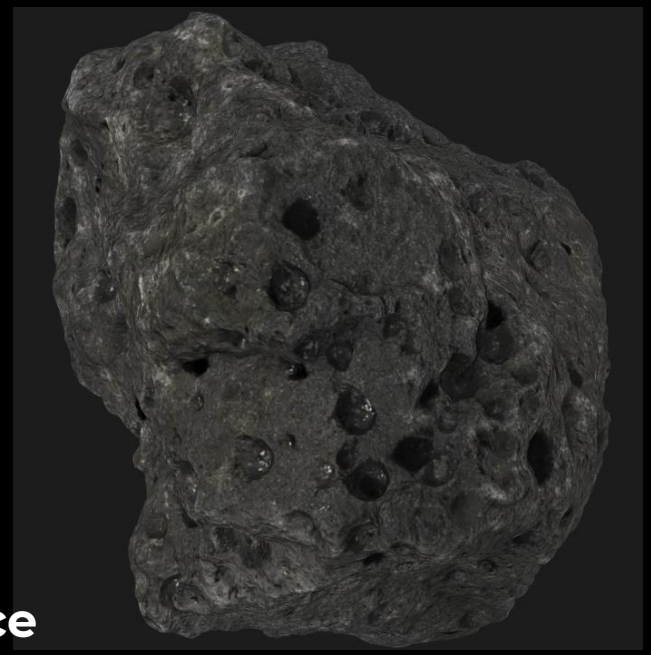
The Billion $$$ Samples



Managing Data from Astromaterials Returned from Space

I acknowledge and celebrate the First Australians on whose traditional lands we meet, the lands of the Wurundjeri people of the Kulin Nation, and pay my respect to the Elders past, present and future.

Artwork from: https://www.wurundjeri.com.au/services/cultural-practices-for-events/artwork/#

This is the Story of the Astromaterials Data System

Billions of $$$

have been spent to return samples from space to Earth.

Millions of $$$

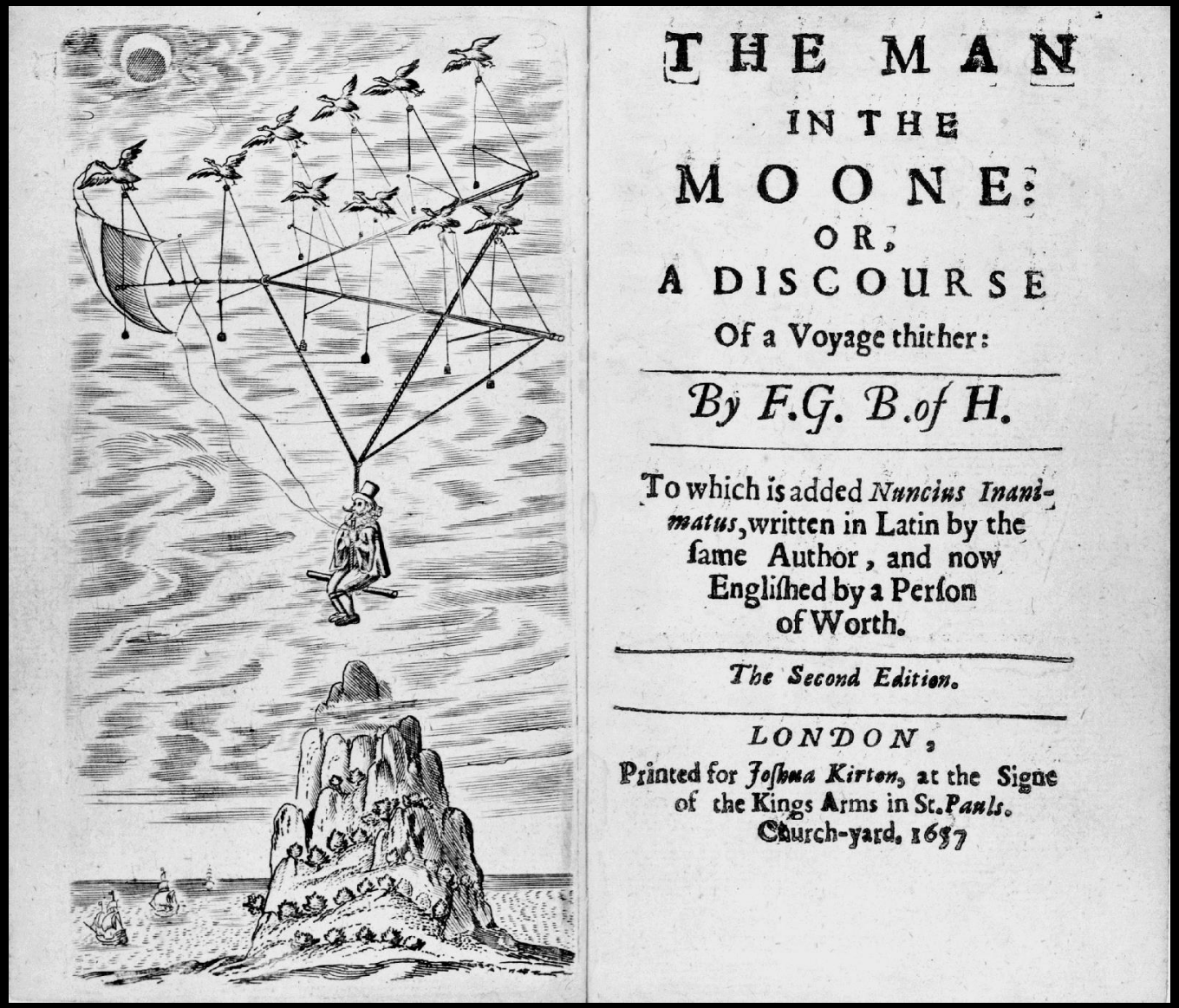
have been spent to curate, disseminate, and analyze these samples.

Zero $$$

were spent to curate and preserve the data of these analyses.

The archive for these data was finally established in 2023!

Space Exploration: From Fiction …



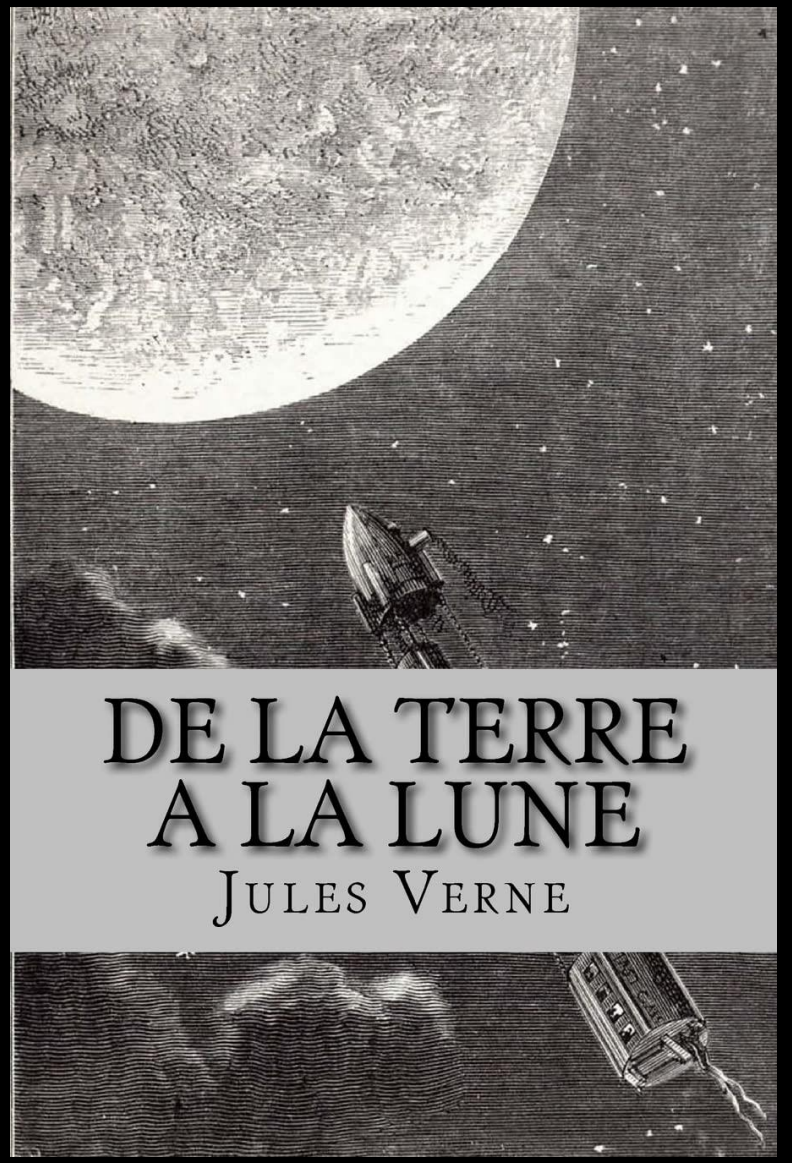
THE MAN
IN THE
MOONE:
OR,
A DISCOURSE
Of a Voyage thither:

By F.G. B.of H.

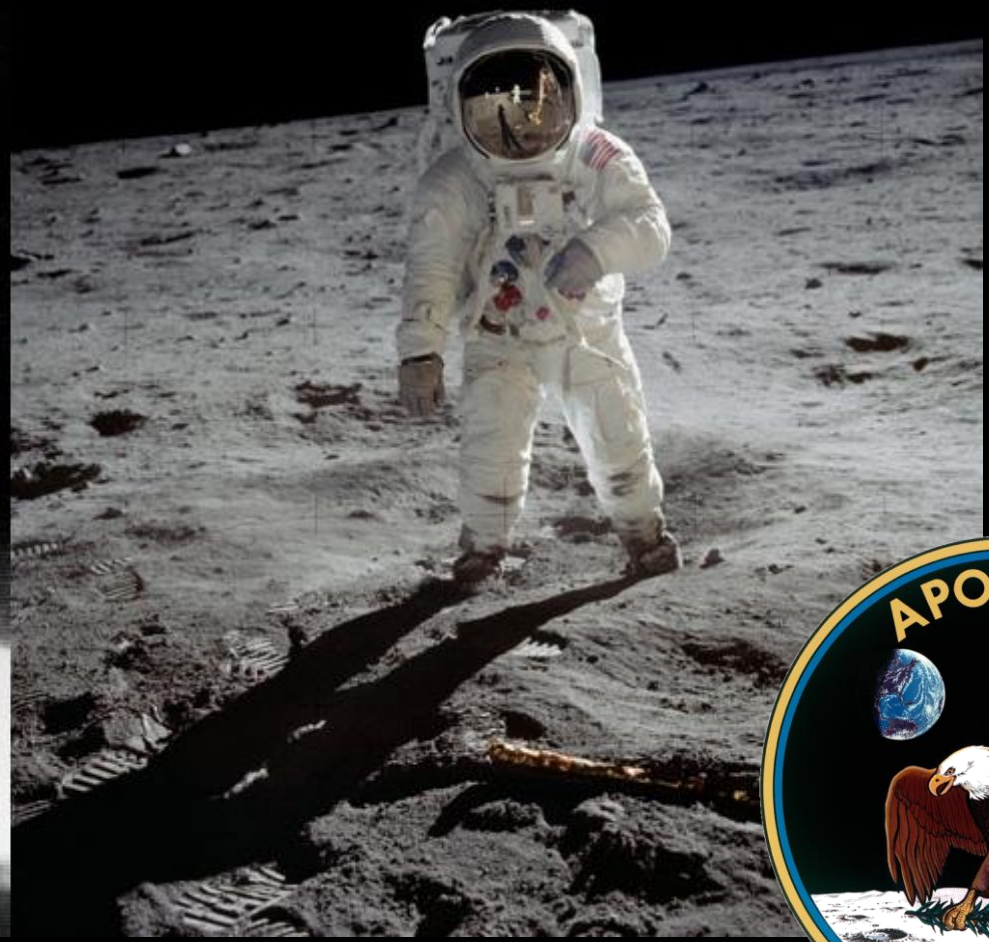
To which is added *Nuncius Inanimatus*, written in Latin by the ſame Author, and now Engliſhed by a Perſon of Worth.

The Second Edition.

LONDON,
Printed for *Joſhua Kirton*, at the Signe of the Kings Arms in St. *Pauls* Church-yard, 1687



… to Reality: One Giant Step for Mankind!



July 20, 1969: Apollo 11 lands in the Sea of Tranquility

Visiting moons, asteroids and planets is great, but taking a piece of them home is even better, according to traditional space wisdom.

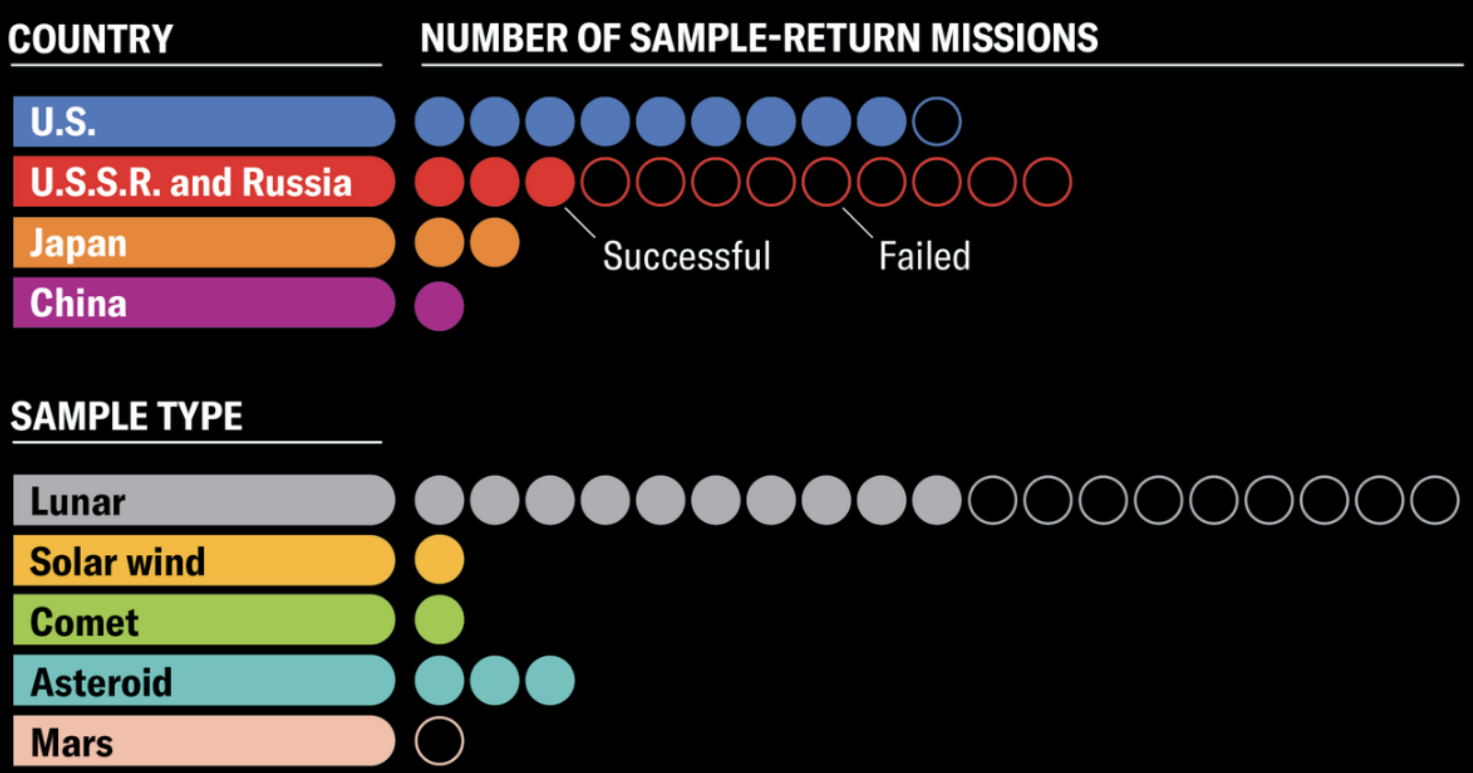
"See Every Bit of Outer Space We've Brought Back to Earth" by C. Moskowitz & J. Knight
Scientific American Magazine Vol. 330 No. 4 (April 2024), p. 82

