Thermal Infrared Spectral Comparisons of Minerals and Asteroids in Relation to the Frost Line

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Introduction: Throughout history, asteroids have often gone through collisions, causing some to migrate throughout the solar system. By looking at whether or not asteroids have hydrated or anhydrous minerals, the formation location of an asteroid could be inferred in reference to the frost line. Asteroids that formed outside the frost line, the distance from the Sun at which water could condense into ice during solar system formation, are more likely to contain hydrated minerals, including phyllosilicates such as lizardite. Asteroid emissivity spectra indicate asteroid composition based on emitted wavelengths of light. Asteroid spectra in the mid-infrared range have not yet been explored in depth, so in our research, we analyzed mid-infrared spectra of asteroids throughout the asteroid belt for indications of dry and wet silicates and attempted to draw connections between the location of asteroids in the main belt and the presence of hydrated and anhydrous minerals.

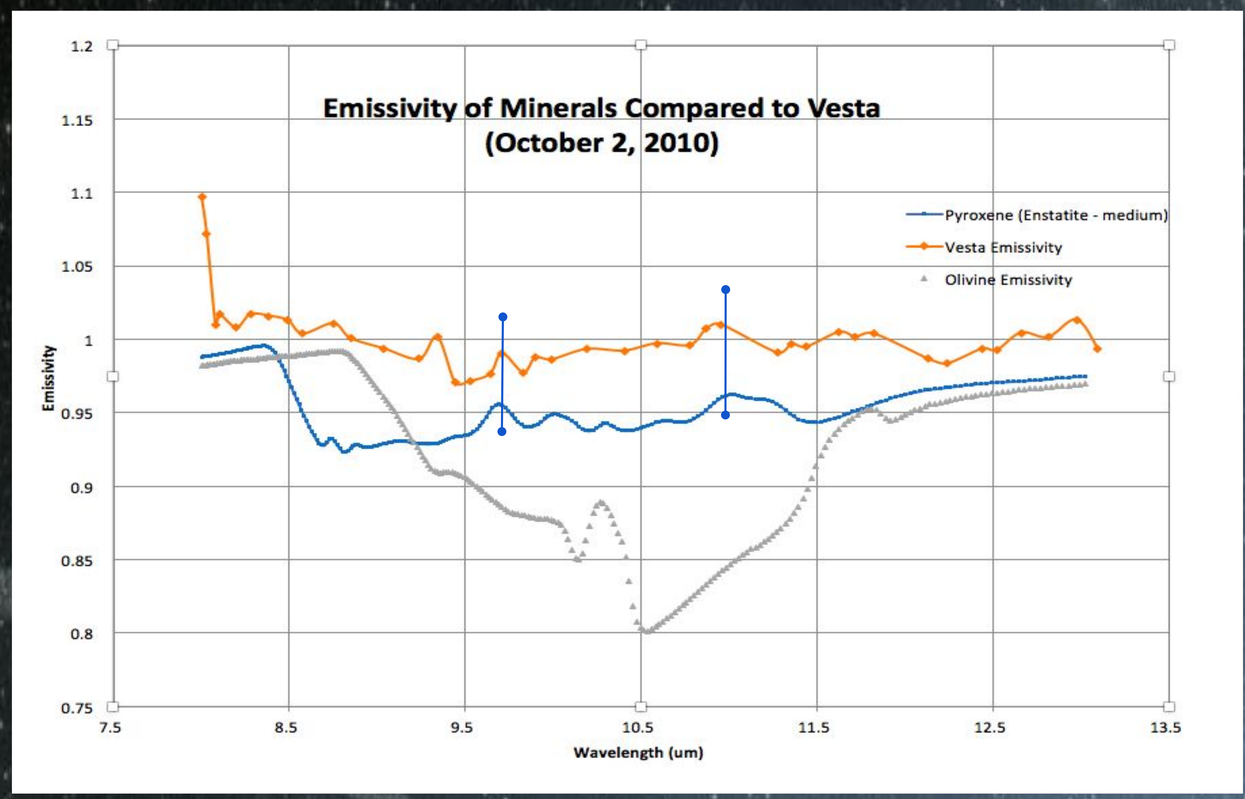
Methods: Emissivity spectra of asteroids in the mid-infrared (8 - 13 um) were obtained from previous telescopic studies using Palomar Observatory[1] and Spitzer Space Telescope [2]. This data for each of eleven asteroids was digitized and plotted along with the emissivity of the minerals: pyroxene (coarse (74-250 um particle size) and medium (45-125 um particle size) enstatite ($Mg_2Si_2O_6$)), olivine (Fo92(Fe2+,MG)SiO_4), serpentine ($(Mg,Fe^{2+},Ni)Si_2O_5(OH)_4$), and lizardite ($Mg_3Si_2O_5(OH)_4$). Mineral reflectance spectra were obtained from the ASTER Spectral Library and converted to emissivity (1-reflectance). These minerals were chosen because they are commonly found in asteroid spectra. Pyroxene and olivine are anhydrous and serpentine and lizardite are hydrated minerals. The asteroid spectra were compared to the mineral spectra to attempt to identify similarities (peaks due to fundamental vibrations in the minerals' crystal lattice) which were determined by eye. Conclusions about the asteroids' location during formation were drawn based on the asteroid's mineral composition.

