Advanced Curation of Astromaterials

Supporting Future Sample Return Missions
<table>
<thead>
<tr>
<th>Mission</th>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar</td>
<td>1969</td>
<td>Apollo program lunar rocks and soils; Luna samples</td>
</tr>
<tr>
<td>Meteorite</td>
<td>1977</td>
<td>Antarctic Search for Meteorites (ANSMET) program</td>
</tr>
<tr>
<td>Cosmic Dust</td>
<td>1981</td>
<td>Cosmic dust grains from Earth’s stratosphere</td>
</tr>
<tr>
<td>Micro-particle Impacts</td>
<td>1985</td>
<td>Space exposed hardware from spacecraft</td>
</tr>
<tr>
<td>Genesis</td>
<td>2004</td>
<td>Genesis solar wind samples at Earth-Sun L1 point</td>
</tr>
<tr>
<td>Stardust</td>
<td>2006</td>
<td>Cometary and interstellar samples from Comet Wild 2</td>
</tr>
<tr>
<td>Hayabusa II</td>
<td>2012</td>
<td>Samples collected from JAXA asteroid mission to Itokawa</td>
</tr>
<tr>
<td>Hayabusa II</td>
<td>2020</td>
<td>Subset of samples collected from JAXA asteroid mission to (162173) 1999</td>
</tr>
<tr>
<td>OSIRIS-REx</td>
<td>2023</td>
<td>Asteroid sample return from 101955 Bennu</td>
</tr>
<tr>
<td>Mars</td>
<td>~ 2030s</td>
<td>Mars Sample Return Over 50 years in the planning (est. 1964)</td>
</tr>
</tbody>
</table>

**Our Future . . . .**

- **Hayabusa II** (2020): Subset of samples collected from JAXA asteroid mission to (162173) 1999
- **OSIRIS-REx** (2023): Asteroid sample return from 101955 Bennu
- **Mars** (~ 2030s +): Mars Sample Return
- **Solar System Future Missions**
  - Asteroids, Moon, Comets, Planets and their moons

**JSC’s Astromaterials Acquisition & Curation Office**

*Our past 50 years – planning for and curating multiple collections*
Sample science forms a critical base for planetary science and understanding solar system evolution

- NASA’s Johnson Space Center curates all of NASA’s extraterrestrial samples – the most extensive set of astromaterial samples available to worldwide research community.
- Our charge is to preserve, protect and provide samples for current and future scientific research, and maintain their scientific and cultural value.
- Sample integrity from each collection is a result of the early partnership between curation scientists and the mission scientists and engineers, a practice started before Apollo.
The Astromaterials Acquisition and Curation Office comprises a large complex of labs and supporting infrastructure:

- 8 clean room suites and associated laboratories including 22 clean rooms (ISO class 4-7), sample vaults for pristine and return samples, experiment labs, thin section labs, core and saw rooms, precision tool cleaning facilities, UPW, Air handling, filtering and N₂ systems.

- 45+ year archives (mission & sample documents, living records of all aspects of sample handling) and public database

- Uniquely trained curatorial and technical staff of ~30

- Close and continuing coordination with mission and research communities
Apollo Lunar Samples: 1969-1972

- 6 Apollo Missions landed on the Moon’s surface, returning 382 kg of sample
- We annually distribute >500 samples to science teams

Careful partnerships with mission scientists/engineers and Earth-based clean room operations enabled key discoveries that include fundamental knowledge about the Earth-Moon system and early history of the solar system

- Moon formed through impact of Mars-sized body early in solar system history
- Lunar samples (many > 4 billion years) provide data for earliest Earth history
- Samples record flux of impacts in inner solar system, spiking 3.9 billion years ago. Drop-off in impacts is coincident to beginning of life on Earth
- The Moon contains water
Enabling Groundbreaking Science from the Apollo Missions

