The Promise of JWST for Asteroid Studies

Exploring the Universe with JWST-II

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Montreal

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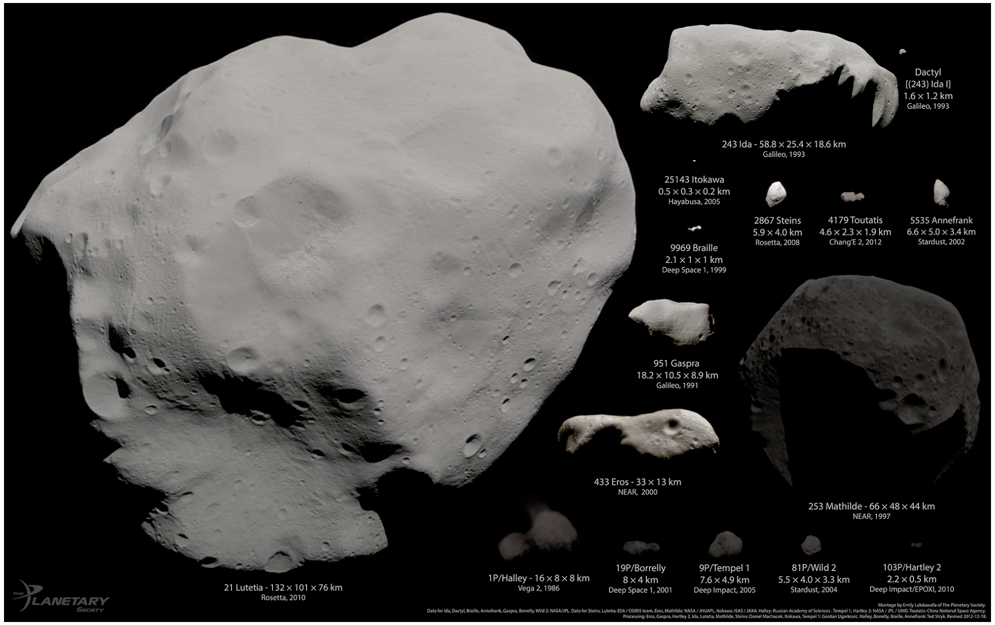
- **Asteroids/planetary embryos important for understanding planetary formation, planetary migration, delivery of water/organics**
- **Not observable in exosystems but must be there**
  - **Observe dust**
- ***Tripod of planetary astronomy, missions, meteorites***
  - ***Meteorite delivery from large asteroids***
  - ***Big diversity of objects***
- **JWST time precious**
  - **Big population studies not going to happen**
  - **Targeted objects**
  - **HST for asteroids?**
- ***Segue into looking at large asteroids***
- ***Segue into asteroid families***
- ***Segue into NEOs***
- ***Include specific discussion of GTO proposals/ERS expectations?***

The Appeal of Asteroids

- **Preserve evidence of conditions early in solar system history**
  - **Physical/geochemical**
  - **Dynamical/positional**
- **Retain wide variety of compositions**
  - **Igneous to pristine**
  - **Water- and organics-poor to -rich**
- **Presumably present in exosystems**
  - **But need to observe them here!**
- **(Non-science reasons to be interested, as well)**



