Database for Aerosols on the International Space Station

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Outline

• Background
  • Aerosols in low gravity
  • Sampling method
  • Unique morphology
• Formation mechanism
• Aerosol sample data
• Particle database examples
• Conclusions
Aerosol Behavior in Low Gravity

• Historic quote from Scott Carpenter
  • One of the Mercury 7
  • The second American to orbit the Earth in 1962

• "Every time I opened up the (food) bag, the crumbs would come crowding out like a swarm of bees”
Aerosol Behavior in Low Gravity

• On Earth, our air quality is improved by gravitational settling
  • In μg, all particles remain airborne until deposited on surfaces, air inlet screens or ventilation system filters

• ‘Dusty air’ has been a complaint of astronauts
  • Indicates high concentrations of inhalable particles

• No particle measurement capability on ISS...yet

• Filter inlets and fan intakes on equipment require regular vacuuming
Aerosol Deposition

Clean Filter

12 days accumulation

Node 3

8 days accumulation

Node 1

8 days accumulation

Node 3

12 days accumulation

Node 1
Aerosol Deposition

'Dirty' air from Spacecraft Cabin

Aerosol Debris → Nomex Screen with 841 μm openings

Air gap

Filter Pleats
First step in characterizing ISS aerosols was sampling
  • Capture particles, bring samples back to Earth for analysis

Aerosol Sampling Experiment funded by Life Support Systems Project
  • December 2016
  • July 2018
Passive Sampling without Gravity
Aerosol Deposition

‘Dirty’ air from Spacecraft Cabin

Aerosol Debris

Nomex Screen with 841 µm openings

Air gap

Filter Pleats

Passive collection surface
Passive Sampler

• Five individually bored, separately sealed collection ‘drawers’
• Drawers open, collect debris, and are closed to protect sample from contamination
• Aluminum block substrate with 2-way sticky carbon tape
  • Block fits in electron microscope
Aerosol Sampling Experiment

• The optimal sampling duration to get the best particle coverage for microscopic analysis varies by location

• Five substrates provided different particle loadings to choose from as well as redundancy to reduce risk

• The operations in Increment 50/51 collected particles for 2, 4, 8, 16 and 32 days
  • Ideal samples for microscopy were mostly in the 16 and 32-day durations

• Operations in Increment 56 collected particles for 26 days on all substrates
  • Better statistics
  • Less crew time
Passive Sampler Deployments

2016 deployment, between day 8 and day 16

2018 LAB1PD3 US Lab Bay 3

2018 NOD3F3 HEPA Register

2018 NOD2D3 Midbay HEPA Return Register
Passive Sampler Microscopy

• A montage for each passive sample was created by combining fields of high-resolution SEM backscattered-electron images*

*Microscopy was performed through a subcontract with RJ Lee Group
Fiberglass, straight

Metals, bright white

Lint Fibers, curved & overlapping

Carbon particles & low z elements, gray-scale
Carbonaceous Particle Analysis

- Passive sampler in US Lab
- All non-fibrous individual particles >5µm
- Weight % concentrations by particle class

The majority of the particles are carbon-based. Metals are a small portion but easiest to analyze...see slide 23
Unique Particle Morphology

• ISS samples had many multi-component particles
  • Individual metal particles embedded in a carbonaceous matrix

• Presents challenges for counting particles by image analysis
  • Must distinguish edges to outline individual particles based on contrast thresholds
  • Fibers were a challenge as well
Multi-Component Particle

Pb-Cu Particle

Cu-S Particles

Area Scan of Structure

Copper/lead-rich particles and copper/sulfur-rich particles associated with carbonaceous material
Formation Mechanism?