OSIRIS-REx rendezvousing with the Asteroid Bennu: https://ares.jsc.nasa.gov/missions/osiris-rex/

Apollo Mission:

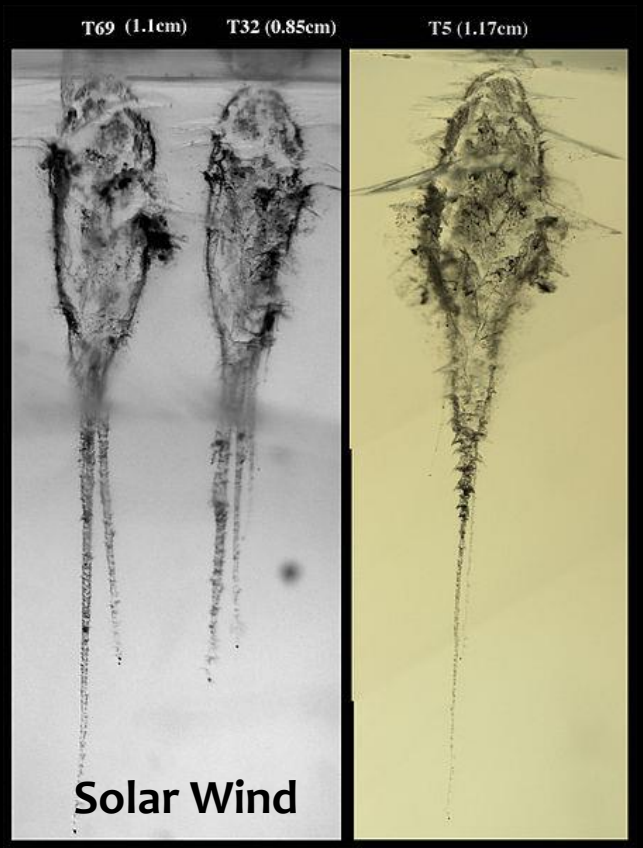
Returned

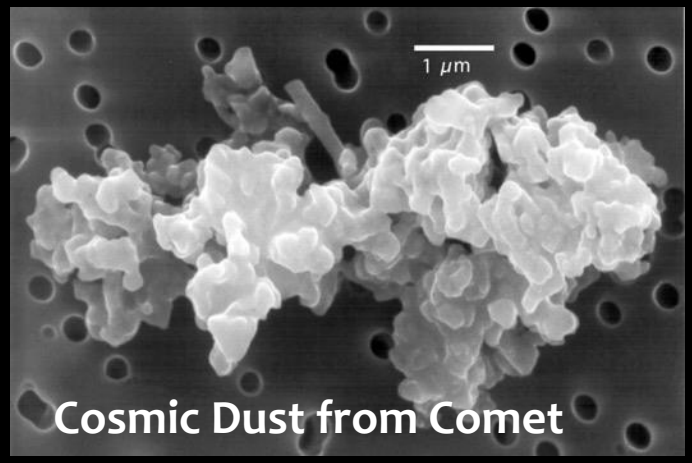
- 382 kilograms of lunar material,
- 2200 individual specimens



From: “See Every Bit of Outer Space We’ve Brought Back to Earth” by C. Moskowitz & J. Knight. Scientific American Magazine Vol. 330 No. 4 (April 2024)

Sample-Return Missions as of 2024





The Billion $$$ Samples!

- **Apollo: $25.8 billion**
  - approximately $257 billion when adjusted for inflation to 2020 $$$
- **OSIRIS-REx: $1.16 billion**
- **Mars Sample Return (MSR): ~$4 billion** (original estimate)
  - could end up costing between $8 billion to $11 billion if moving forward.

Why Invest in Sample Return Missions?

- Humankind's curiosity about the origin of Life, Earth, our Solar System & the universe
  - What are the geological and chemical histories of varied celestial bodies, including Earth, Moon, Sun, planets, asteroids, and comets?
  - How may life on Earth have originated and why did Earth evolve to be the only apparent life-supporting body in our solar system?
  - Are there other habitable planetary bodies?

Commercial Interest

Economics of the Stars: The Future of Asteroid Mining and the Global Economy

08.APR.2022 . 6 MIN READ

Shriya Yarlagadda

Shriya is the former Editor-in-Chief of the Harvard International Review. She enjoys reading and writing about human rights, international security, and environmental politics.

Harvard International Reviews

Pt elements, water, ^{3}He

https://www.space.gov.au/exploring-space-australian-resources-ingenuity

How Society Benefits from Returned Samples

- Predict and mitigate potential threats from cosmic bodies.
- Advance technologies useful for applications outside space exploration.

- Capture public imagination & inspire younger generations to pursue STEAM (science, technology, engineering, arts, and mathematics) careers.

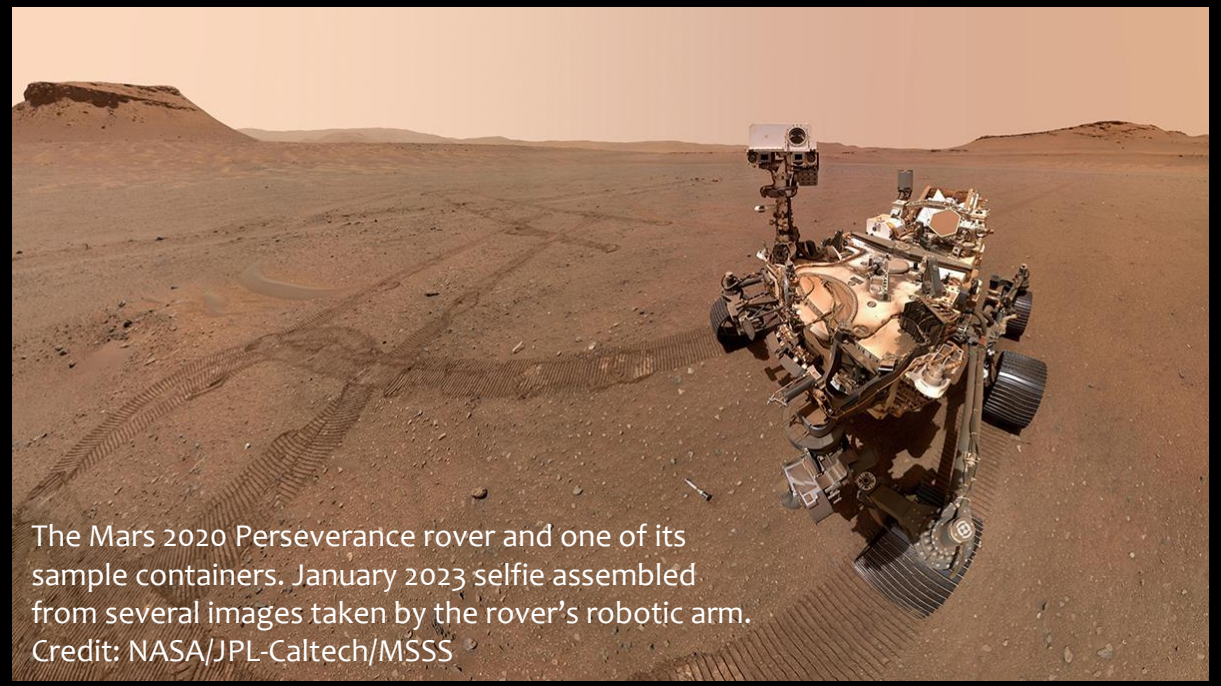
Davidson, J., & J. Barnes (2024), Eos, 105, 17 July 2024. https://doi.org/10.1029/2024EO240291.

The Past, Present, and Future of Extraterrestrial Sample Return

Retrieving samples from distant solar system bodies has revolutionized our understanding of the cosmos and our place in it.

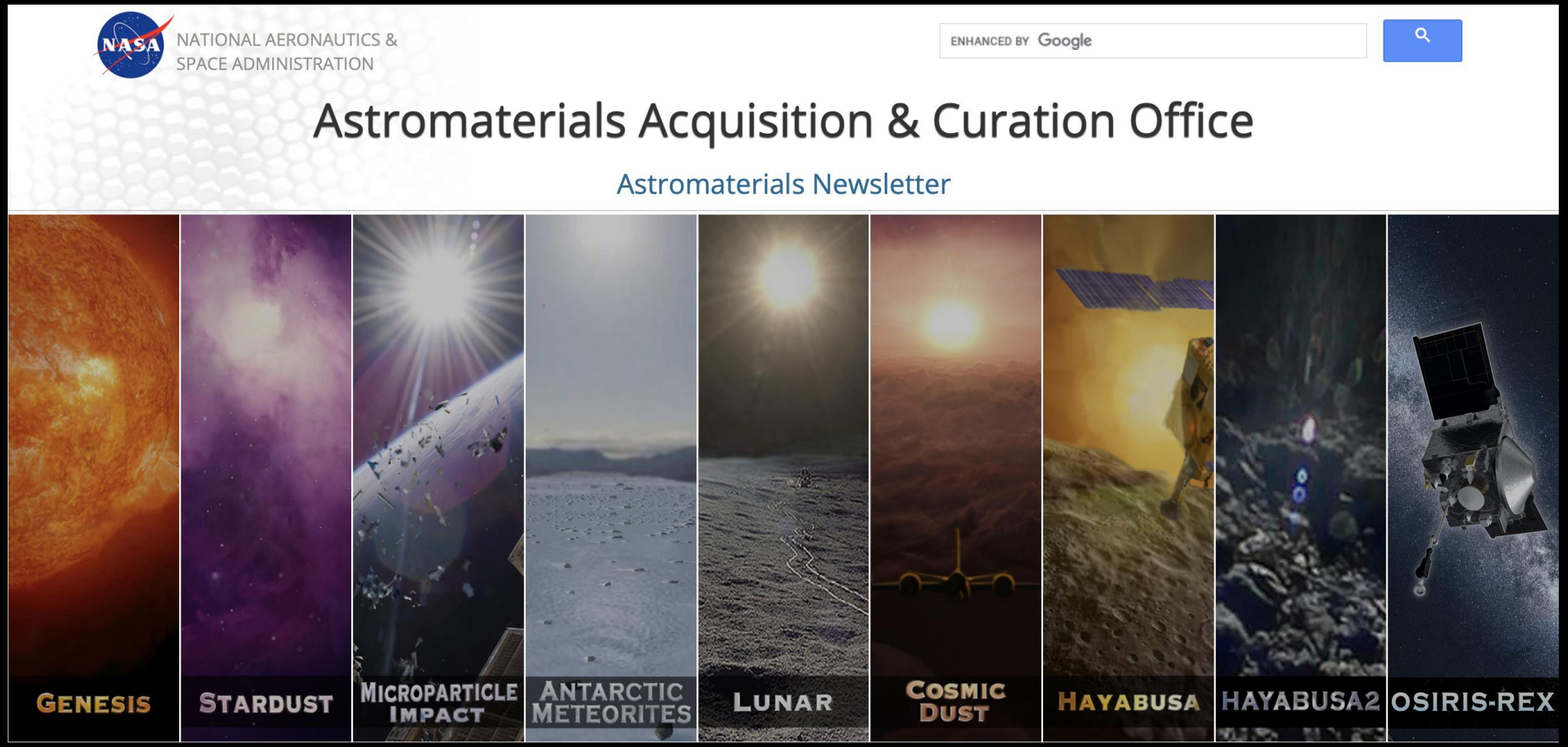
By **Jemma Davidson** and **Jessica Barnes** 17 July 2024

"Samples returned from space and kept in their original state are gifts that keep on giving."



The Mars 2020 Perseverance rover and one of its sample containers. January 2023 selfie assembled from several images taken by the rover's robotic arm. Credit: NASA/JPL-Caltech/MSSS