Montage by Emily Lakdawalla, Planetary Society
Image data from NASA, ESA, JAXA…

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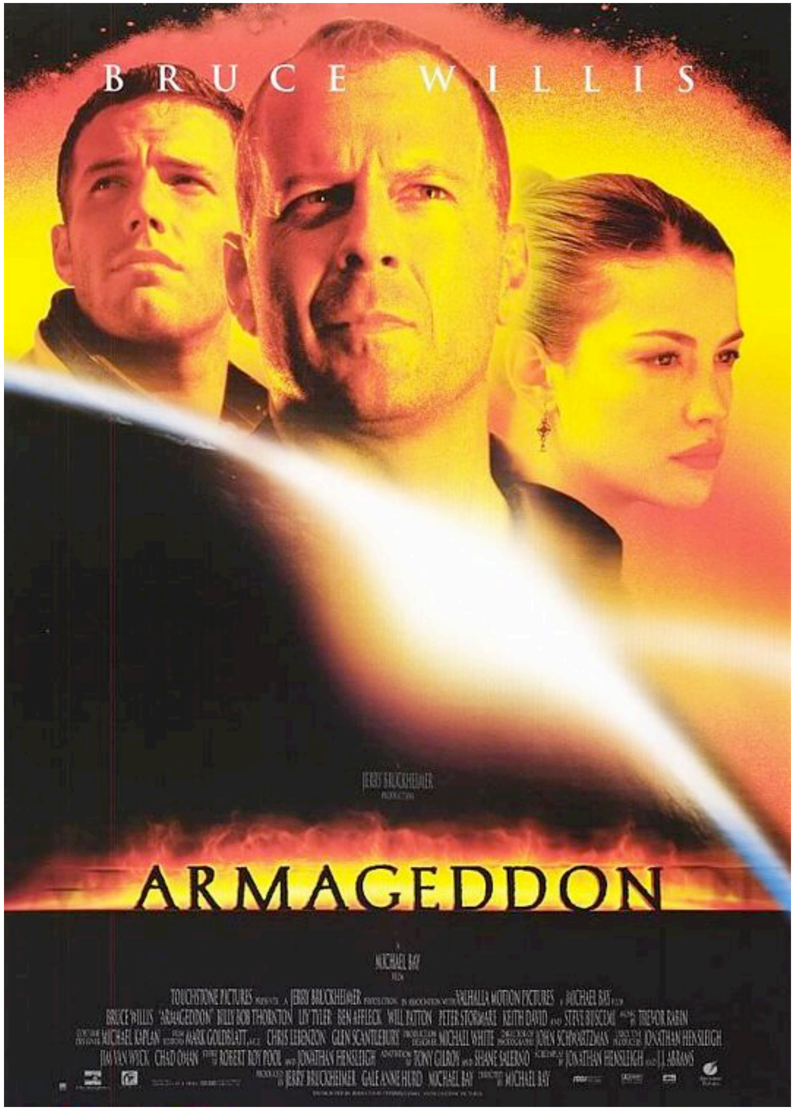
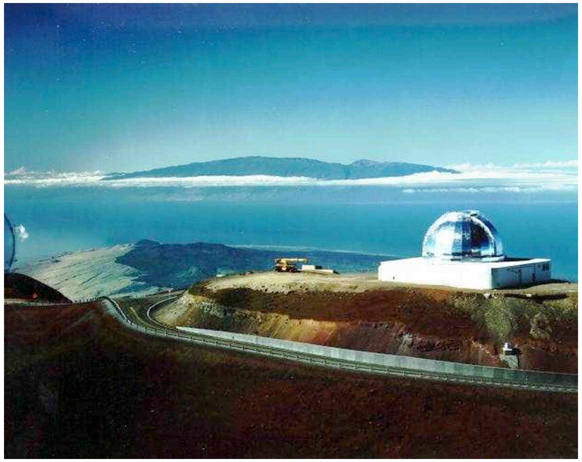