- Curation scientists participated in mission design, sampling strategy, tool design, astronaut training, sample return, early processing, and curation
- Lunar lab complex is our largest suite of clean rooms and labs (ISO 5-6)
  - Clean room, storage and working areas designed to minimize contamination from the environment and other samples
  - Preliminary examination techniques, documentation and databases developed to share samples and data with global research community
  - Our labs and protocols have successfully preserved samples for increasingly sophisticated analyses over 45 years, enabling new discoveries.
Key Developments:
Apollo Program Isolation Technology

- High Vacuum Complex (F-201 Vacuum Glovebox) & Class III Biological Gloveboxes used behind biocontainment barrier
  - Materials were chosen with emphasis on reducing contamination with low particle shedding and outgassing properties: Stainless Steel (316L and 304), Teflon; Aluminum (6061 and 6063); Viton (fluorinated hydrocarbon); Pyrex Glass

- After Apollo 12, hi vacuum complex replaced with gaseous N2 gloveboxes: Sterile negative P line & non-sterile positive P line

- After Apollo 14, no quarantine requirements (sterile negative pressure N2); only positive pressure gloveboxes were used.

- Today, Lunar samples are handled in positive P gloveboxes in an ISO Class 6 cleanroom environment. The gloveboxes are constructed with 316L stainless steel, polycarbonate and glass windows, Viton seals, and neoprene gloves.
Each field season, hundreds of new meteorites are found on Antarctica’s blue ice fields

- To date, more than 21,000 meteorites have been collected from the Moon, Mars and more dozens of asteroid bodies
- NASA Curation cleans & assembles field sampling tools, collection bags, tags, and coordinates sample transportation and initial receiving of samples
- Restricted materials and well-developed protocols keep samples uncontaminated at time of collection, contained, and frozen to preserve sample integrity
Careful curation of meteorites enable key discoveries

- Martian meteorites – our only samples from Mars – provide a snapshot of Mars history (4.5 billion 165 MY)
  - Most samples have water in minerals - suggests water was present throughout much of Mars history
  - Key samples for discussion of life existing beyond Earth
- Meteorites are from a rich continuum of bodies – undifferentiated, differentiated planetesimals, asteroids, the Moon and Mars
- Carbonaceous chondrites contain primitive solar system & organic materials.
  - Provide constraints on condensation processes in early solar system
  - Suggest ubiquity of organic materials
Cosmic Dust from the Stratosphere

- Tons of dust grains fall into the atmosphere each day.
- NASA collects samples on collectors using high altitude aircraft.
  - Clean room protocols (ISO 5) and specialized sample handling techniques allow isolation and preservation of samples from comets, asteroids, and interstellar dust.
  - Collectors are archived as part of the collection.
  - Cosmic dust curation protocols has required the science community to develop skills for handling and analyzing very small particles (<<10 microns), enabling missions like Stardust.
  - Key studies provide insight into the nature and abundance of organic matter in primitive bodies in the solar system.
Genesis Mission demonstrates key benefits gained from early partnerships between mission team (engineers and science team) and curation scientists including collaboration on materials, cleaning, assembly, documentation & archival.

- Enabled science success despite hard landing
- Solar wind atoms provide a direct measure of solar composition and >99% of solar nebula material at the time of planet formation.
- Results have changed our understanding of early solar system processes – e.g. rocky planets were enriched in heavy oxygen, and Solar nitrogen is more like Jupiter.
Key Developments: Genesis Mission Technology

- Cleaned, assembled, closed-out science canister in an ISO Class 4 Cleanroom; used semiconductor grade ultrapure water (UPW)
- Mission planning and design; continued through recovery, receiving, and early science
- Mission Design
  - Collector material purity, cleanliness and variety
  - Thruster plume not in line-of-sight of exposed collectors
  - Re-entry filtration/sorbent during re-pressurization
- Genesis Reference Coupons
  - Enabled critical blanks for measurement of solar wind
  - Extensive cleaning and contamination testing
  - Experimental implants for assessing solar wind loss during surface cleaning
  - Complete environmental history documentation
Comet particles collected in aerogel collectors