Sample Curation Enables Long-lasting Reuse & Impact

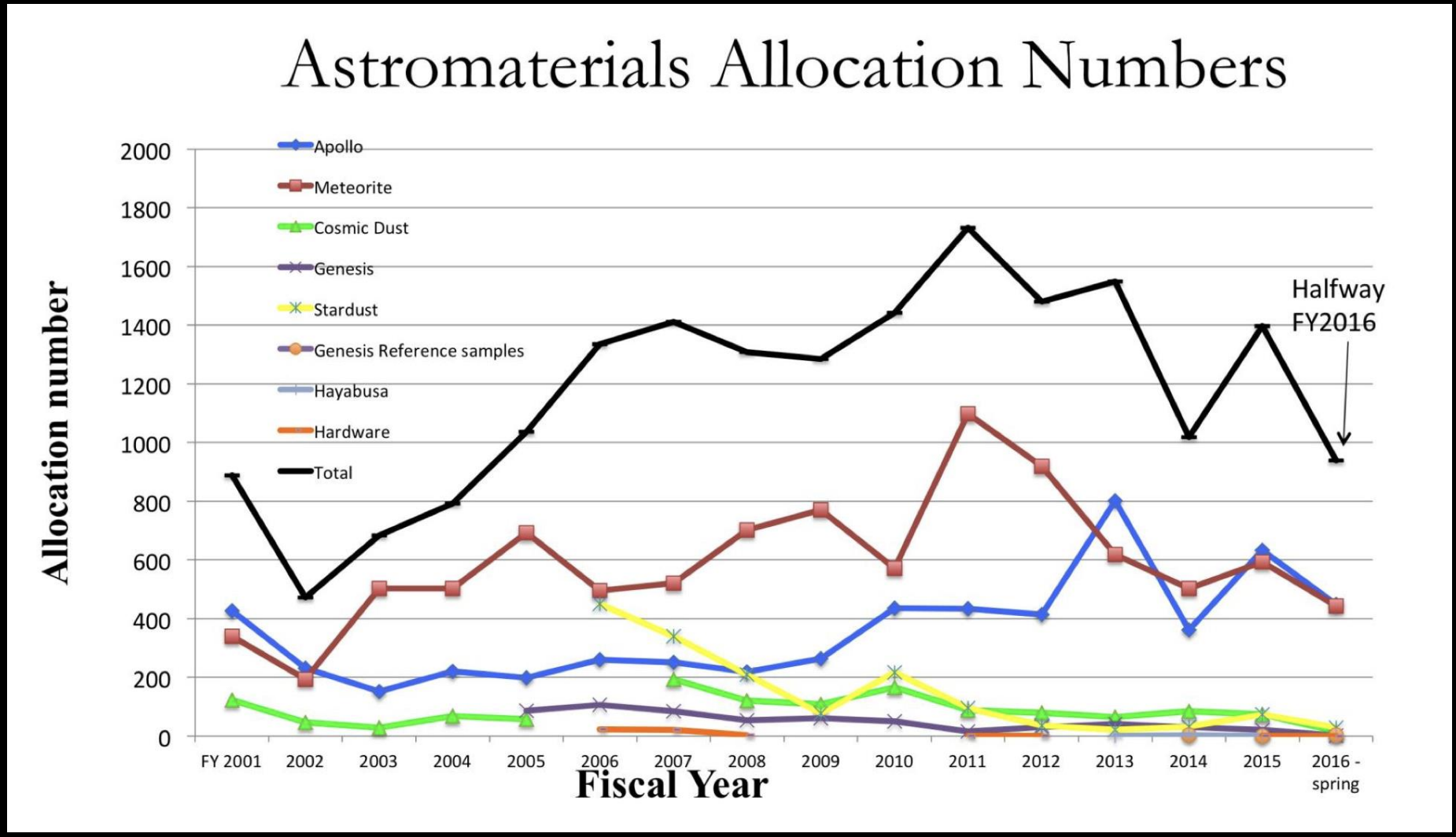


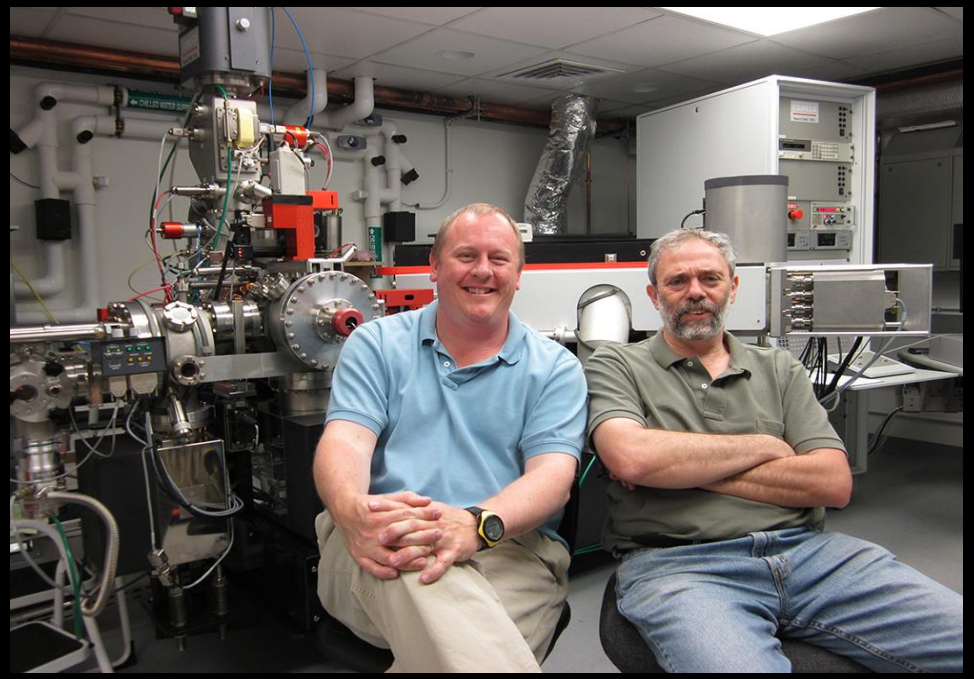
- Curates 250,000 astromaterials samples
- Disseminates astromaterials samples to the global community

Dissemination of NASA's Astromaterials Samples

Source:

Zeigler, Ryan, et al. "Curating NASA's Past, Present, and Future Astromaterial Sample Collections." Horizon 2020 EURO-CARES Work Package 3 meeting. No. JSC-CN-36137. 2016.





Erik Hauri and Alberto Saal with an ion microprobe at the Carnegie Institution for Science used to detect water in lunar samples.
Credit: Steven Jacobsen/Northwestern University

Thousands of studies have been conducted on the astromaterials curated at JSC-ARES.

These studies generated vast amounts of laboratory data.

chemical, mineralogical, geochronological, experimental…

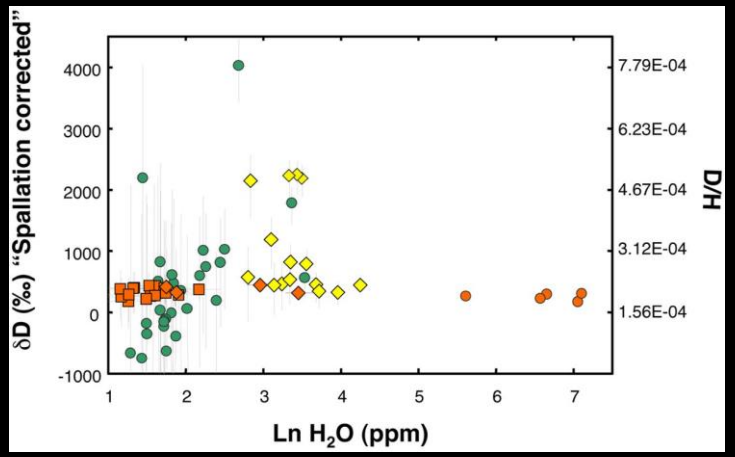


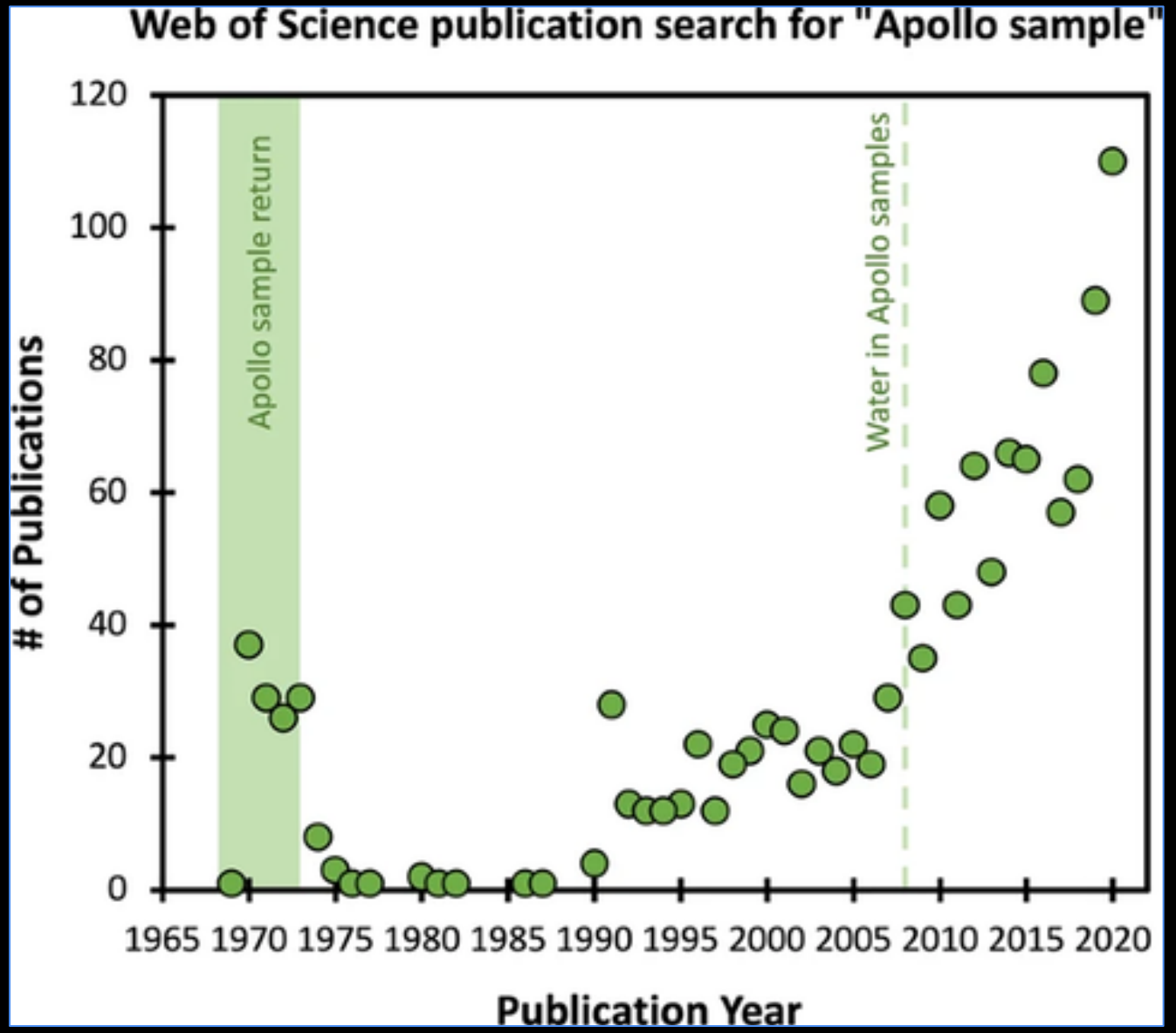
TABLE 20.2 Results from the Analysis of Basalt 10072, Returned from the Sea of Tranquility by the *Apollo 11* Astronauts in 1969. (Data from D. A. Papanastassiou, D. J. DePaolo, and G. J. Wasserburg, "Rb-Sr and Sm-Nd Chronology and Genealogy of Mare Basalts from the Sea of Tranquility," *Proceedings of the Eighth Lunar Science Conference*, Pergamon Press, New York, 1977.)

$^{147}_{62}Sm/^{144}_{60}Nd$	$^{143}_{60}Nd/^{144}_{60}Nd$
0.1847	0.511721 ± 18
0.1963	0.511998 ± 16
0.1980	0.512035 ± 21
0.2061	0.512238 ± 17
0.2715	0.513788 ± 15
0.2879	0.514154 ± 17

Table S1: Water concentration and D/H ratios of lunar glasses and melt inclusions

	Measured H_2O ppm	±2σ ‰ [4]	Olivine Crystallization Corrected H_2O ppm [3]	Spallation corrected H_2O ppm [4]	Measured δD ‰ [5]	±2σ ‰ [6]	Spallation corrected δD ‰ [7]	±2σ ‰ [8]	Combined Analytical and Spallation ±2σ ‰ [9]
Sample 74220 High-Ti glasses									
Melt inclusions									
74220 A2	1410.0	3	1144	1144	189	19	187	+1/-1	+19/-19
74220 A1	1270.0	4	1202	1202	328	32	327	+1/-1	+32/-32
74220 N6	931.0	6	766	766	313	37	311	+1/-2	+37/-37
74220 N8	1107.0	4	705	705	246	46	245	+1/-1	+46/-46
74220 N9	370.0	6	270	270	285	32	281	+3/-4	+32/-32
Matrix glass									
N5 glass	6.4	18		6.4	573	71	347	+152/-234	+168/-245
N6 glassL	19.3	19		19.3	533	46	458	+50/-75	+68/-88
N6 glassL2	31.6	19		31.6	375	40	329	+31/-46	+51/-61
N6 glassR	5.6	18		5.6	684	73	428	+171/-266	+186/-275
Large single beads									
74220 L3	5.0	43		5.0	736	158	446	+195/-304	+251/-342
74220 L4	3.5	54		3.5	614	205	194	+283/-448	+350/-493
74220 L5	4.6	45		4.6	598	175	283	+212/-331	+275/-374
74220 L6	5.5	40		5.5	673	151	412	+175/-271	+231/-310
74220 L7	4.6	46		4.6	769	165	453	+212/-331	+269/-370
74220 L8	4.9	44		4.9	586	168	291	+199/-309	+260/-352
74220 L9	4.4	47		4.4	567	182	235	+223/-350	+288/-394
74220 L10	3.8	51		3.8	799	184	416	+258/-407	+317/-446
74220 L11	3.2	57		3.2	727	209	269	+309/-491	+373/-534
74220 L12	8.7	31		8.7	558	117	392	+111/-171	+162/-207
74220 L13	6.7	36		6.7	518	143	299	+146/-226	+204/-267
74220 L14	5.7	40		5.7	587	155	330	+172/-267	+232/-309
74220 L18	3.7	52		3.7	794	186	406	+262/-413	+321/-453
74220 L22	3.1	57		3.1	855	200	396	+310/-493	+369/-532
74220 L25	3.5	54		3.5	722	197	307	+280/-442	+342/-484

The Impact of Sample Curation



A lunar sample renaissance (T.C. Prissel & K. B. Prissel
Nature Communications **volume 12**, Article number: 7053 (2021)

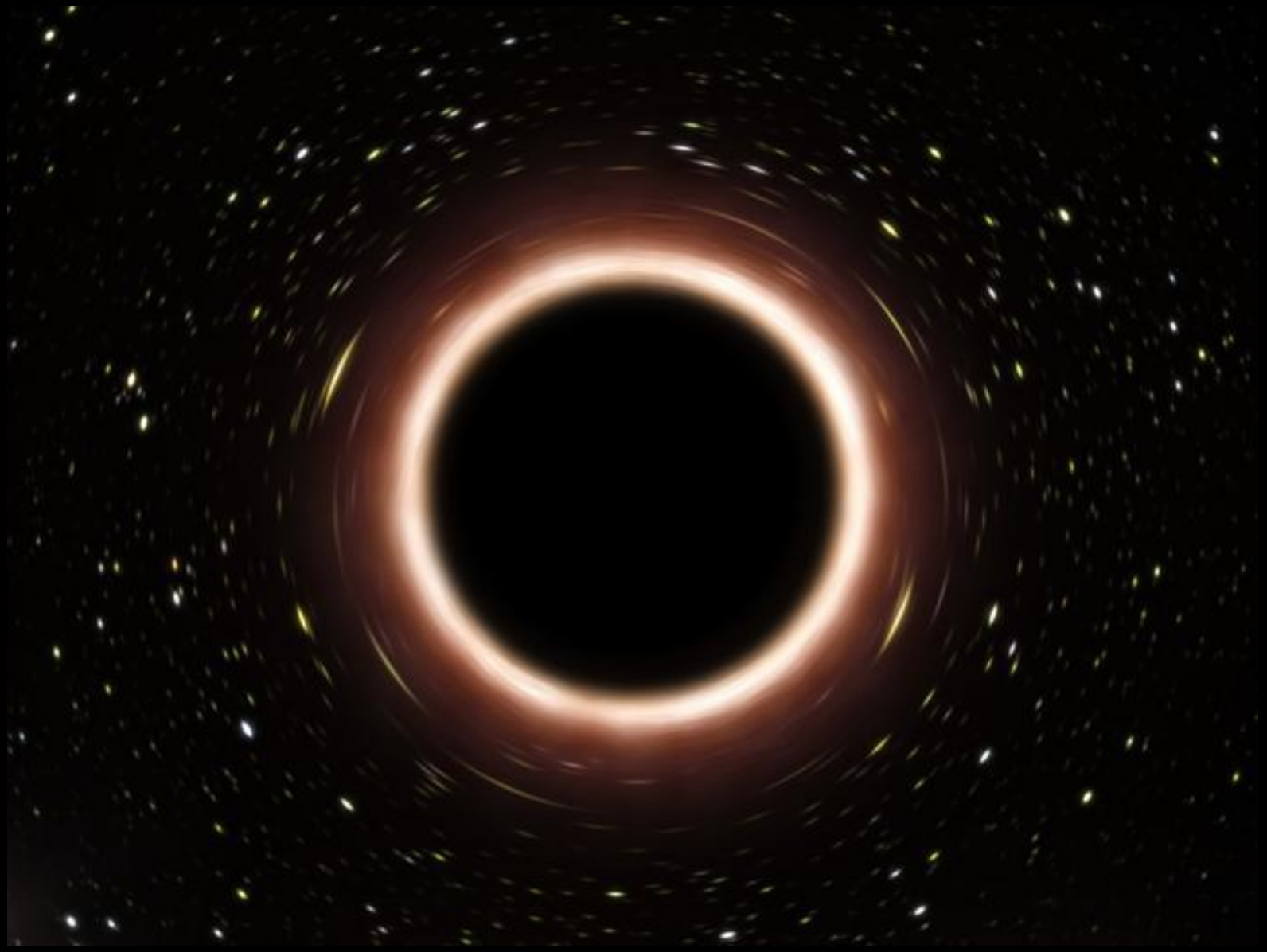
Lesson #1

The Value of Sample Curation

There are many samples on Earth that are unique and irreplacable.