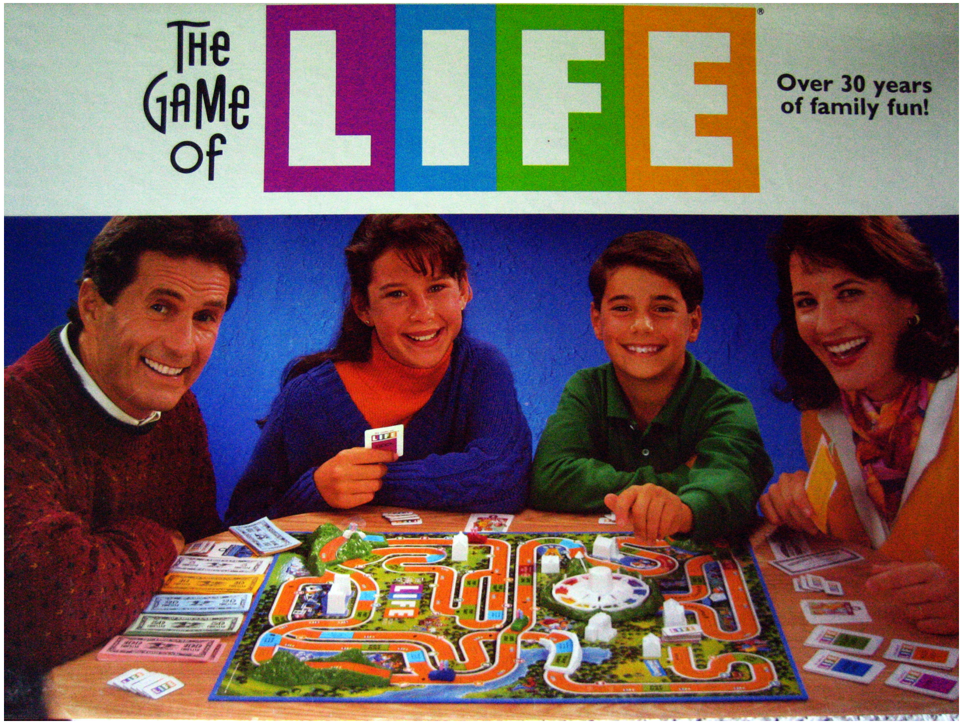
The "Tripod" of Asteroid Data

- **Spacecraft Missions**
  - Collect highest-quality data
  - Only way to measure some things
  - (Relatively) expensive, infrequent
  - Not all objects equally accessible
- **Meteorites**
  - Use cutting-edge technology
  - Wide variety of material
  - Dependent upon luck for delivery
  - Unrepresentative of asteroid population?
- **Planetary Astronomy**
  - Utilize wide range of wavelengths, techniques
  - Observe objects not in meteorite collection



Stages of Asteroid Evolution

- Formation as 100-km scale objects through pebble accretion
- Planetary migration scatters objects into (and out of?) asteroid region
- Objects experience processes such as aqueous or thermal alteration
- Some objects suffer large or catastrophic impacts, create collisional/dynamical families
- Collisional grinding continues, sufficiently small objects move via non-gravitational forces into resonances and become planet-crossing
- Some planet-crossers impact terrestrial planets, others eventually impact Sun

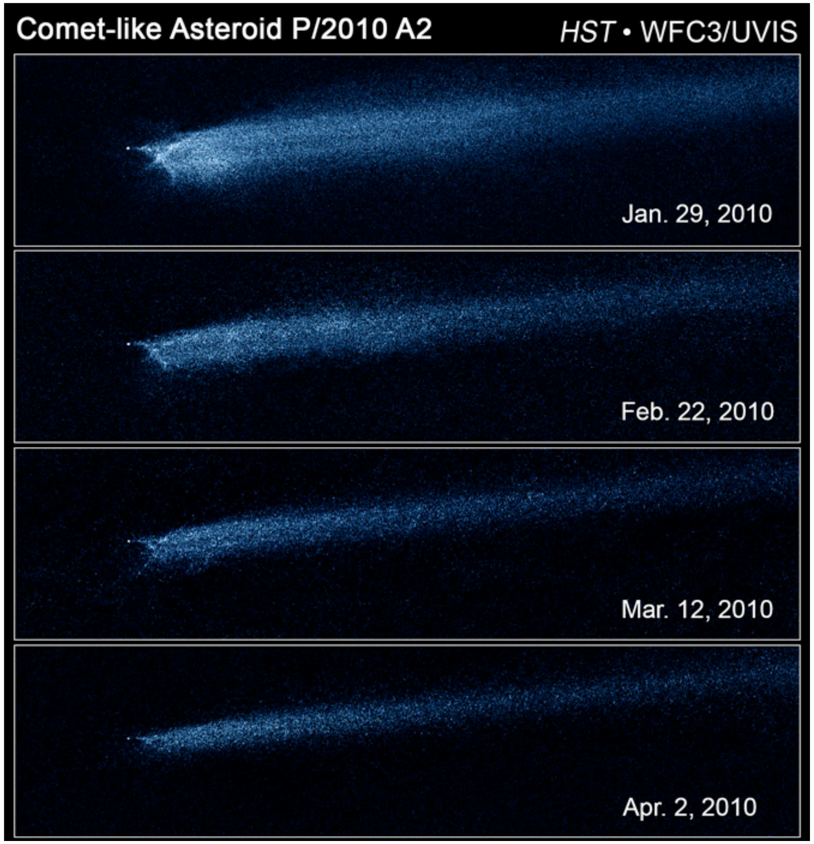


Optimally Using JWST for Asteroid Science

- Concentrate on special objects
- Observe “typical” objects
- Focus on spectral ranges unobtainable from the ground
- Large “big data” projects are out
- Observations needing long observing periods are probably out

Asteroid Science Highlights from HST

- **Observations of Active Asteroids**
- **Multi-spectral imagery of Vesta, Ceres**
- **Binary asteroid observations**



Jewitt et al (2011)