Stardust revolutionized our understanding of the early solar nebula:

- Comet particles have materials formed at high (>1300 °C) & low (-243°C) temperatures, indicating large scale mixing in the early solar system.
- Comet particles are complex with very different minerals similar to chondritic meteorites, suggesting a comet-asteroid continuum.
- We collected **Interstellar particles** from outside our solar system

Science success enabled by development of contamination control plan and careful archival of witness plates and materials coupons
Key Developments: Stardust Mission Technology

- Assembly of convertible ISO Class 5 cleanroom
- Curation of spacecraft materials for contamination knowledge
- Advanced curation focused on sample handling
  - Detailed imaging of aerogel to locate tracks and particles
  - Extraction by keystoning aerogel with tracks
  - Sample handling and subdivision of extremely small (microns) and fragile samples embedded in aerogel to enable coordinated analyses
  - Subdivision and transport enabled collaborative analyses across disparate laboratories on individual particles
- Techniques leveraged from Cosmic Dust experience and applicable to future small particle collections
Advanced Curation Timeline
Progressive Development of Critical Curation Capabilities

**MISSIONS**
- Apollo
- ANSMET Meteorites
- Cosmic Dust
- Space Exposed Hardware
- Genesis
- Stardust
- Hayabusa (JAXA)
- Hayabusa II (JAXA)
- OSIRIS-REx
- Mars Icy Worlds, Etc

**CAPABILITIES**
- Curation EARLY in Apollo program
  - EVA hardware developed w. Curation
  - Vacuum gloveboxes, then dry N₂ cabinets
  - Precision inorganic contamination control
  - Organics-specific contamination control: Cleaning, validation, monitoring
- Curation part of early mission planning
  - ISO 4 Cleanroom
  - Cleaned spacecraft sample collection HW
  - Sample return capsule retrieved w. Curation
- Curation participation at start of US component
  - Carbon-rich sample handling
- Curation part of early mission planning
  - Archiving, removal, and sub-sectioning of grains in aerogel
- Early US Curation collaboration
  - Partnership w. foreign space agency for sample allocation
- Next Generation organic contamination control – sub-ng/cm² TOC
- Robotic sample handling and subdivision
- Cold samples
- Volatiles
- Planetary Protection level 5 sample handling

**Timeline**
- 1969
- 1977
- 1981
- 1985
- 2004
- 2006
- 2012
- 2020
- 2023
- ~2030

**Curation Highlights**
- Specialized sample handling techniques for isolation and preservation of tiny samples from comets, asteroids, and interstellar dust
- Clean collection, storage of 100s of samples/yr from deep-field Antarctica.
- Lunar Curation protocols adopted for field procedures.
New Initiatives in Astromaterials Curation

- Collaborate with mission teams on new high precision cleaning and validation techniques for sampling materials and witness plates
  - *Adventitious contamination* – especially carbon – is pervasive
  - *Cleanliness is technique dependent*: surface species v. total contaminants in surface volume
  - *Material composition and surface properties are critical*
- Achieving and maintaining increasingly high levels of cleanliness (organic and inorganic) for sampling devices and labs
  - Goal: enable methods of analyses for all elements and all relevant organic species
  - Work to date: baseline lab measurements, including particle counts and compositions; test plan for increased monitoring
New Initiatives in Astromaterials Curation

• Sample handling and containment challenges
  • 10-300 micron handling & precision subdivision procedures are required
  • Robotic sample handling, particulate cross contamination
  • Gas containment and extraction

• Cold curation research
  • Build requirements for cold containment and sample handling
  • Design tests related for preservation and handling of samples at extremely low temperatures (<-25°C)
New Initiatives in Astromaterials Curation

New examination & documentation tools

• Remote lab access - Networked cameras and microscope on Lunar Glovebox

• Non-destructive characterization: Detailed imaging in 3D – visible imaging of external surface and micro-CT imaging of interior