Asteroids are assigned to asteroid spectral types based on their spectrum, color, and sometimes albedo. C-, V- and S-type asteroids are three common spectral types. C-type asteroids are carbonaceous, V-type asteroids or vestoids are asteroids with spectral types like Vesta's, and S-type asteroids are asteroids with high silica content. Below is background research about each asteroid and minerals this study observed in their spectra[4]:

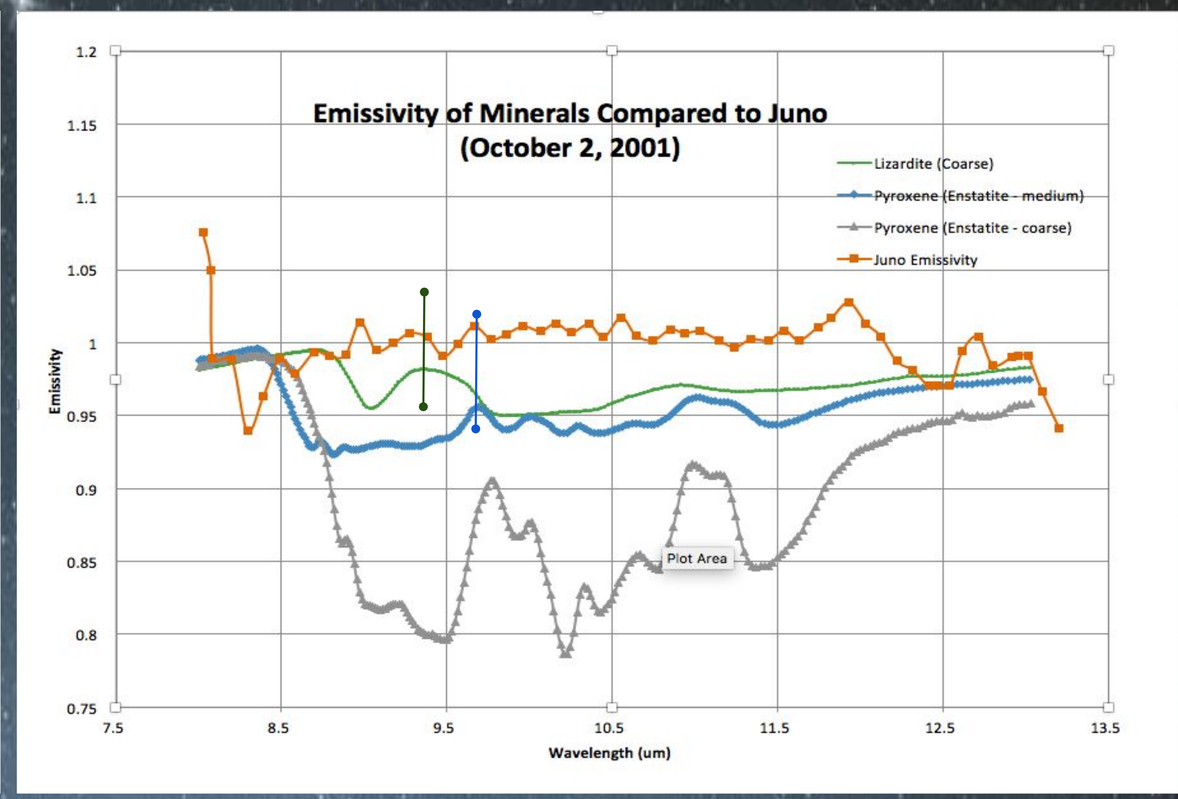
Asteroid	Location	Distance from Sun (AU)	Class	Composition Notes	Spectra Comparisons
4 Vesta[1]	Main Belt	2.3618	V-Type	Metallic iron-nickel core with olivine mantle. Surface dominated by pyroxenes. Rocky mantle. Progenitor of HED meteorites.	Pyroxene and olivine
3 Juno[1]	Main Belt (Juno clump)	2.671	S-Type	High albedo. Iron bearing silicates pyroxene and olivine. Progenitor of chondrites	Pyroxene and lizardite