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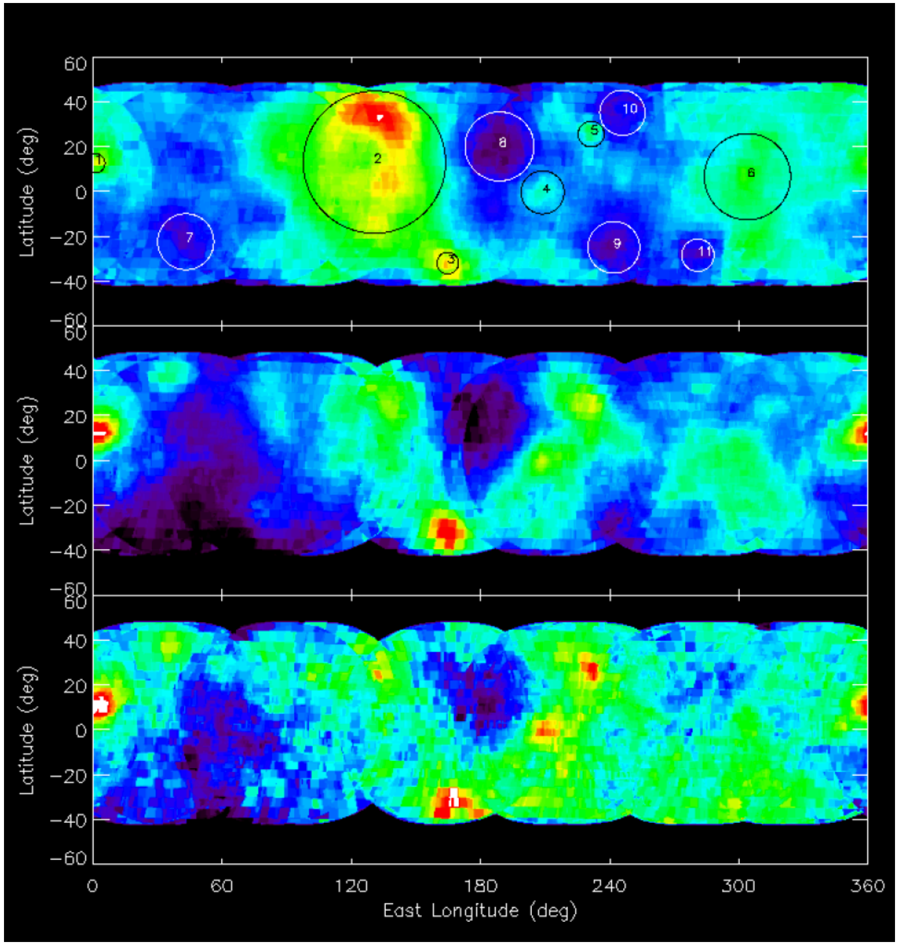
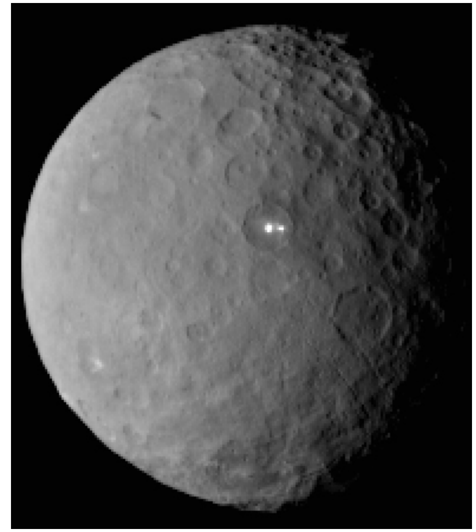
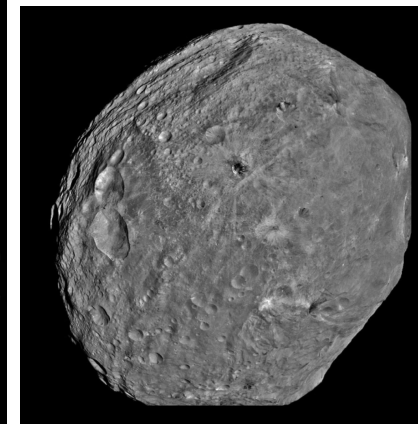


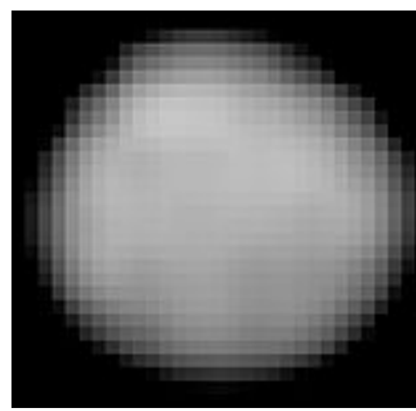
Li et al. (2006)