• Did many individual particles agglomerate after becoming airborne on ISS?
• Were the parent materials composites to begin with?
• Astronaut Don Pettit performed some “informal particle aggregation experiments” in plastic bags on ISS in 2003, 2008 and 2011*
  
  • CAPCOM/astronaut Stanley Love recognized these experiments could be representative of planetary accretion

Several types of particle materials were mixed in different types of bags in microgravity

- Particles between 100 and 7000 micrometers (7 mm)
- Salt, sugar, coffee, meteorite particles, acrylic and glass beads

Some particles aggregated with strong cohesion

- Low number densities
- On the order of seconds

Smaller particles aggregated more quickly and with higher cohesive strength

Angular particles aggregated readily whereas round smooth particles did not

Overall, electrostatic forces dominated the process
Possible Formation Mechanism of ISS Cabin Aerosols

• The particle sizes in Don’s experiments are similar to the passively sampled metal particles

• State of charge of ISS particles?
  • Mechanically generated particles are more likely to have high levels of charge
  • Sodium chloride and polymeric aerosols are more likely to exist in a charged state than conducting materials

• These informal experiments indicate that agglomeration is a plausible formation mechanism of the multi-component particles on ISS
Cadmium-rich potential wear particle containing lesser amounts of zinc and chlorine.

Nickel-rich particles on the surface of carbonaceous material.

Cadmium-rich inclusions containing a trace amount of zinc embedded in a carbonaceous particle.

Zinc/cadmium-rich material.
Unique Particle Agglomerate

Mechanically generated wear particle, rich in cadmium and containing lesser amounts of zinc and chlorine

Nickel-rich particles on the surface of carbonaceous material

Cadmium-rich inclusions containing a trace amount of zinc embedded in a carbon matrix

Zinc/cadmium-rich material

Sampled in Node 3
Sample Analysis Technique

• Computer-Controlled SEM (CCSEM)
  • IntelliSEM* software

• Bright metal particles within complex structures were analyzed *individually*
  • Atomic number titanium and higher (bright enough)

• The result was not total particle counts, but rather a characterization of metal inclusions in larger multi-component particles

• CCSEM metals analyses created a large dataset
  • Geometry and elemental composition

*IntelliSEM was performed through a subcontract with RJ Lee Group*
Data Source: IntelliSEM Workbench

Barium chromium-rich particle

EDS Spectrum and counts

Multi-component particle with many individual metal particles in a carbon matrix

Statistics of elements present in the metal particles analyzed
Particle classes rules were defined to categorize CCSEM results based on relative abundance of elements in the sample and frequently occurring combinations of these elements.

**Ag-rich Particle Class Example in IntelliSEM**

**Single Particle EDS Results**

<table>
<thead>
<tr>
<th>Element</th>
<th>Ag</th>
<th>Bi</th>
<th>Br</th>
<th>Ca</th>
<th>Cl</th>
<th>Cm</th>
<th>Cu</th>
<th>Fe</th>
<th>K</th>
<th>Mg</th>
<th>Mn</th>
<th>Na</th>
<th>P</th>
<th>Pb</th>
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<th>Si</th>
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<th>Zn</th>
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<tr>
<td>%</td>
<td>71</td>
<td>14</td>
<td>14</td>
<td>16</td>
<td>9</td>
<td>1</td>
<td>2</td>
<td>2</td>
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<td>2</td>
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<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Example from US Lab, sampler deployed for 26 days in 2018**

Graphic representations of abundance of Ag in individual particles
ISS Particle Database

• Collaboration with aerosol scientist Dr. Meytar Sorek-Hamer and Irina Hallinan at NASA Ames Research Center

• Database of the IntelliSEM results
  • R programming language, ‘Shiny’ software package

• 2016 Experiment 5738 particles

• 2018 Experiment 54,477 particles
Titanium and higher atomic numbers identified in analysis

Database tells which are statistically significant
Gold on ISS - 2018

0.2 % of all particles (by weight) contain some gold

41 in sleep and docking area

Many are ~70% gold by weight
Silver on ISS - 2018

9.8% of all particles (by weight) contain some silver

~2000 in eating area with nearly 80% silver by weight

3300 in exercise and hygiene area are 30% silver (mean weight %)
Silver on ISS - 2018

From Node 1 - Eating Area
Silver on ISS - 2018

From Node 1 - Eating Area
From Node 1 - Eating Area

<table>
<thead>
<tr>
<th>Energy [keV]</th>
<th>View field: 105 µm</th>
<th>WD: 12.94 mm</th>
<th>SEM MAG: 3.95 kx</th>
<th>Det: BSE</th>
<th>20 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>cps/eV</td>
<td>SEM HV: 20.0 kV</td>
<td>Est. Beam: 1.6 nA</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MIRA3 TESCAN
RJLee Group, Inc.
Silver on ISS - 2018

