M-Type asteroids: primitive, metallic, or both?

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The M-Type Asteroids

- M-types are the moderate-albedo group of the spectrally degenerate X taxon
- Many have a 3-μm hydration feature (e.g., Rivkin et al. 2000, Landsman et al. 2015)
- Most have weak silicate features at 0.9 μm ± 1.9 μm (e.g., Fornasier et al. 2010, Hardersen et al. 2011)
- Many have elevated radar albedos, suggesting high surface density (e.g., Neeley et al. 2014, Shepard et al. 2015)
Previous Work (Landsman et al. 2015)

- Studied 6 M-types in the 2 – 4 μm region using the IRTF
- Evidence for a 3-μm hydration feature on all 6, with band depths from ~4 – 8%
- Diversity in the shape of feature among the asteroids
M-types in the Mid-Infrared

- Thermal modeling allows insight into surface properties of asteroids
  - Albedo, thermal inertia, surface roughness, etc.
- Emissivity spectra contain information about mineralogy and grain size
- This project:
  - Perform thermophysical modeling on 5 – 40 μm Spitzer InfraRed Spectrograph (IRS) spectra of M-type spectra
  - Also look at emissivity spectra
  - Focus on asteroids well-characterized at other wavelengths
Emissivity Spectra
## Preliminary TPM Results

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Our TPM</th>
<th>Previous TPM work</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R (km)</td>
<td>Γ (SI units)</td>
</tr>
<tr>
<td>(16) Psyche</td>
<td>140 ± 40</td>
<td>80 ± 80</td>
</tr>
<tr>
<td>(21) Lutetia</td>
<td>65 ± 5</td>
<td>10 ± 10</td>
</tr>
<tr>
<td>(77) Frigga</td>
<td>45 ± 5</td>
<td>&lt;10</td>
</tr>
<tr>
<td>(135) Hertha</td>
<td>75 ± 5</td>
<td>&lt;10</td>
</tr>
<tr>
<td>(136) Austria</td>
<td>18 ± 2</td>
<td>&lt;10</td>
</tr>
<tr>
<td>(216) Kleopatra</td>
<td>145 ± 5</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>

Conclusions and Future Work

- We are using Spitzer spectra (5 – 40 μm) to better constrain the composition of M-type asteroids.
- Initial emissivity spectra show signatures of silicates on the entire sample so far.
- Initial thermal inertias are typical for main-belt asteroids.
- Still a work in progress – we’re running more complex models and improving precision of derived quantities.

Sincere thanks to NASA and the SBAG Steering Committee for Early Career Travel Support!
Backup Slides
Thermal Inertia vs. Diameter for various asteroid classes

Fig. 9 from Delbo et al. in Asteroids IV

Fig. 9.— $\Gamma$ values vs. $D$ from Tab. 2 for different taxonomic types (see key). Top plot: original measurements, bottom plot: $\Gamma$ corrected to 1 au heliocentric distance for temperature dependent thermal inertia assuming Eq. 13 and the heliocentric distance at the time of thermal infrared observations reported in Tab. 2. Trojans, Centaurs and trans-Neptunian objects are not displayed.
Spitzer IRS spectrum of M-type (136) Austria, well fit by thermophysical models with $\varepsilon=0.9$ (red), 0.7 (blue), or 0.5 (green).

\[ \Gamma = 10 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2} \]

\[ \varepsilon = 0.9 \]

\[ \Gamma = 100 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2} \]