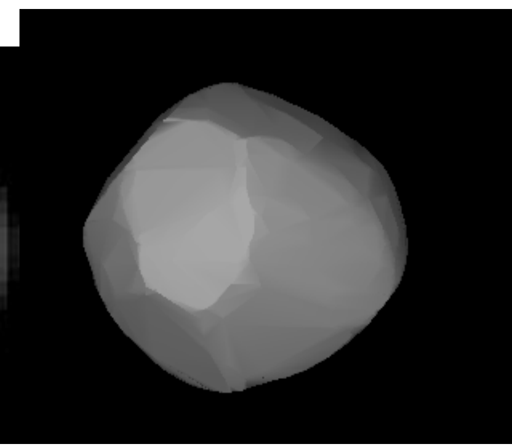
Surviving Embryos of Terrestrial Planets

- There are 28 asteroids larger than 200 km diameter
  - Still intact from solar system origin
- 23 of 28 are low-albedo objects, thought to be water-rich
  - Only ~half have spectral analogs in the meteorite collection
- Rudimentary information for many of them
  - For instance, pole position unknown for 5th-largest asteroid, 300+ km diameter



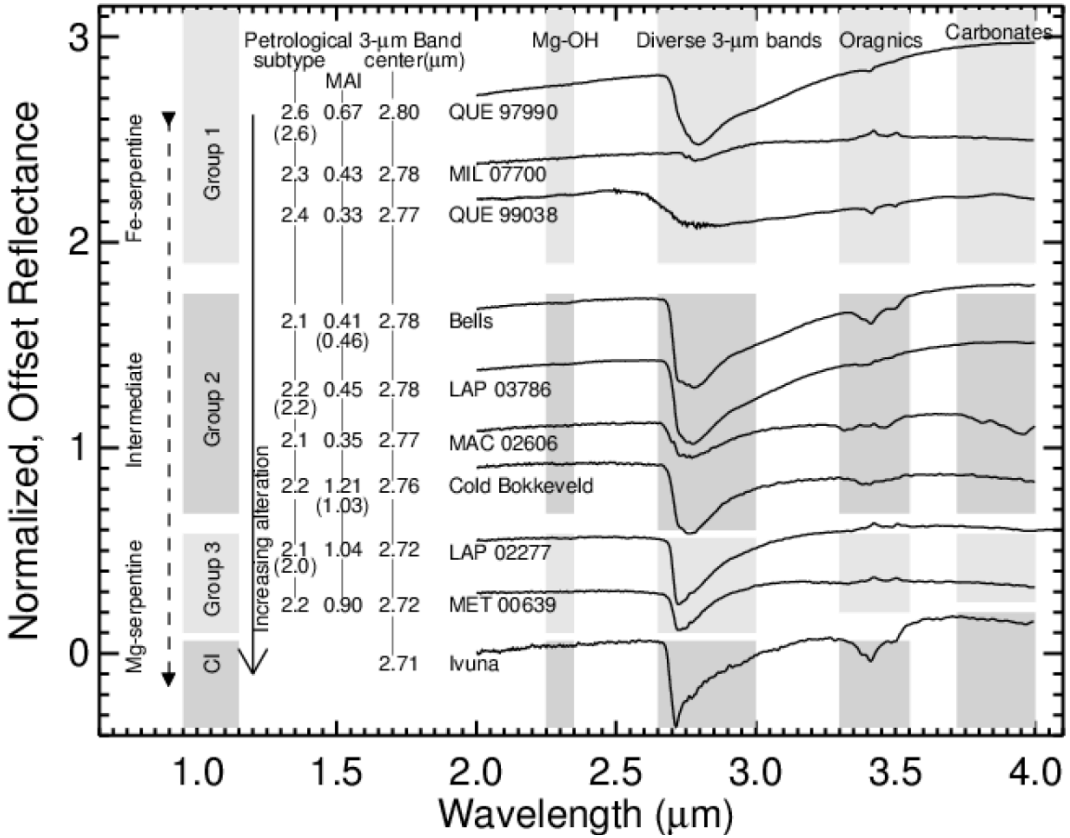






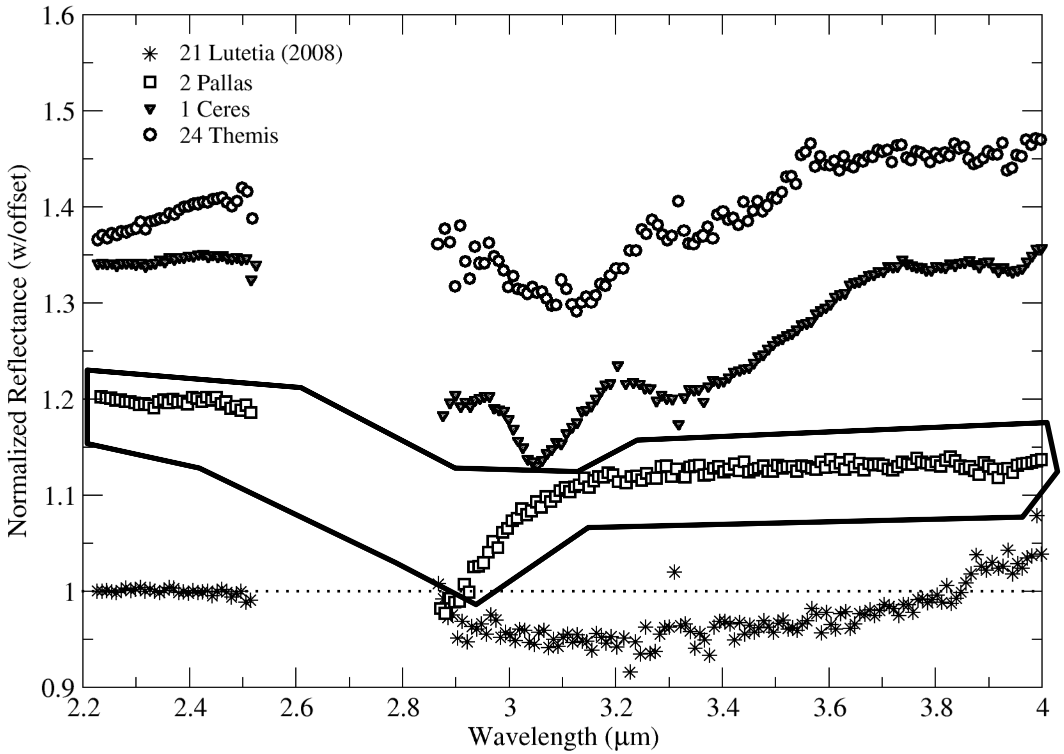
The Hydrated Mineralogy of Planetary Embryos

- **Many carbonaceous chondrite groups have phyllosilicates**
  - OH in structure
  - Spectral features in 3-, 10-μm regions