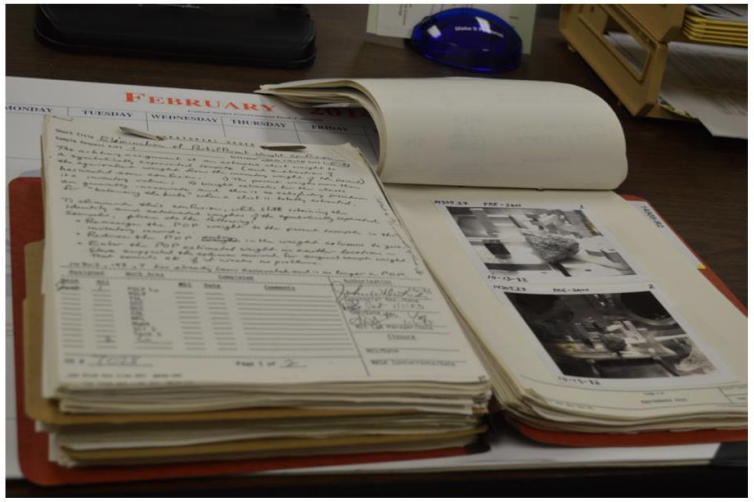
We need to ensure their preservation and access for reuse.

Where are the Data from Astromaterials Samples?



At the ARES Curation Office?

ARES focuses on Curation Data



- Need a database to track your sampl
  differe
  - Nee
    amo
  - Diffe
  - Leve
- Other
  sampl
  - >100k sample images
  - > 125 meters of shelving w/ processing notes
  - ~50,000 return sample histories
  - Countless information about geologic context, spacecraft data, or catalogs need to be included.
- Need an external website to advertise your wares.
- Data issues are going to get worse!

- **Each collection has its own database**
  - Internal database for sample tracking
  - Public sample catalog with images
- **Each collection has different metadata**
- **Each collection has a different naming protocol for the samples.**

Source:

Zeigler, Ryan, et al. "Curating NASA's Past, Present, and Future Astromaterial Sample Collections." Horizon 2020 EURO-CARES Work Package 3 meeting. No. JSC-CN-36137. 2016.

THE LUNAR SAMPLE COMPENDIUM

Compiled by Charles Meyer
for
Astromaterials Research & Exploration Science (ARES)

Contents

Basalt	Breccia	Plutonic	Soil	Core	SCR	Thin	Display
Apollo 11	Apollo 12	Apollo 14	Apollo 15	Apollo 16	Apollo 17	Luna	
15357	15358	15359	15362	15379	15380		
15382	15385	15386	15387	15388	15401		
15405	15410	15415	15418	15420	15425		
15431	15435	15436	15445	15455	15459		
15465	15466	15467	15468	15471	15475		
15476	15485	15486	15495	15498	15499		

"This Compendium allows easy access to the scientific literature by briefly summarizing the significant findings of each rock along with the documentation of where the detailed scientific data are to be found."

15555

Olivine-normative Basalt
9614 grams

Figure 1: Photo of S1 surface of 15555, illustrating large mirometeorite crater (zap pit) and vuggy nature of rock. NASA S71-43954. Scale is in cm.

Introduction

Lunar sample 15555 (called "Great Scott", after the collector Dave Scott) is one of the largest samples returned from the moon and is representative of the basaltic samples found on the mare surface at Apollo 15. It contains olivine and pyroxene phenocrysts and is olivine normative in composition (Rhodes and Hubbard 1973, Ryder and Shuraytz 2001). The bulk composition of 15555 is thought to represent that of a primitive volcanic liquid and has been used for various experimental studies related to the origin of lunar basalts (e.g. Walker et al. 1977).

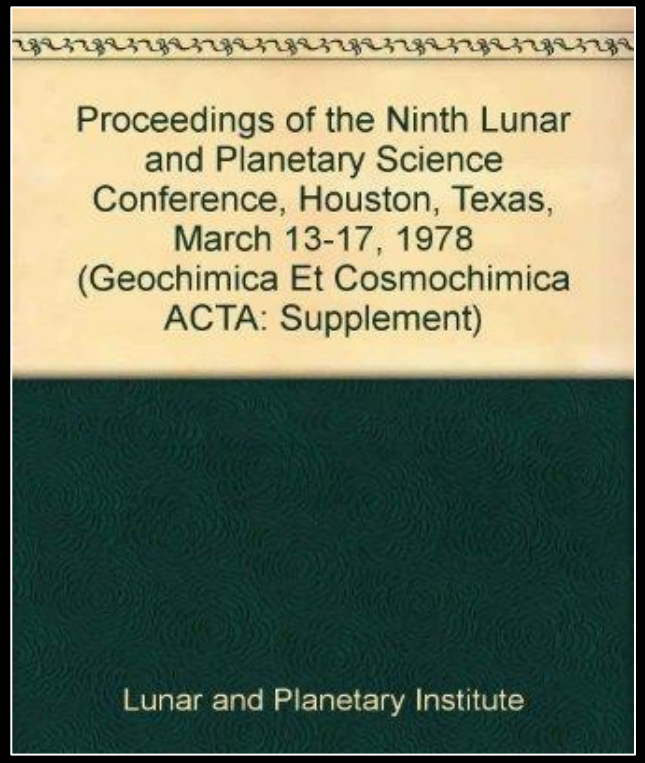
15555 has a large zap pit (~1 cm) on the S1 face, various penetrating fractures and a few percent vugs (figure 1). It has a subophitic, basaltic texture (figure 4) and there is little evidence for shock in the minerals. It has been found to be 3.3 b.y. old and has been exposed to cosmic rays for 80 m.y.

Mineralogical Mode of 15555

	Longhi et al. 1972	McGee et al. 1977	Heuer et al. 1972	Nord et al. 1973
Olivine	12.1	5-12	20	20
Pyroxene	52.4	52-65	40	40
Plagioclase	30.4	25-30	35	35
Opaques	2.7	5		
Mesostasis	2.3	0.2-0.4	5	5
Silica		0.3-2		

Downloadable PDF
Current version from 2010

Data in Publications?

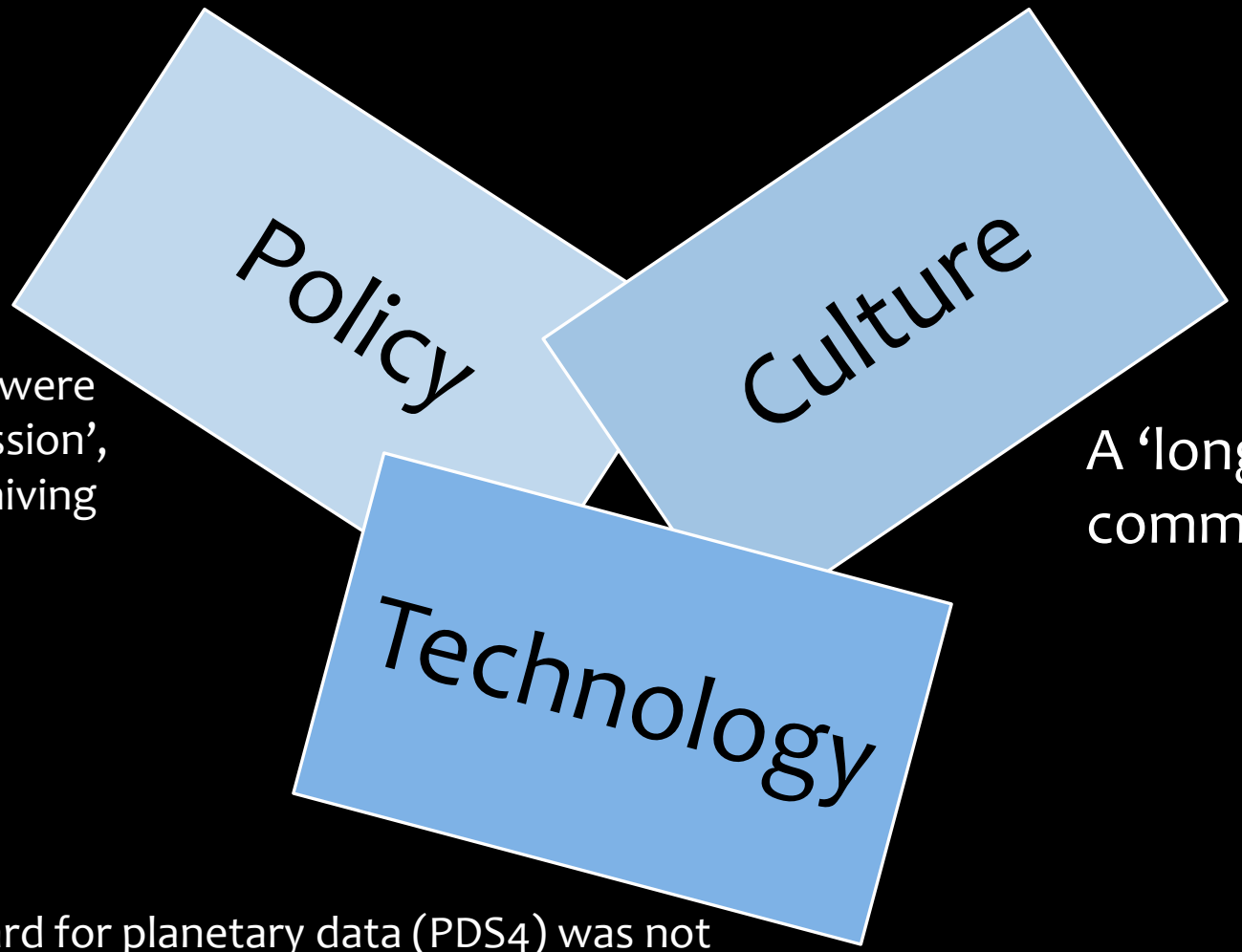


Data are dispersed across decades of scientific publications and conference abstracts. Only a fraction of the lab analytical data are included in older publications.

A lot of data have already been lost forever.

- Stored in notebooks, on printouts, or outdated digital media.
- Researchers are retiring, some have already passed.

Why Astromaterials Samples Data Were Not Archived



Laboratory analytical data were considered to be 'post-mission', did not fall under data archiving mandates for missions.

A 'long-tail', small data community.

The standard for planetary data (PDS4) was not designed with sample-based data in mind and is difficult to apply to laboratory analytical data.

Lesson #2

The Need for Expert Data Curation

Data will get lost and become unusable if it is not properly curated.

Sample curators are not necessarily the best data curators.

This is where the story of the Astromaterials Data System starts …

Astromat Birth & Infancy

2014 - 2018

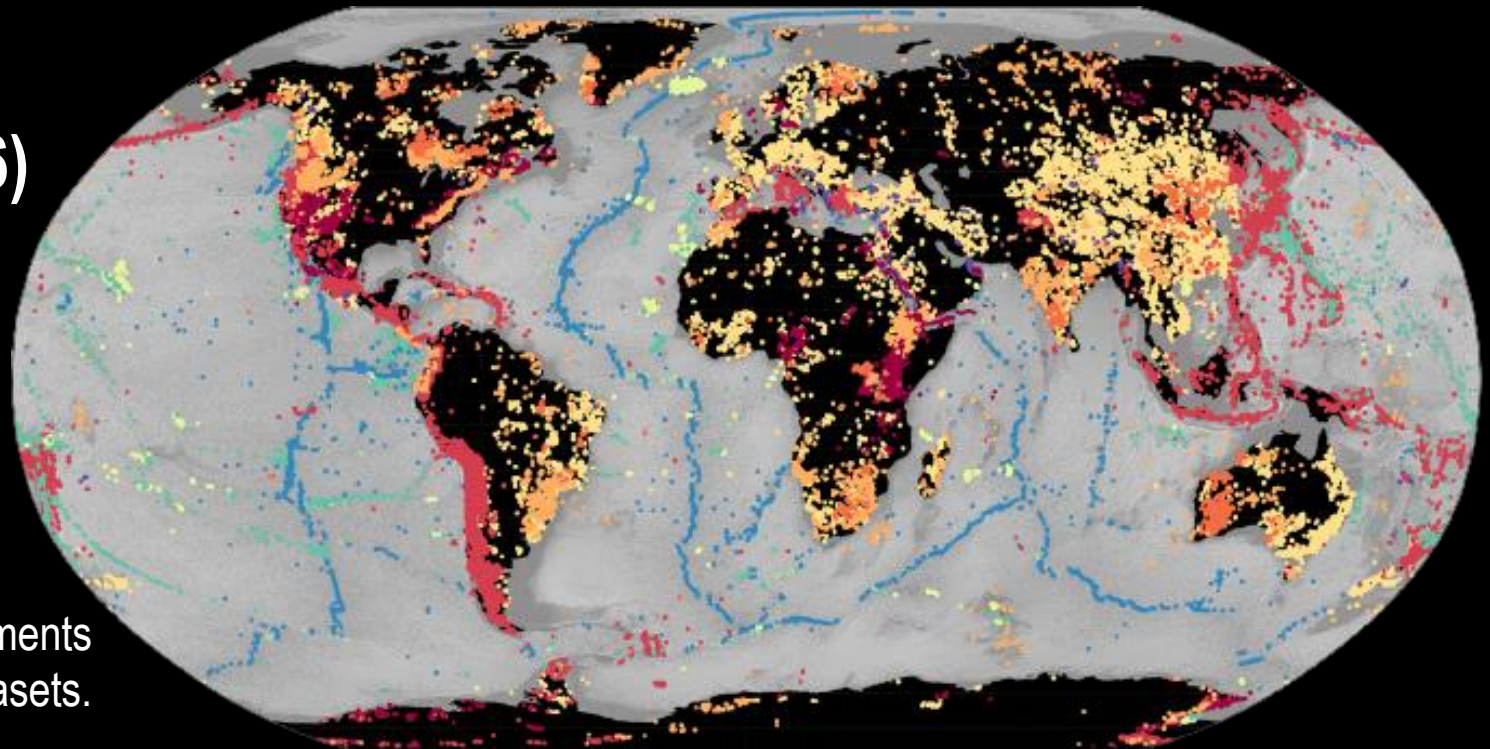
Hubble’s legendary “Pillars of Creation”

2013: Coincidence? Serendipity? Destiny?