Ice-Snow Line

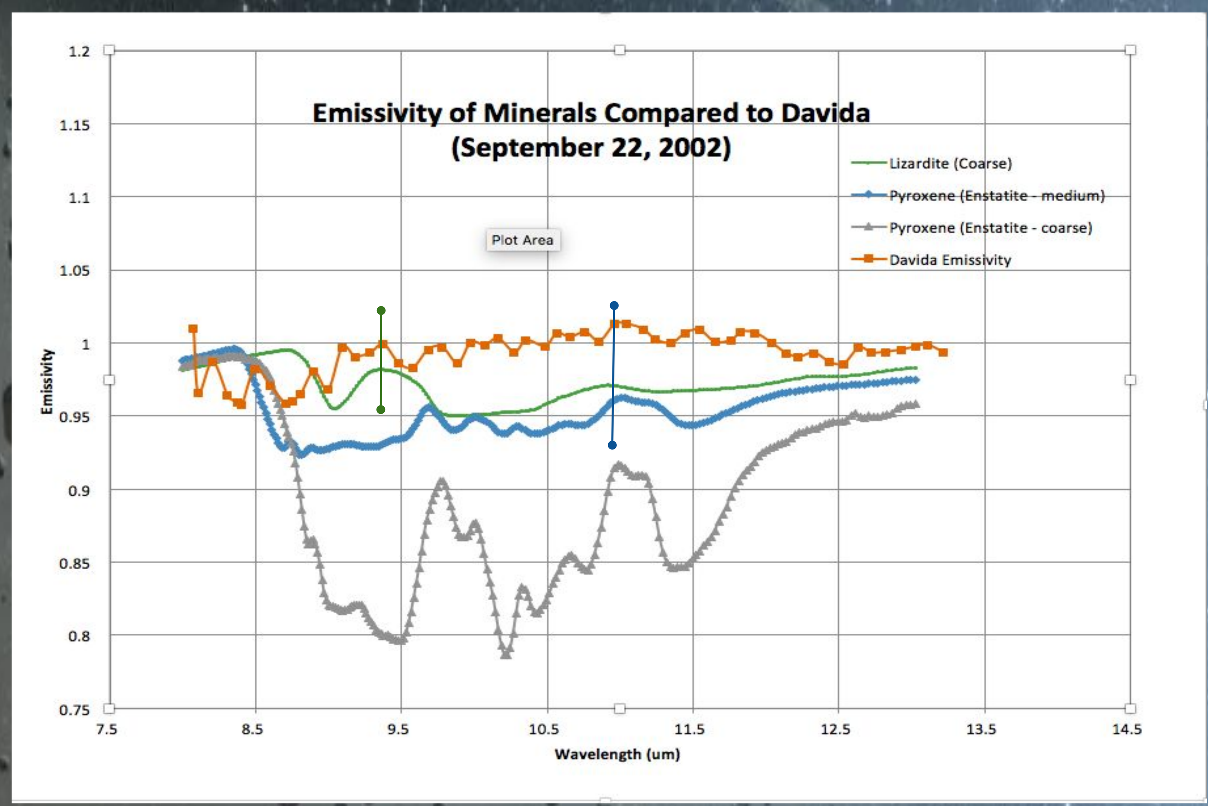
1 Ceres[1]	Main Belt	2.7675	C- Type	Differentiated (rocky core, icy mantle - hydrated minerals - carbonates and clay). Contains carbonate minerals.	Pyroxene and lizardite
2 Pallas[1]	Main Belt (central)	2.7716	B-Type	surface composed of silicates (olivine and pyroxene), resembles carbonaceous chondrite meteorites. Looks like it went through partial differentiation - protoplanet	Possibly lizardite. No pyroxene.
492 Gismonda[2]	Outer belt (Themistian)	3.1136	C-Type	composition believed to be similar to that of carbonaceous chondrites	No pyroxene. Possibly lizardite.
526 Jena[2]	Outer belt (Themistian)	3.1218	C-Type	composition believed to be similar to that of carbonaceous chondrites	Pyroxene and lizardite
10 Hygiea[1]	Main belt (outer)	3.1421	C-type	Dark, probably primitive carbonaceous materials surface	Possibly pyroxene, Possibly lizardite
383 Janina[2]	Main belt (outer)	3.1442	C-Type	Probably composed of primitive carbonaceous chondritic material	No pyroxene No lizardite
511 Davida[1]	Main belt (outer)	3.1647	C-type	Dark, carbonaceous chondrite	Pyroxene and lizardite
65 Cybele[2]	Main Belt (outer)	3.4283	D,P, and C-Type	Surface is fine anhydrous silicate grains with a small amount of water ice and complex organic solids.	No pyroxene. Possibly lizardite.
624 Hektor[2]	Jupiter Trojan	5.2561	D-type	Dark, might be coated in tholins from solar radiation	No conclusion