- **All meteoritic hydrated minerals share similar band shapes**



Asteroidal band shapes in 3-µm region

- **"Pallas type", linear shape beyond 2.8 µm**
  - → **CM meteorite-like, phyllosilicates.**
  - → ***Aqueous alteration on parent body***
- "Ceres type", minimum ~3.05 µm, additional minima
  - → Carbonates
  - → Brucite? Ammoniated minerals?
  - → *Heavy alteration. Minerals formed in subsurface ocean?*
- "Themis type", minimum ~3.1 µm
  - → Frost, organics
  - → *Original ice? Supplied from subsurface ocean? Water cycle?*



JWST observations fill in "water gap"

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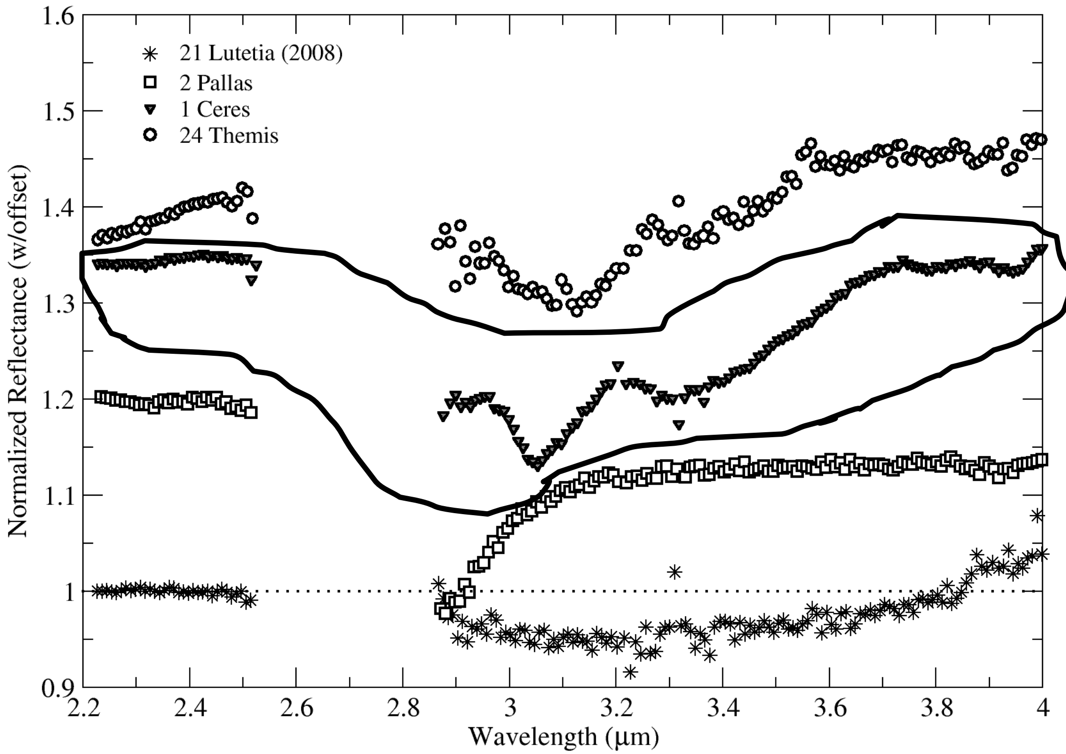