- President Obama releases memo “Expanding Public Access to the Results of Federally Funded Research” → **JSC needs a home for lab analytical data.**
- A group of senior cosmochemists receives an IEDA Data Rescue mini-award to digitize lunar geochemical data. → **The community starts to see the necessity and benefits of data management and publication.**
- ARES sample curators visit Kerstin’s poster about geochemical databases at the AGU Fall Meeting 2013. → **ARES curators see an opportunity.**

Opportunity:
A Group with Expertise in Sample & Laboratory Data

- **Birthplace of the PetDB database (1996)**
- **Birthplace of the System for Earth Sample Registration SESAR (2004)**
- **Birthplace of the IGSN (2004)**
- **Birthplace of EarthChem (2006)**
- **All systems thriving in 2024**

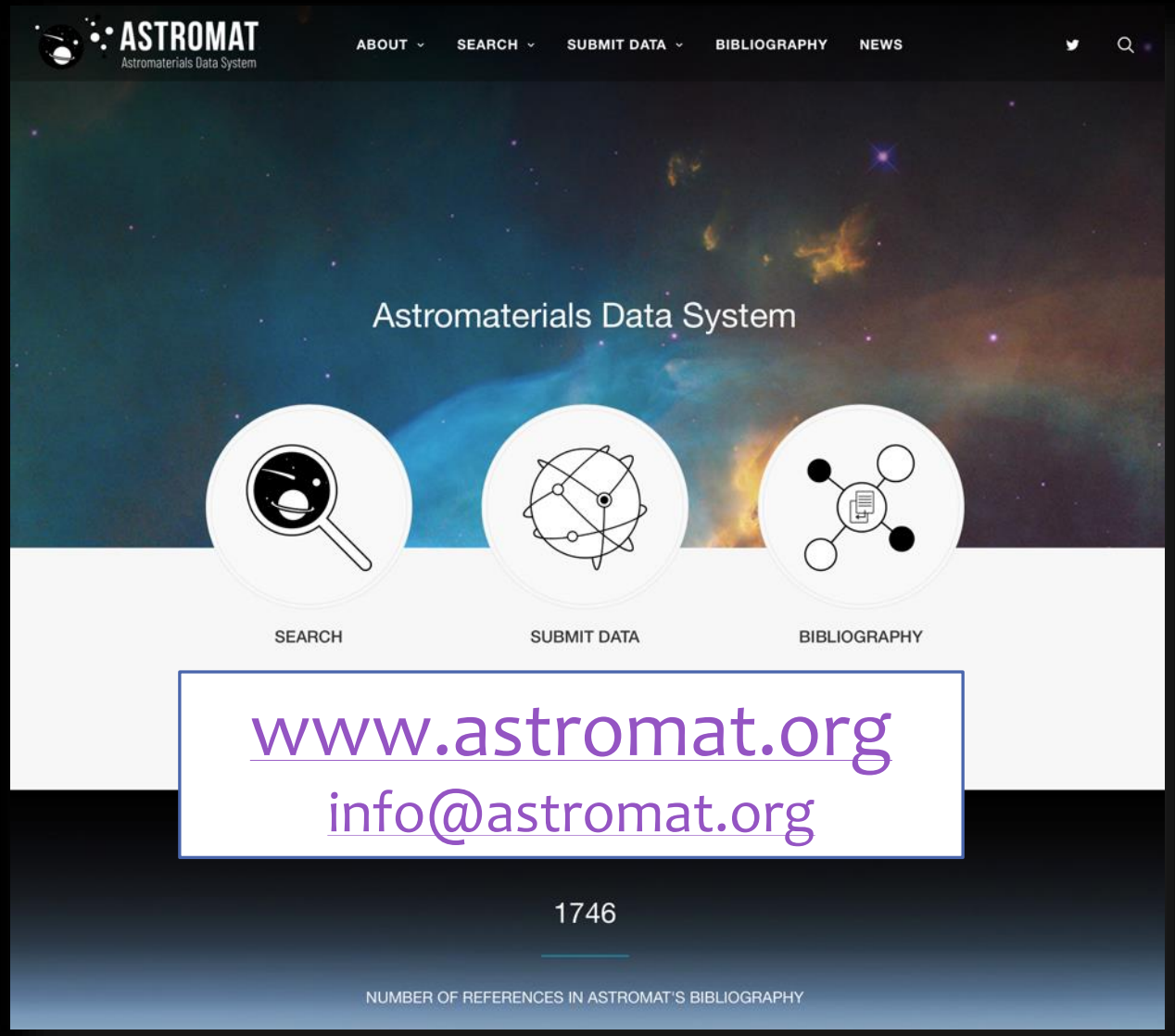


EarthChem Portal: Mine >49 million analytical measurements from thousands of published datasets.

Progress

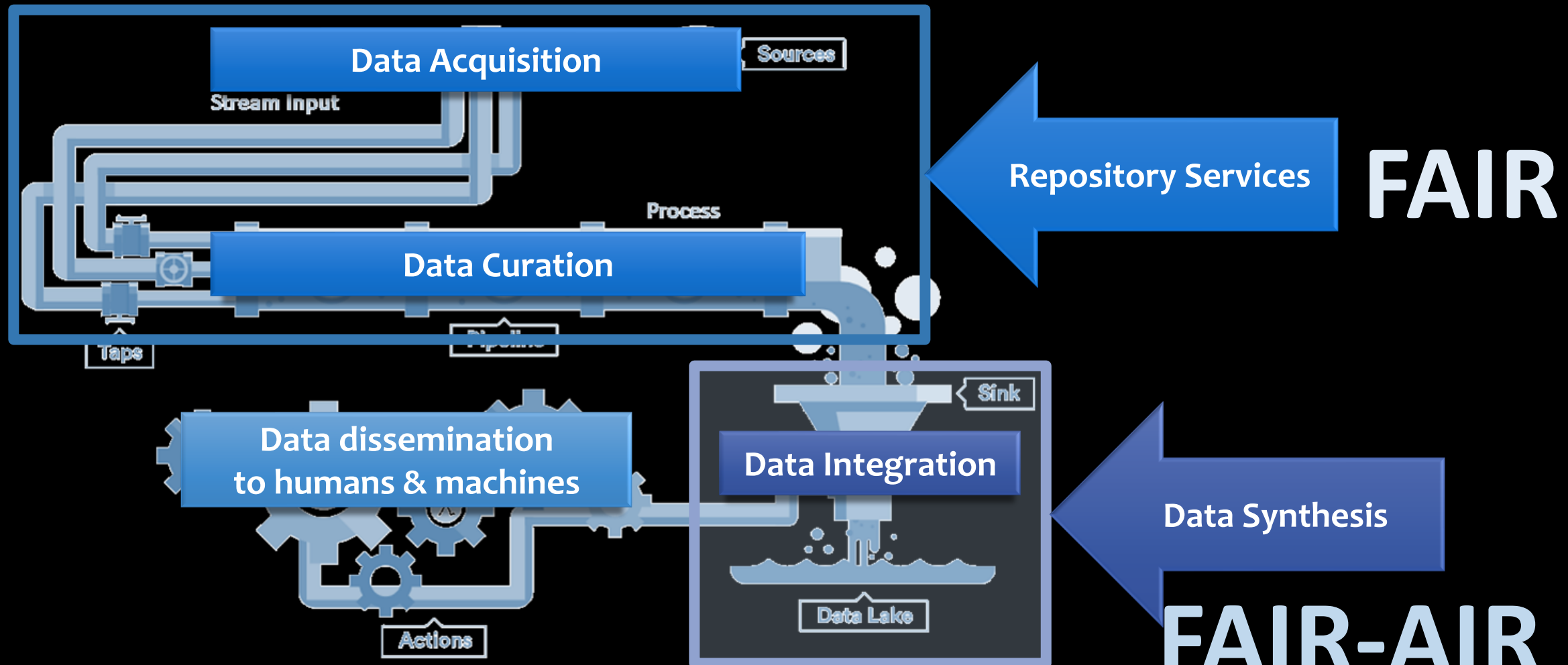
- 2014: Invitation to visit Johnson Space Center
- 2014: *"MoonDB"* data restoration project starts
- 2018: JSC visits the Lamont
- 2018: JSC requests proposal to extend data services to all JSC astromaterials collections
- 2019: Proposal funded & development of Astromat starts

The Astromaterials Data System is Here! (2019)



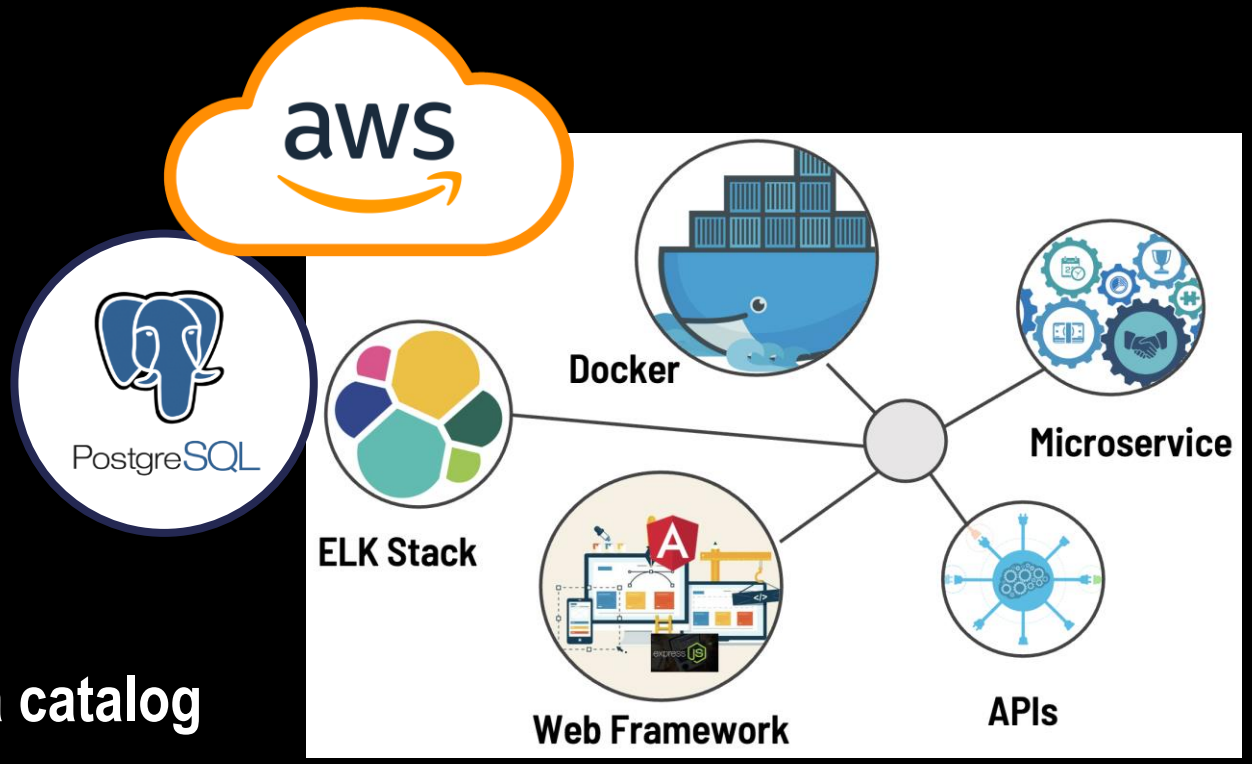
- Preserve past, present, & future astromaterials data
- Provide easy access
- Support innovative reuse & advanced data mining

Astromat Data Systems & Services



Credit: https://vibhor-gupta.medium.com/what-are-the-main-building-blocks-of-a-data-pipeline-9c0b79a0dcf9

Implementation 2020



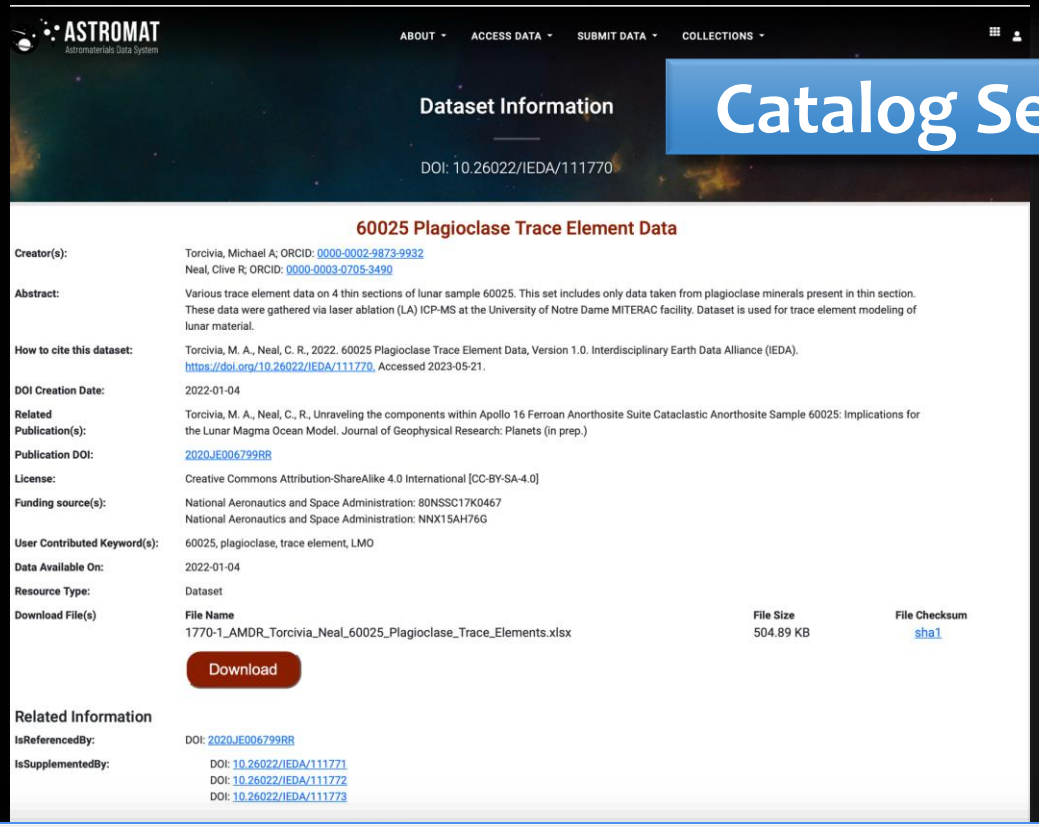
- **Repository Database**

  Reuse of EarthChem Library metadata catalog

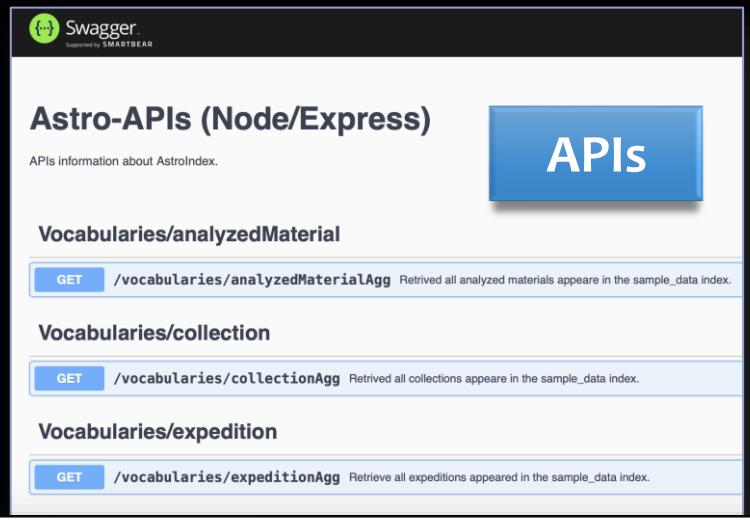
- **Synthesis Database**
  - **Evolved from ODM2 (Observation Data Model* - aligned with O&M)**
  - **Sync'ing data into various indexes to meet the needs of different apps**

* HORSBURGH, J. S., et al. (2016), "Observations Data Model 2: A community information model for spatially discrete Earth observations", Environmental Modelling & Software, volume 79, 55–74.