From Node 1 - Eating Area
Silver on ISS - 2018

From Node 3 –
Exercise & Hygiene Area

View field: 147 µm  WD: 11.70 mm
SEM MAG: 2.35 kx  Det: BSE  20 µm
SEM HV: 20.0 kV  Est. Beam: 1.6 nA

MIRA3 TESCAN
RJLee Group, Inc.
ISS Bromine Particles

- Both smooth and angular morphologies
- Diameters of bromine particles in agglomerates ranged from 5 to 100 micrometers

### 2016 Sampling Statistics

<table>
<thead>
<tr>
<th>Passive Sampler</th>
<th>Location</th>
<th>Sample Duration, days</th>
<th>% Bromine Particles, by Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-16</td>
<td>Node 1 Deck 1</td>
<td>16</td>
<td>0.5</td>
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<tr>
<td>D-16</td>
<td>Node 3 Deck 3</td>
<td>16</td>
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<tr>
<td>E-32</td>
<td>PMM</td>
<td>32</td>
<td>0</td>
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<tr>
<td>F-32</td>
<td>Node 2 Deck 2</td>
<td>32</td>
<td>9.3</td>
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<tr>
<td>G-8</td>
<td>Node 3 Forward 3</td>
<td>8</td>
<td>1.7</td>
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<tr>
<td>J-32</td>
<td>US Lab Bay 1</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>K-16</td>
<td>US Lab Bay 3</td>
<td>16</td>
<td>1.2</td>
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</tbody>
</table>

Sources in Nodes 2 and 3
Choose Plot Variables:
- Elemental composition
- Size
- Roundness
- Relative abundance
- ISS location
- Proportion of all particles by weight percent
In Node 2, for Bromine-containing particles, the median weight % was consistently around 80%.

78787 analyzed particles, 2236 contained Bromine (2.8%)
Randomly oriented rod-like bromine particles are distributed over a carbon matrix.

Possibly abraded or fractured from a plastic parent material that contains bromine fire retardant dispersed in the carbon matrix.
• Round morphology does not indicate mechanical abrasion

• May be representative of a homogeneous solid-phase fire retardant that was added to a raw material along with other additives
Spherical Particles

126 Particles with Roundness > 0.9
Spherical Particles

From Node 3 – Exercise & Hygiene Area

View field: 177 μm
WD: 11.83 mm
SEM MAG: 1.95 kx
Det: BSE
SEM HV: 20.0 kV
Est. Beam: 1.6 nA

Si - Ca
Spherical Particles

From Node 3 – Exercise & Hygiene Area

*Image analysis cannot capture this as a sphere because the lint fiber ‘cuts’ it in half*

**Ba – Ti - Ca**
Spherical Particles

126 Particles with Roundness > 0.9

Fe – Rich
6 μm Fe - Rich
Conclusions

• Plausible ISS particle formation mechanism of complex particles
  • Agglomeration by electrostatic forces

• Extensive data set of individual metal inclusions in particles sampled in 2016 and 2018

• Searchable database can explore particles by
  • Elemental composition
  • Size
  • Roundness
  • Relative abundance by ISS location
  • Proportion of all particles by weight percent

• Working on making the database publicly available
Backup Slides
Sampling Locations
Definitions ASTM F1877-16

Standard Practice for Characterization of Particles

• *agglomerate, n*—a jumbled mass or collection of two or more particles or aggregates, or a combination thereof, held together by relatively weak cohesive forces caused by weak chemical bonding or an electrostatic surface charge generated by handling or processing.

• *aggregate, n*—a dense mass of particles held together by strong intermolecular or atomic cohesive forces that is stable with normal mixing techniques, including high-speed stirring and ultrasonics.

• *roundness (R), n*—a measure of how closely an object represents a circle
  • The $R$ varies from zero to one in magnitude with a perfect circle having a value of one

$$R = \frac{(4A)}{\pi \left( d_{\text{max}} \right)^2}$$

where: $A = \text{area}$, and $d_{\text{max}} = \text{the maximum diameter}$