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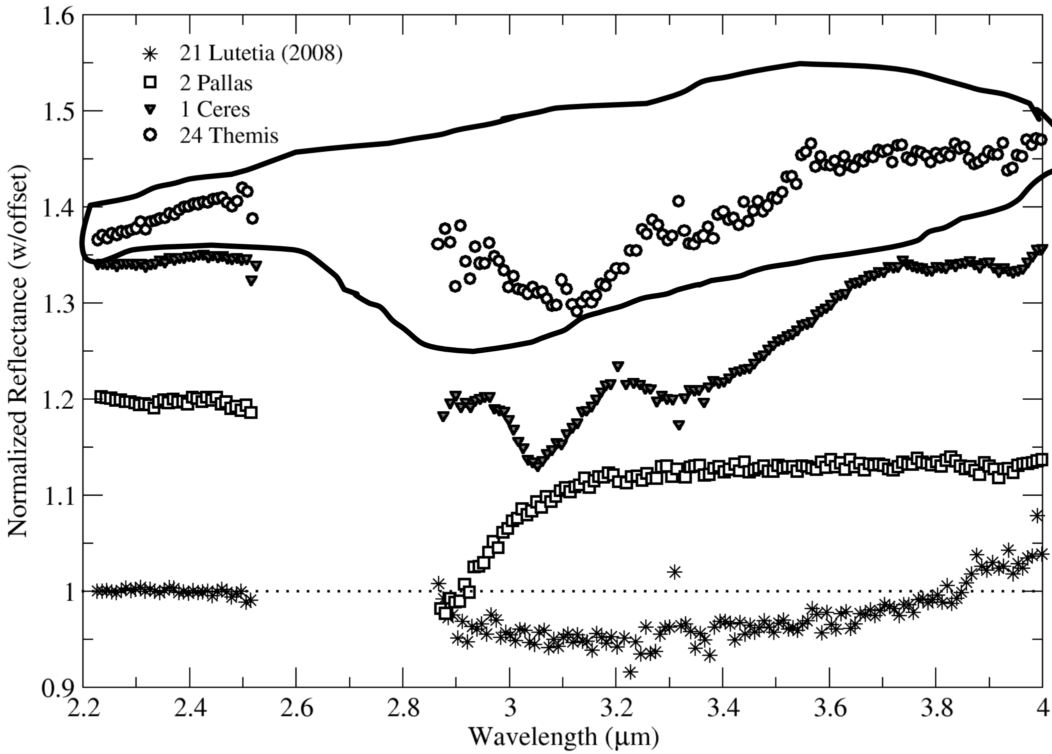
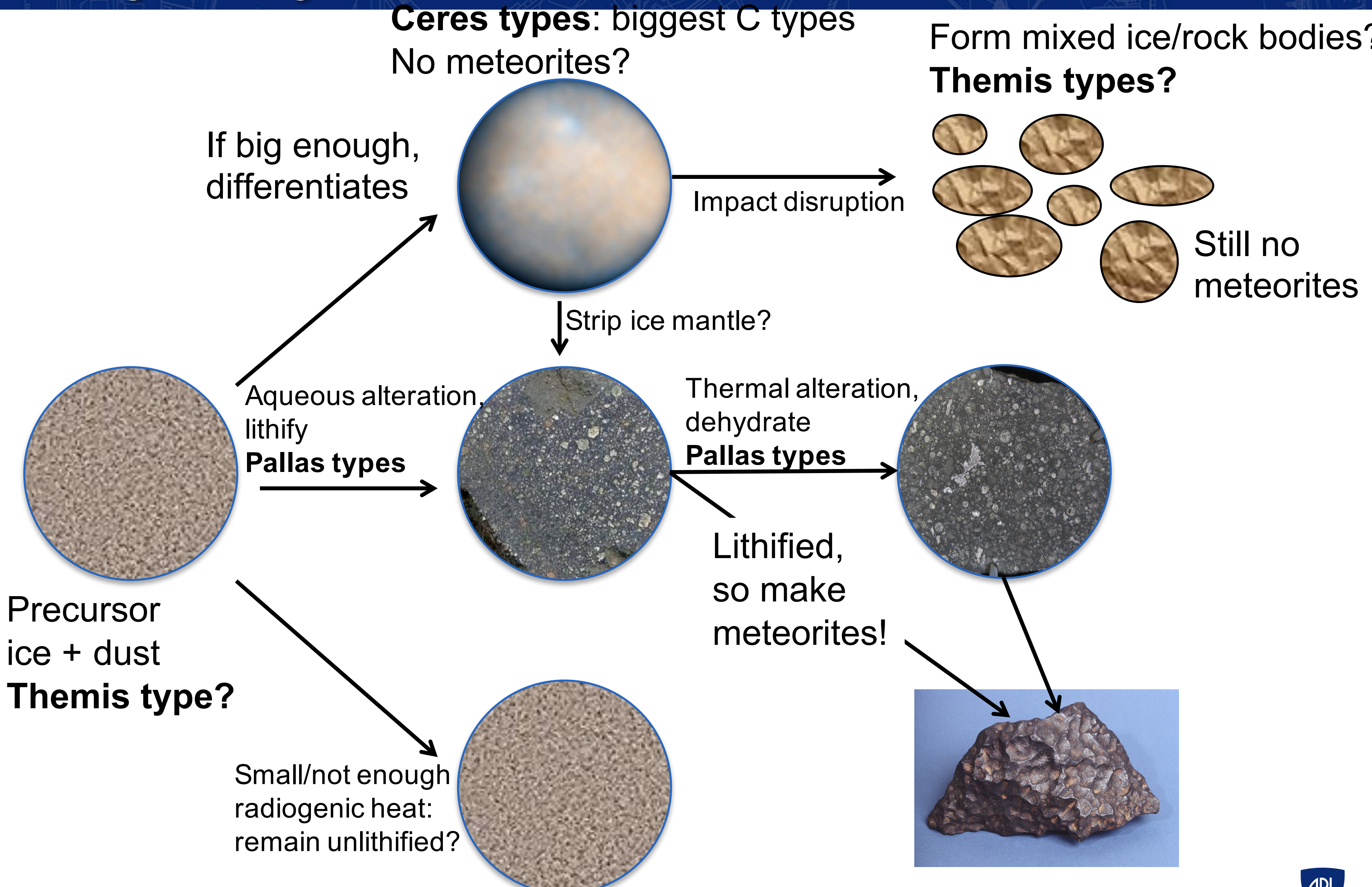