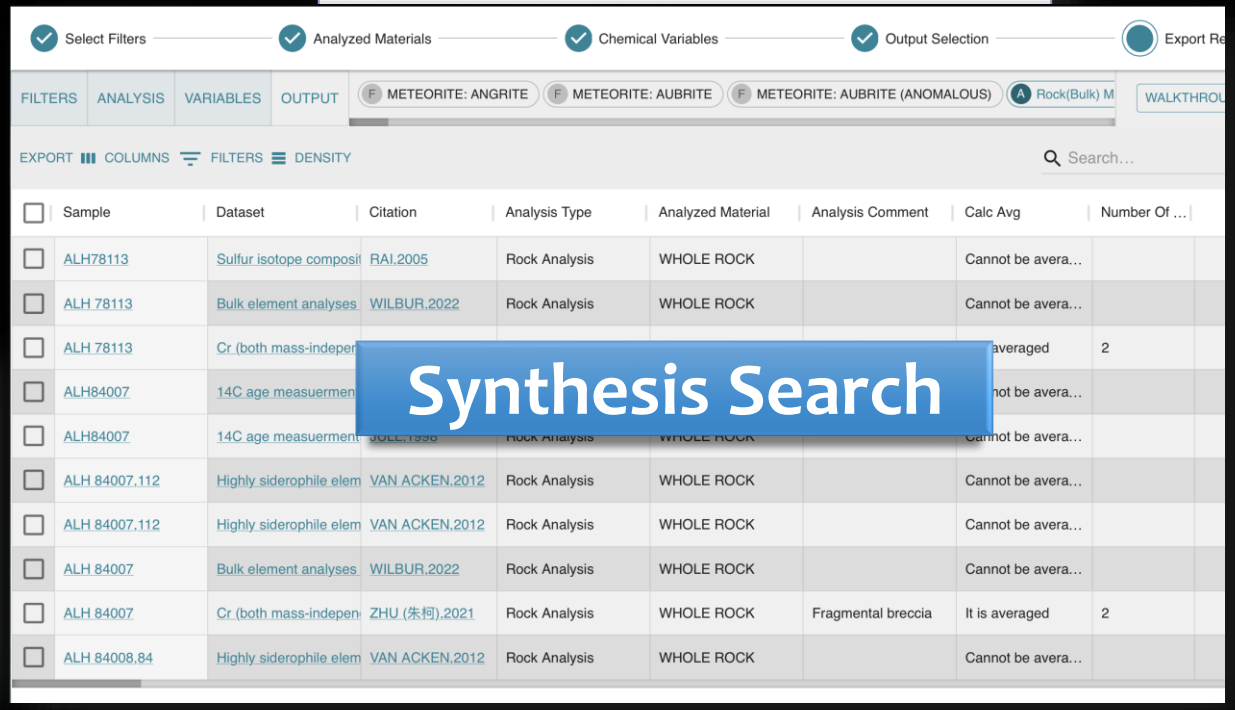
Astromat Data Access for Humans & Machines



Catalog Search



APIs



Synthesis Search

schema.org

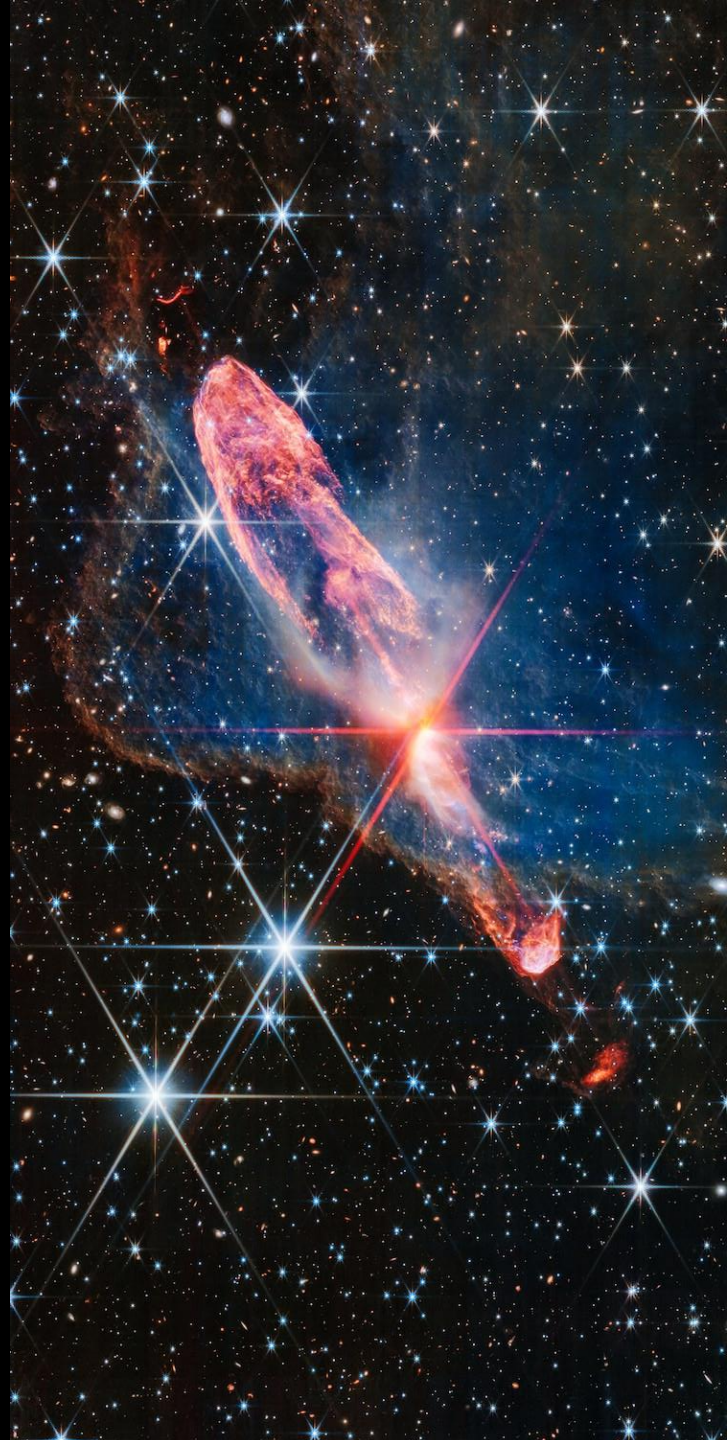
Astromat Evolves

2019 - 2023

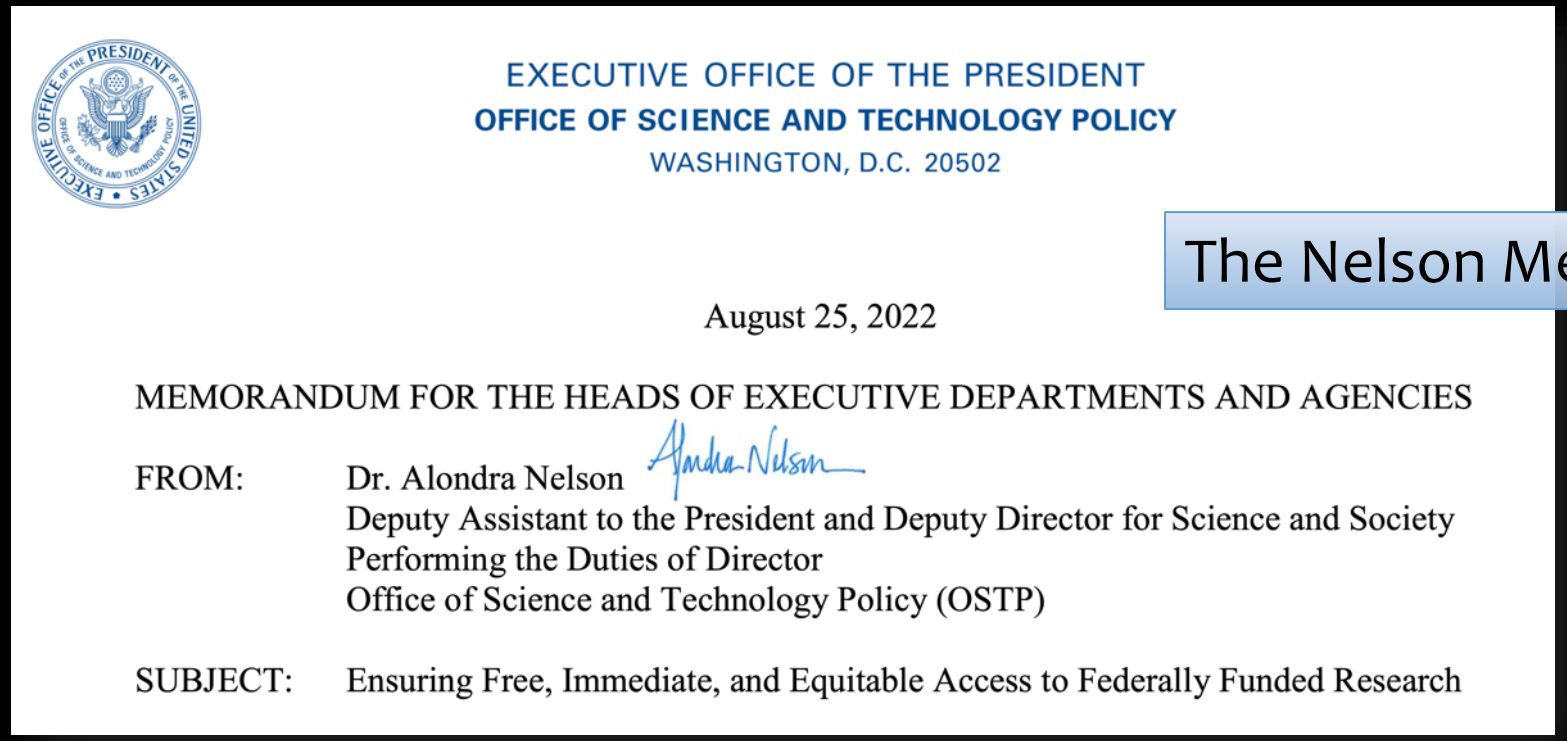
Detailed pictures of one of the first galaxies show growth in the early Universe was much faster than first thought

By Dr Kit Boyett, University of Melbourne

https://pursuit.unimelb.edu.au/



The US Government's Push for Open Science



EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
WASHINGTON, D.C. 20502

The Nelson Memo 2022

August 25, 2022

MEMORANDUM FOR THE HEADS OF EXECUTIVE DEPARTMENTS AND AGENCIES

FROM: Dr. Alondra Nelson
Deputy Assistant to the President and Deputy Director for Science and Society
Performing the Duties of Director
Office of Science and Technology Policy (OSTP)

SUBJECT: Ensuring Free, Immediate, and Equitable Access to Federally Funded Research

- Provide free, immediate (without embargo), and equitable access to research that is federally funded.
- Applies to all federal agencies.
- Applies to both peer reviewed publications and underlying scientific data.

NASA's Commitment to Open Science

Open Science at NASA

NASA is making a long-term commitment to building an inclusive open science community over the next decade. Open-source science is a commitment to the open sharing of software, data, and knowledge (algorithms, papers, documents, ancillary information) as early as possible in the scientific process.

NASA Open-Source Science Initiative

OCSDO Activities and Missio

- Open Science
- Transform to Open Science (TOPS)
- Core Data and Computing
- Artificial Intelligence and Machine Learning
- Science Mission Directorate Science Data
- Scientific Information Policy

https://science.nasa.gov/open-science/

NASA's Response: SPD-41A

NASA SPD-41A Policy Embraces FAIR

"Data should not only be archived but also be curated – that is, the data are assured to have continued accessibility and usability for multiple decades."

- **Publicly available without fee or restriction of use.**
- **Machine-readable data formats.**
- **Robust, standards-compliant metadata that clearly and explicitly describe the data.**
- **Clear, open, and accessible data license so data are reusable.**

Lesson #3

The Value of Meaningful Policy

NASA's SPD-41A and its implementation strategy have been critical to advancing FAIR data practices across all of NASA's science divisions.

2020: Review of the Planetary Data Ecosystem

Planetary Data Ecosystem Independent Review Board (PDE-IRB)

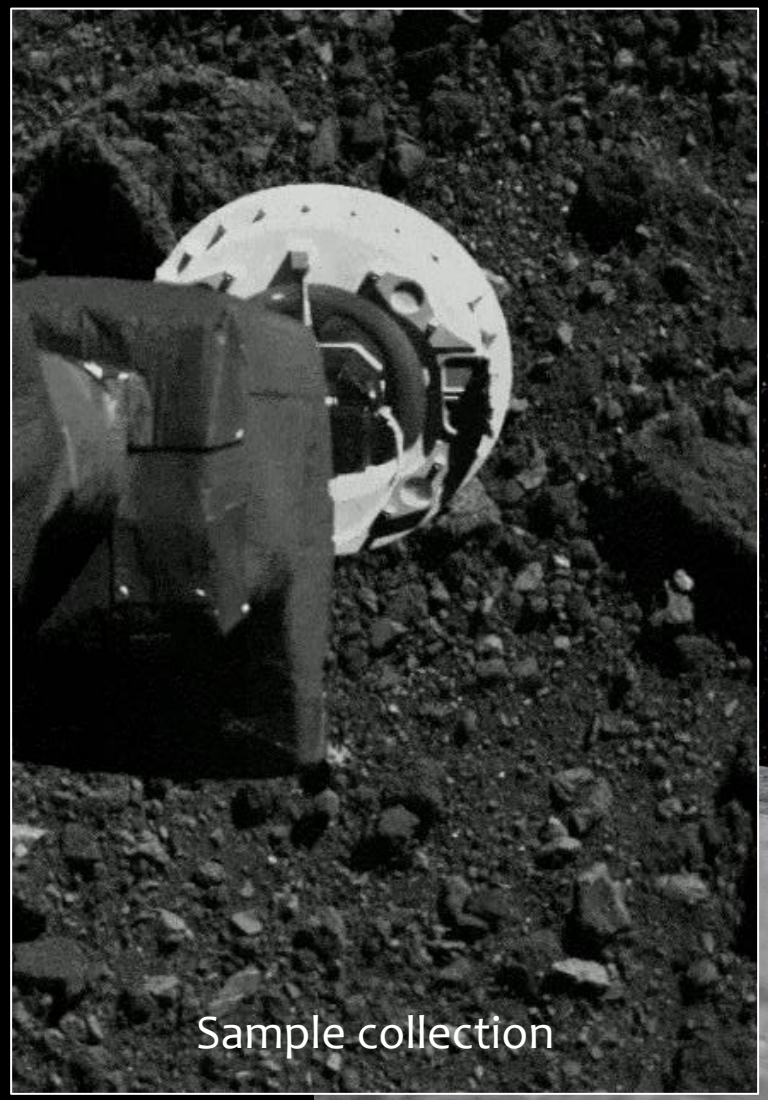
Report released in 2021 recommends the preservation of data produced by laboratory analysis of returned samples in an approved archive.