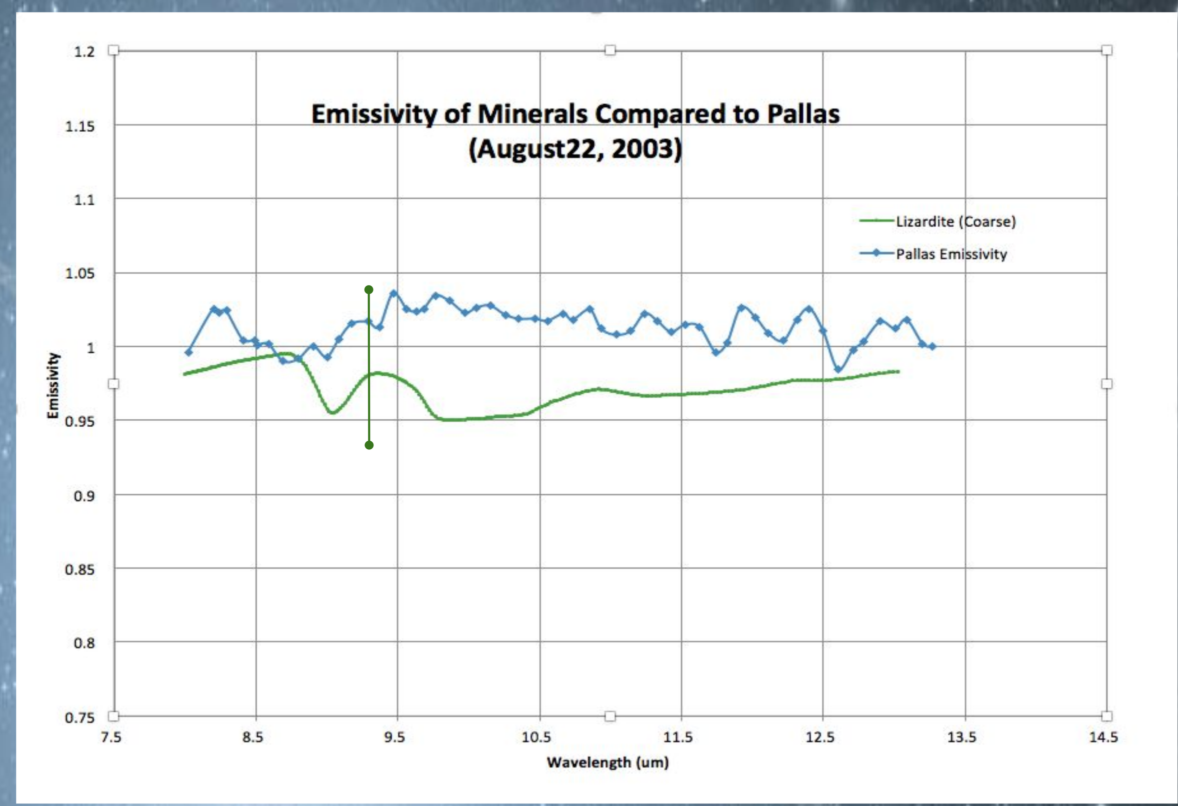
Vesta's spectra matches pyroxene (medium) with peaks at 9.3 um and at 11.0 um. This is the only asteroid in which olivine might be apparent.



Juno's spectral shape at 9.3 um matches lizardite. A peak at 9.7 um matches coarse pyroxene.



Davida's spectra matches lizardite at 9.7 um and matches pyroxene at 11.02 um.



Pallas's spectra has a peak at 9.3 um which could correspond to lizardite. No correlation to pyroxene is seen.

Conclusions: Because the emissivity spectra of asteroids in the mid-infrared are so flat (very low spectral contrast), it is difficult to draw any comparisons between the spectra of the minerals and the asteroid spectra. We observed possible correlations leading to the following conclusions. Further investigation could attempt to normalize the mineral spectra in order to compare them on the same scale as the asteroid spectra. Other forms of pyroxene and other phyllosilicates could also be used for comparison.

- Features of pyroxene and lizardite were observable in most of the mid-infrared spectra of the asteroids studied, however we were unable to detect serpentine or olivine in most of them based on their mid-infrared spectra.
- The spectra of 3 Juno indicated the presence of lizardite, even though it is currently located inside the frost line. This asteroid therefore may have formed outside the frost line and migrated inward.
- The spectrum of 383 Janina shows no presence of lizardite, indicating that Janina likely formed inside the frost line and migrated outward.
- The spectra of 2 Pallas and 65 Cybele showed no presence of pyroxene, probably due to their low albedo.
- The spectral contrast in the asteroids' spectra is a closer match to the medium grain enstatite than to the coarse grain enstatite in all examples indicating that the particle size of each asteroid's surface are likely in the 45-125 um range.

References:

1. Lim, L. F., McConnochie, T. H., Bell, J. F., III, & Hayward, T. L. (n.d.). *Thermal infrared (8-13 um) spectra of 29 asteroids: The Cornell Mid-Infrared Asteroid Spectroscopy ("MIDAS") Survey*. Unpublished working paper, Cornell University, Ithaca, NY.
2. Licandro, J., et al (2012). 5-14 μm Spitzer spectra of Themis family asteroids. *Astronomy & Astrophysics*. https://doi.org/10.1051/0004-6361/201118142
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4. Information sourced from Wikipedia articles on each asteroid

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