Left: Anaglyph Structure-From-Motion (SFM) 3D reconstruction of Apollo Lunar Sample 60639 produced from the high-resolution precision images. 60 micron resolution.
Right: MicroCT image of bencubbinte meteorite MIL07411,0
New Initiatives in Astromaterials Curation

Serving more and better data

- Curation database upgrades enabling broader access to imagery and meta-data associated with samples (curator.jsc.nasa.gov)

- Data recovery of legacy Lunar datasets, host these on database with access to IEDA/Earthchem/PetDB tools (www.earthchem.org)
Advanced Curation Elements for Mission Success

- NASA’s Astromaterials Acquisition & Curation Office has 5 decades of mission experience
  - End-to-end mission support and successful planning
  - Archival of diverse collections of astromaterials and associated hardware.
- Curation supports mission science, engineering & operations
  - Ensure that sampling and contamination concerns for any sample return mission are understood and integrated into a design with materials selection, seals and containment, precision cleaning, assembly and operational scenarios.
- Future mission challenges require new technologies
  - High precision cleanliness (new materials – new surfaces),
  - Sample collection-preservation-handling at low temperatures,
  - Preservation and subdivision of volatiles,
  - Precision sample subdivision of micron and sub-micron particles,
  - Possible collection and curation of samples from destination that could harbor life.
<table>
<thead>
<tr>
<th>Inorganic Cleanliness</th>
<th>Sample Handling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knowledge Gap:</strong> achieve and maintain high levels of inorganic cleanliness across the periodic table.</td>
<td><strong>Knowledge Gap:</strong> study handling; containment of astromaterials.</td>
</tr>
<tr>
<td><strong>Partnership Opportunities:</strong></td>
<td><strong>Partnership Opportunities:</strong></td>
</tr>
<tr>
<td>- High-precision cleaning &amp; validation methods</td>
<td>- Particulate &amp; cross-contamination research (organic/inorganic) contamination control</td>
</tr>
<tr>
<td>- New materials that are easy to clean</td>
<td>- Precision sample subdivision</td>
</tr>
<tr>
<td>- Keeping materials clean</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Organic Cleanliness</th>
<th>Robotics / Sample Handling Tech</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knowledge Gap:</strong> achieve and maintain high levels of organic cleanliness – below 1 ng/cm².</td>
<td><strong>Knowledge Gap:</strong> robotic sample handling solutions to control inorganic/organic contamination, planetary protection requirements, extreme environments.</td>
</tr>
<tr>
<td><strong>Partnership Opportunities:</strong></td>
<td><strong>Partnership Opportunities:</strong></td>
</tr>
<tr>
<td>- High-precision cleaning &amp; validation methods</td>
<td>- Robotic and astronaut handling hardware</td>
</tr>
<tr>
<td>- Cleanliness preservation</td>
<td>- Automated robotic sample handling</td>
</tr>
<tr>
<td>- Organic species detection/measurement</td>
<td>- Short &amp; long-term sample containment</td>
</tr>
<tr>
<td>- Microbial identification, curation, biocontainment</td>
<td>- Transport containers in space and on-Earth</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cold Curation</th>
<th>Mission Ops / Spacecraft Design</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Knowledge Gap:</strong> collect samples that have been preserved at sub-freezing or even cryogenic temperatures.</td>
<td><strong>Knowledge Gap:</strong> curation requirements for spacecraft HW, mission operations – materials, design, and ops procedures for maintaining contamination control.</td>
</tr>
<tr>
<td><strong>Partnership Opportunities:</strong></td>
<td><strong>Partnership Opportunities:</strong></td>
</tr>
<tr>
<td>- Cryogenic curation at 40 K</td>
<td>- Sample handling/collection/containment</td>
</tr>
<tr>
<td>- Low Temperature curation at – 25°C</td>
<td>- Sample return capsule (SRC) development</td>
</tr>
<tr>
<td>- Working with small particles at low T</td>
<td></td>
</tr>
</tbody>
</table>