Apr 23, 2021

Planetary Data Ecosystem Independent Review Board Delivers Final Report to NASA

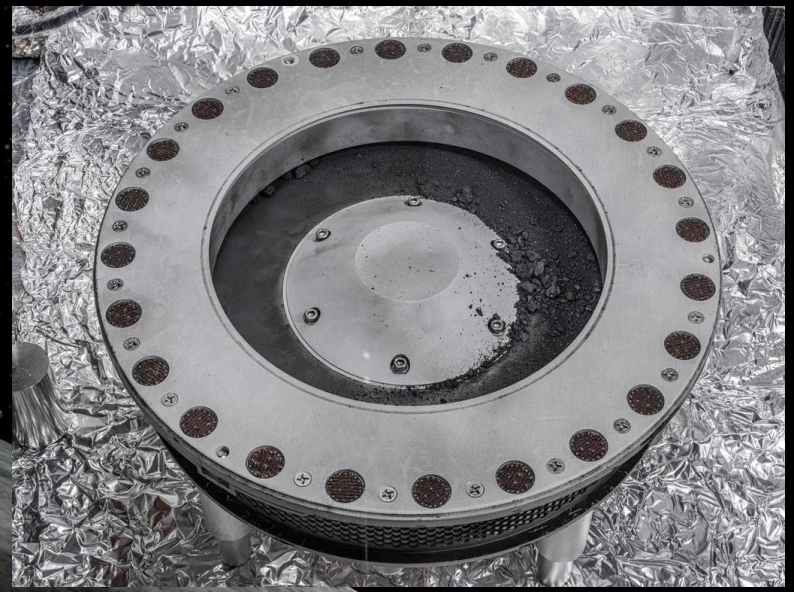
NASA's Planetary Data Ecosystem (PDE) Independent Review Board (IRB) delivered its final report and briefing to NASA on April 20, after examining information collected about planetary data. The IRB provided prioritized actionable recommendations for the agency's Planetary Science Division's (PSD) long-term planning and support of the Planetary Data Ecosystem (PDE).

Then Came OSIRIS-Rex …



Sample collection

Sample container



Data Dilemma of OSIRIS-REx

- Data Management Plan required archiving of all data generated by the Sample Analysis Team (SAT) in a publicly accessible approved archive.
- Sample Analysis MicroInformation System (SAMIS) was built to manage data internally during the mission.
- The SAT (and NASA's PSD) needed a data archive!

O-REx Chief Scientist Dante Lauretta

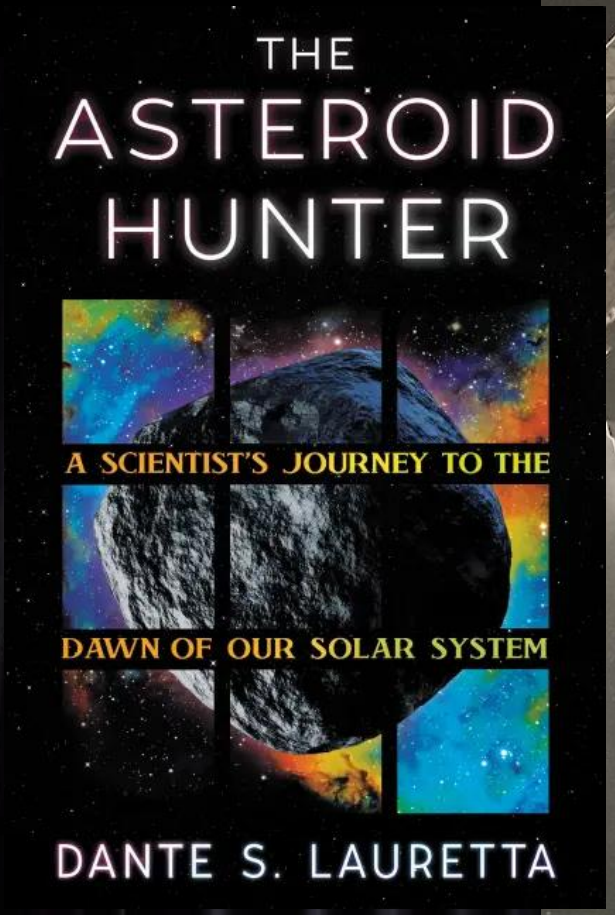


Photo: Andres Kudacki for The New York Times

Source: https://brianmay.com/brian-news/

Astromat's Rapid Growth to Adulthood

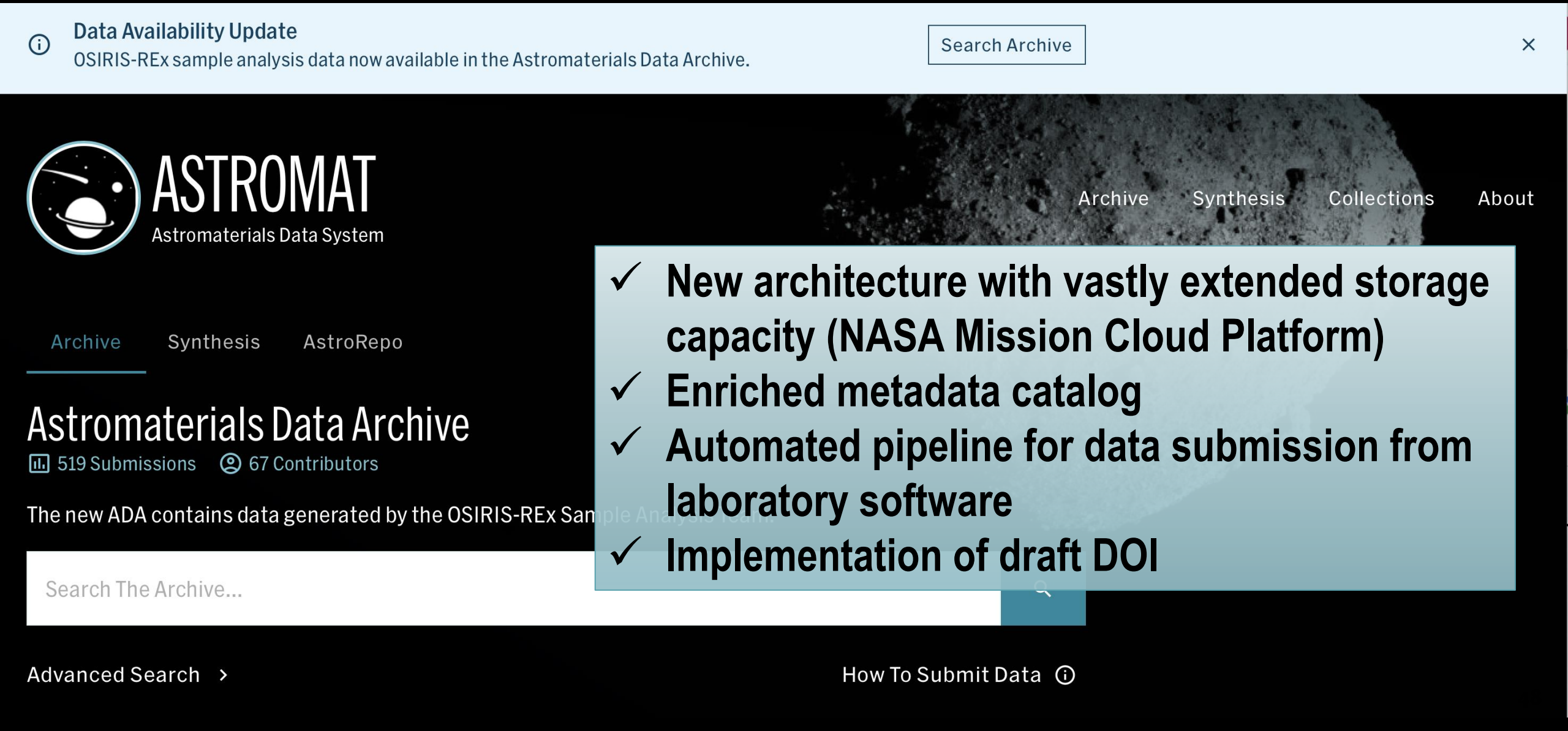
- 2021: Lots of discussions with NASA & Lauretta
- Early 2022: NASA requests Special Study "Requirements for Archiving Astromaterials Samples Data" – delivered September 2022 (R. Downs)
- September 2022: NASA requests an Implementation Plan for an archive that can manage & store the OSIRIS-REx Sample Analysis data
- October 2022: Development of the ADA and pipeline for OSIRIS-REx Sample Analysis data from SAMIS to ADA starts
- January 2023: First test datasets are ingested into the archive.

The New Astromaterials Data System

"… AstroMat has been identified as the primary NASA-sponsored archive for laboratory analyses of returned samples."

Planetary Science Division
Information & Data Management Policy
Supplement to SPD-41A
February 2, 2024

The New Astromat



- ✓ New architecture with vastly extended storage capacity (NASA Mission Cloud Platform)
- ✓ Enriched metadata catalog
- ✓ Automated pipeline for data submission from laboratory software
- ✓ Implementation of draft DOI

Now to the Headaches …

- How do we properly curate the diversity of data types acquired by the OSIRIS-Rex Sample Analysis Team?
- How do we fulfill NASA's requirement for external peer review of submitted data?

Variety of Data Types & Analytical Methods

Data Standards relevant to each Bundle Delivery Document
(last updated on 08/18/2023)

BDD 0-10	EMPA	Raman	XCT	VLM	QRIS	GC-MS	LC-MS	VNMIR	NanoSIMS	SLS	
BDD 10-20	μL²MS	FTICR-MS	SS-NMR	GC-C-IRMS	NMR	MC-ICP-MS	EA-IRMS	SIMS	XRD	SEM/FIB-SEM	
BDD 20-30	TEM	EBSD/TKD	XANES	XPS	HR-ICP-MS	SHRIMP	LAF	APT	TIMS	NI-MI	PSFD
BDD 30-40	Q-ICP-MS	FINESSE	NG-NS-MS	ICP-OES	GPYC	SCBTCA	DSC	HR-CL	EDS	EELS	
BDD 40-50	NanoIR	S-XRF	TGA	LA-ICP-MS	NI-NGMS	RI-TOF-NGMS	ESI-Orbitrap M	SThM	PCD-AFM		
BDD 50-60	XRF	ARGT	SNMS	AMS	COMPT	SV-RUEC	CAPD	DSSM	LIT	ARM	
BDD 60-70	IC	ToF-SIMS	CE-MS	S-IR							

Notes

- X Tabular Data
- X Images (2D Arrays)
- X Data Cubes (3D Arrays)
- X Data Collection
- X Documents

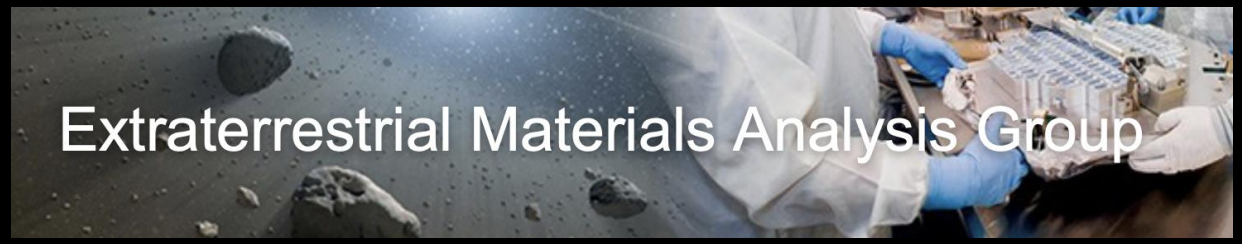
65 analytical methods are used to study the OSIRIS-Rex returned samples

Peer Review Challenges

- **Lack of lab analyses data standards:** What criteria to use?
- **Diversity of data types:** How can we scale the process?
- **Small size of reviewer community:** Where will we find reviewers?
- **Volume of data submissions:** How can we streamline the process?
- **Community culture:** How do we incentivize submitters & reviewers?
- **Integration with publication workflows of journals:** How do we avoid delays for researchers to publish?

Working on Solutions

Engage with the astromaterials samples community to gather input on best practices & advance adoption.



https://www.lpi.usra.edu/exmag/

Implement tools that streamline the curation workflow

Kotahi

The Next Generation of Scholarly Publishing Platform

As used by eLife, Johns Hopkins University, Amnet, Biophysics Colab and more..

https://kotahi.community

Promote publication of protocols

Participate in the OneGeochemistry initiative to develop, promote, and govern data standards for laboratory analytical data

ONEGEOCHEMISTRY

The WorldFAIR Project

https://worldfair-project.eu

Global cooperation on FAIR data policy and practice

Lesson #4

Don’t ever think it’s easy.

But collaboration helps.

A Giant Step for Returned Samples

From PSD supplement to SPD-41A:

"PSD recognizes that the availability of archives and repositories for physical materials that meet the SPD-41A guidelines for an SMD-acceptable data repository (see SPD-41A, Appendix D) is a work in progress.

For now, PSD requires that, at a minimum, all physical materials covered by this policy must be registered with the International Generic Sample Number (IGSN) Organization and the IGSN numbers must be used to cite the physical samples in publications.

It is acceptable to register physical samples in the National Science Foundation (NSF) System for Earth Sample Registration (SESAR), which is an IGSN Allocating Agent."

Proudly Presenting Our Achievements

- A new infrastructure for access & preservation of FAIR laboratory analytical data of returned samples.
- Restoration and synthesis of >2 million analytical measurements.
- First applications of advanced data analytics emerging.
- Aligning standards and best practices for laboratory analytical data and samples across Earth & Planetary sciences.

First Results of OSIRIS-Rex Sample Analysis Published with links to data in Astromat!

METEORITICS & PLANETARY SCIENCE

The Meteoritical Society

Article | Open Access

Asteroid (101955) sample c ted b

Dante S. Lauretta, Ronald-L. Ballouz, Jessica J.

First published: 26 June 2024

The OSIRIS-REx

Open Research

Data Availability Statement

The OSIRIS-REx sample analysis data products that support the findings of this study are available via AstroMat (astromat.org) at the DOIs given in Table S1 . The image mosaics of Bennu and Nightingale in Figure 1 are available at asteroidmission.org . PolyCam images shown in Figure 2 are available from the NASA Planetary Data System (arcnav.psi.edu /urn:nasa:pds:context:instrument:ocams.orex); their IDs are listed in Table S1 . Data plotted in figures are tabulated in Table S2 .

Emerging Applications of the Synthesis

Creating a Multivariate Data Set

How do we make use of our resources?

ASTROMAT
Astromaterials Data System

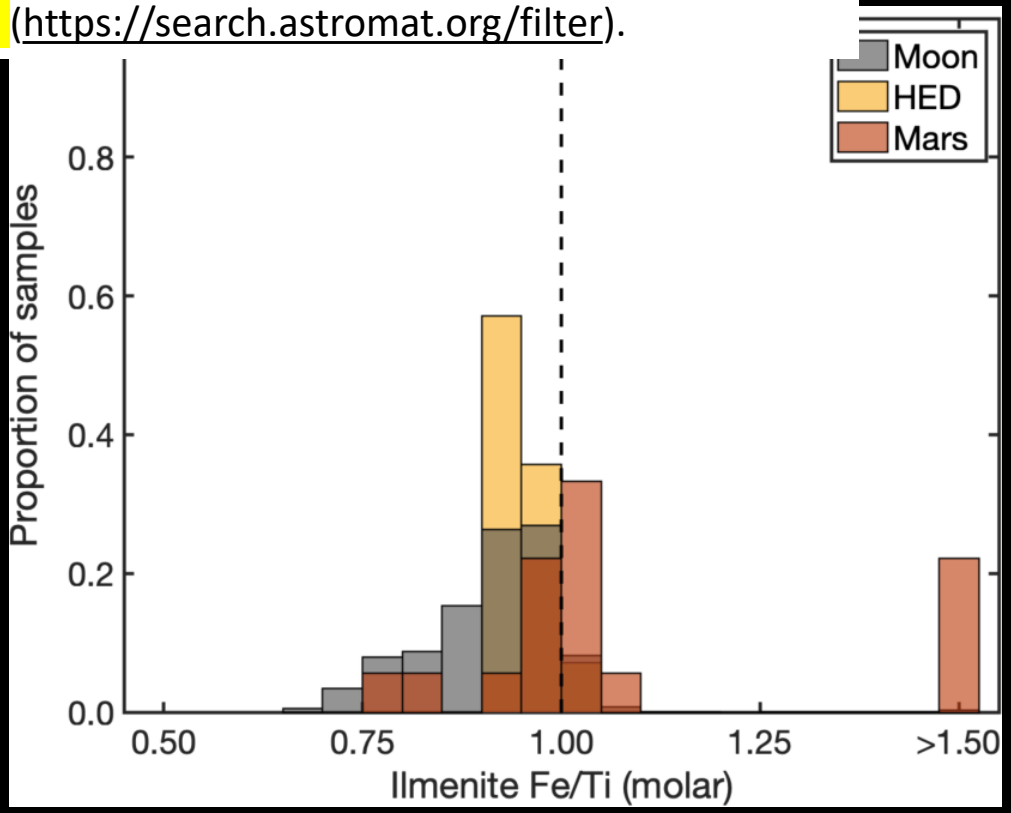
ChondriteDB
(Hazel et al., 2016)

MetBase
World's Largest Collection of Meteorite Data

From: Ostroverkhova A et al. 2023:
"Unraveling the Enigma of Ungrouped Chondrites: A Data Science Approach for Exploring their Origins."
AGU Fall Meeting 2023. San Francisco, CA.