\[ \varepsilon = 0.5 \]
### Preliminary TPM Results

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>$\varepsilon=0.9$</th>
<th>$\varepsilon=0.7$</th>
<th>$\varepsilon=0.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R$ (km)</td>
<td>$\Gamma$ (SI units)</td>
<td>$R$ (km)</td>
</tr>
<tr>
<td>(16) Psyche</td>
<td>122 - 188</td>
<td>0 - 160</td>
<td>127 - 200</td>
</tr>
<tr>
<td>(21) Lutetia</td>
<td>65 - 66</td>
<td>0 - 20</td>
<td>60 - 70</td>
</tr>
<tr>
<td>(22) Kalliope</td>
<td>-</td>
<td>-</td>
<td>136 - 143</td>
</tr>
<tr>
<td>(55) Pandora</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(69) Hesperia</td>
<td>-</td>
<td>-</td>
<td>117 - 125</td>
</tr>
<tr>
<td>(77) Frigga</td>
<td>45 - 45</td>
<td>&lt;10</td>
<td>44 - 49</td>
</tr>
<tr>
<td>(135) Hertha</td>
<td>76 - 77</td>
<td>&lt;10</td>
<td>74 - 81</td>
</tr>
<tr>
<td>(136) Austria</td>
<td>18 - 20</td>
<td>&lt;100</td>
<td>19 - 23</td>
</tr>
<tr>
<td>(216) Kleopatra</td>
<td>134 - 144</td>
<td>&lt;10</td>
<td>114 - 126</td>
</tr>
<tr>
<td>(337) Devosa</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Thermophysical Model

- See Emery et al. 2006, Emery et al. 2014 for details
- Surface roughness implemented as spherical section craters of half-opening $\gamma$ and fractional crater coverage $f$
  - See also Emery et al. 1998
- Solve heat diffusion equation using the Crank-Nicholson finite-difference method
- Use Brent’s method (Brent 1973) for $\chi^2$ minimization
Potential M-type Asteroid Analogs

- Iron meteorites
  - Enstatite chondrite
  - CR/CH chondrites

- Stony-irons
  - Low inferred metal content
  - Weak or non-existent silicate bands
  - Examples (Neeley et al. 2014):
    - 21 Lutetia
    - 135 Hertha

- CB chondrites
  - Moderate to high inferred metal content
  - Weak or non-existent silicate bands
  - Examples (Neeley et al. 2014):
    - 16 Psyche
    - 216 Kleopatra

- Enstatite chondrite
  - CR/CH chondrites

- Low inferred metal content
  - Weak or non-existent silicate bands
  - Examples (Neeley et al. 2014):
    - 21 Lutetia
    - 135 Hertha
## Radar Studies

<table>
<thead>
<tr>
<th>Tholen Class</th>
<th>Radar Albedo ($\sigma_{oc}$)</th>
<th>Range</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>$0.127 \pm 0.050$</td>
<td>$0.179$</td>
<td>2</td>
</tr>
<tr>
<td>G</td>
<td>$0.084 \pm 0.042$</td>
<td>$0.109$</td>
<td>5</td>
</tr>
<tr>
<td>F</td>
<td>$0.093 \pm 0.055$</td>
<td>$0.148$</td>
<td>6</td>
</tr>
<tr>
<td>PD</td>
<td>$0.090 \pm 0.049$</td>
<td>$0.161$</td>
<td>9</td>
</tr>
<tr>
<td>S</td>
<td>$0.140 \pm 0.044$</td>
<td>$0.184$</td>
<td>2</td>
</tr>
<tr>
<td>M (Magri et al. 2007)</td>
<td>$0.255 \pm 0.170$</td>
<td>$0.527$</td>
<td>7</td>
</tr>
<tr>
<td>M (Neeley et al. 2014)</td>
<td>$0.30 \pm 0.07$</td>
<td>$0.430$</td>
<td>1</td>
</tr>
</tbody>
</table>

| All | $0.131 \pm 0.076$ | $0.561$ | 8 |

Shepard et al. 2010: Laboratory studies show radar albedo is primarily a function of surface bulk density. ~1/3 of M-types have radar albedos $> 0.4$, consistent with $\rho_{\text{bulk}} = 3.8 \text{ g/cm}^3$ (corresponds to iron-nickel with porosity of 50%)
Distribution of 3-micron feature shapes (Takir & Emery, 2012)

Grimm & McSween (1993) heliocentric zones with 3-μm feature shapes

Schörghofer 2008: Buried ice can survive ~10^9 years on dusty surfaces
Origin of Hydration on M-types

**Exogenic**
- Delivered by impacts of CM-like material?
- Solar wind interactions?

**Endogenic**
- CR2 Chondrites? Cloutis et al. 2011:
  - Moderate reflectance
  - Weak silicate bands
  - Red slopes
  - Phyllosilicates present, but no 0.7-µm feature
2 – 4 μm Results: Hydration on 6/6