Prissel K et al.: "*Feiite: Synthesis, stability, and implications for its formation conditions in nature*." American Mineralogist 2023
https://doi.org/10.2138/am-2022-8633

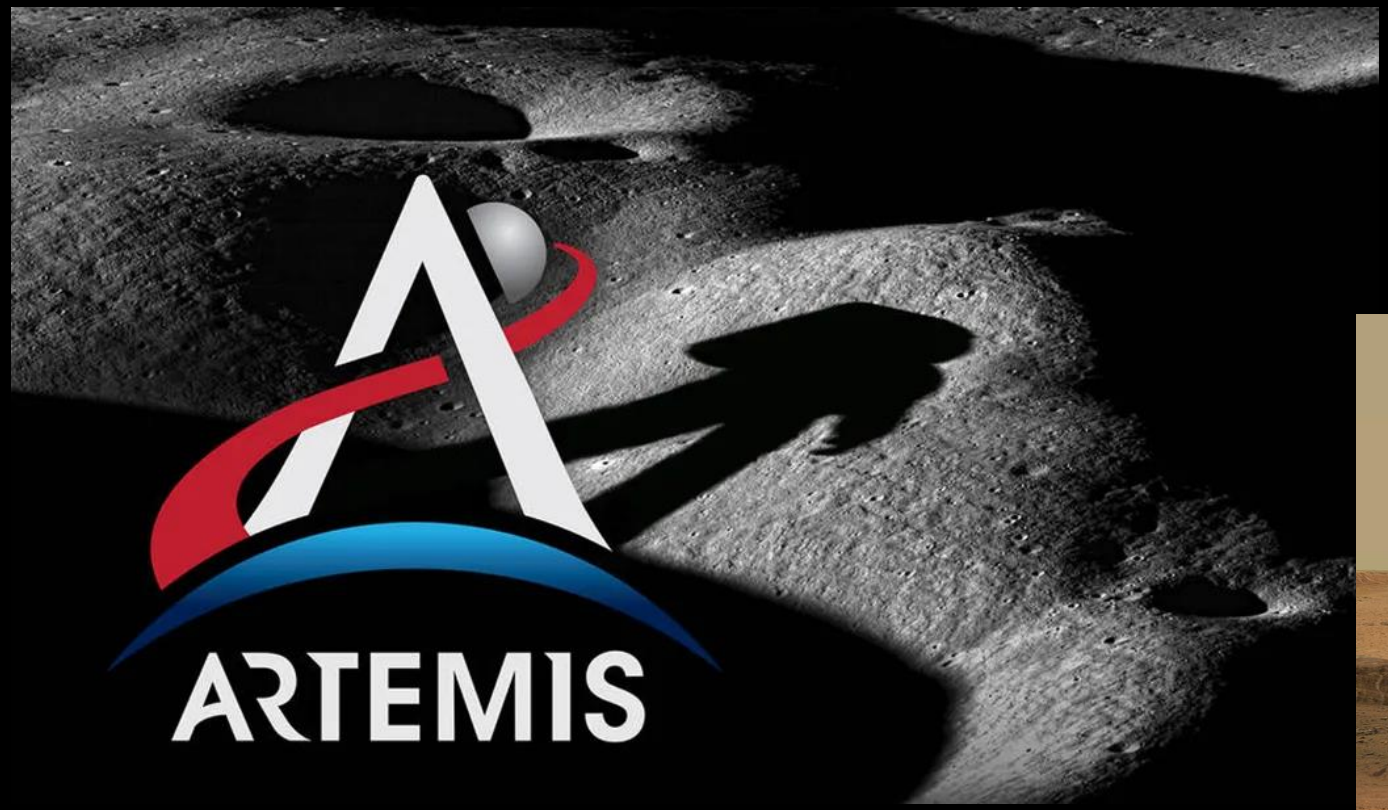
Ilmenite data accessed May 2022 from AstroDB" (https://search.astromat.org/filter).

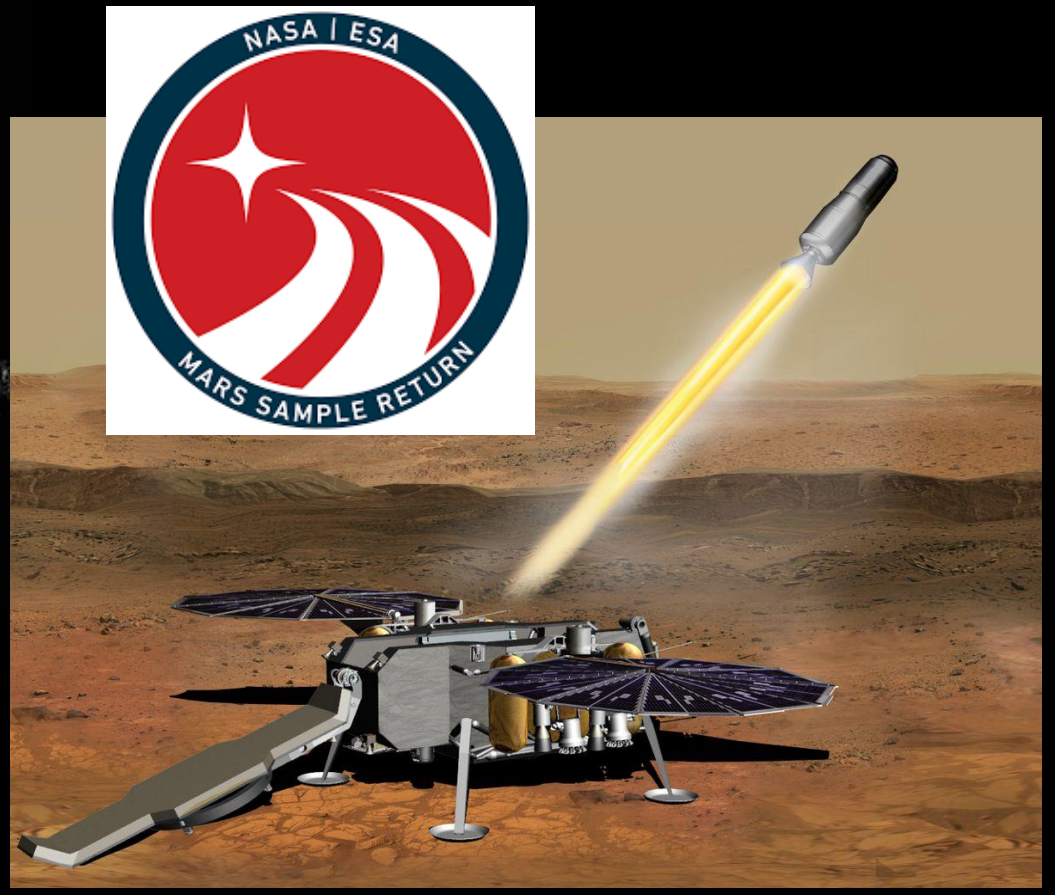


The Lessons

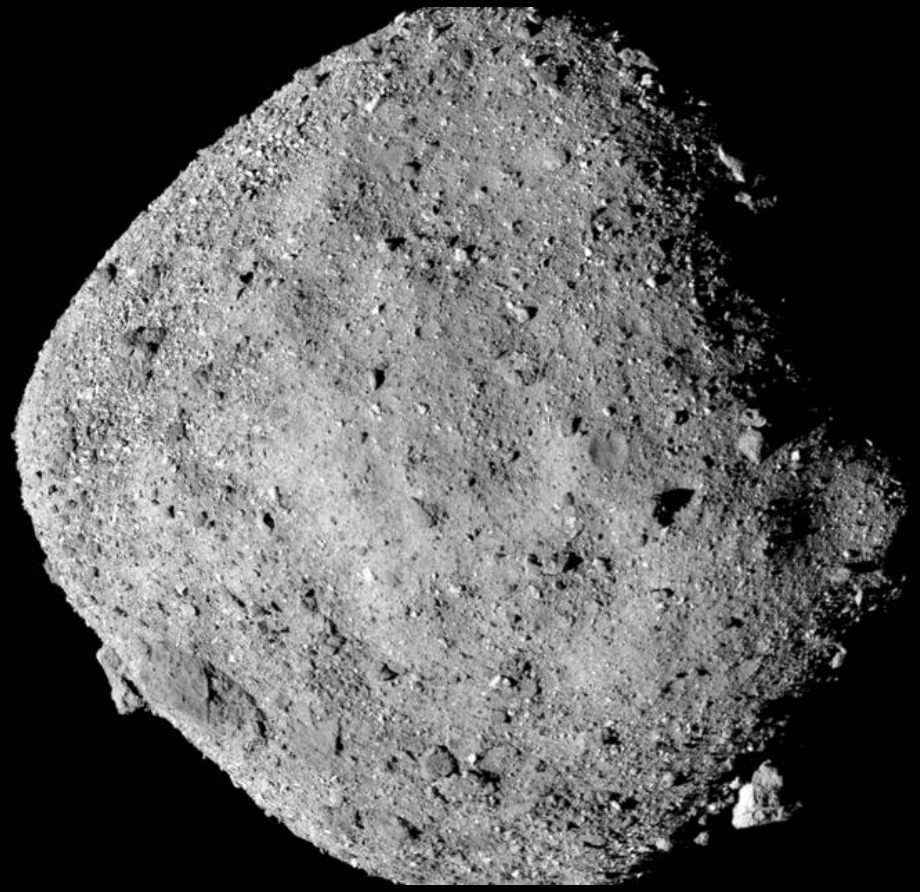
- The Value of Sample Curation
- The Need for Expert Data Curation
- The Value of Meaningful Policy
- Don’t ever think it’s easy

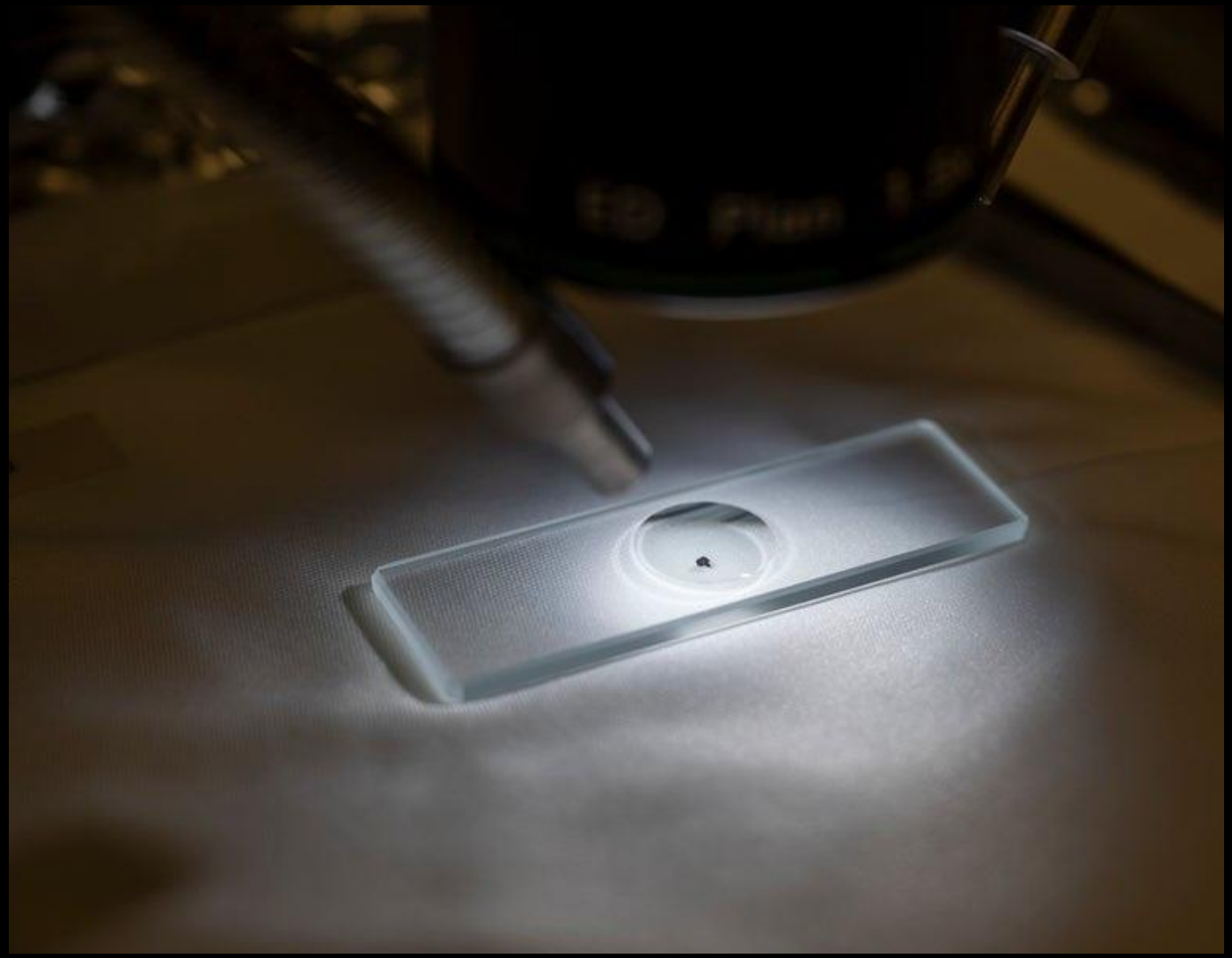
Astromat is Ready for the Next Adventures





New Challenges Ahead!





astromat.org

info@astromat.org

Thank You!

The Lamont Geoinformatics Research Group

Consultants:

Results from Bennu Samples

A microscope image of a dark Bennu particle, about a millimeter long, with a crust of bright phosphate. To the right is a smaller fragment that broke off. Credit: From Lauretta & Connolly et al. (2024) Meteoritics & Planetary Science, doi:10.1111/maps.14227

"The sample's composition and mineralogy indicate substantial aqueous alteration and resemble those of Ryugu and the most chemically primitive, low-petrologic-type carbonaceous chondrites. Nevertheless, we find distinct hydrogen, nitrogen, and oxygen isotopic compositions, and some of the material we analyzed is enriched in fluid-mobile elements.

Our findings underscore the value of sample return—especially for low-density material that may not readily survive atmospheric entry—and lay the groundwork for more comprehensive analyses."