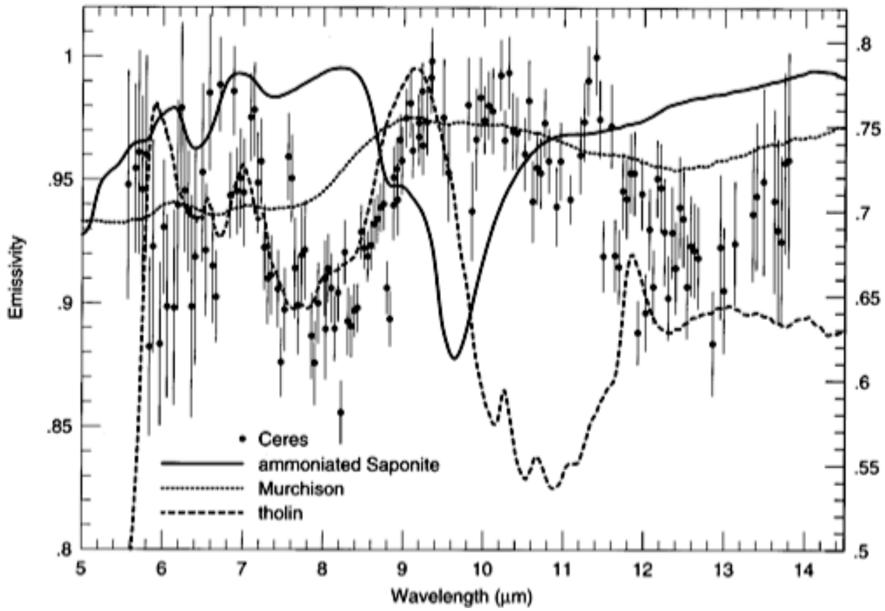
JWST observations fill in "water gap"

A comprehensive, speculative, unvetted theory of hydrated asteroids



Mid-IR

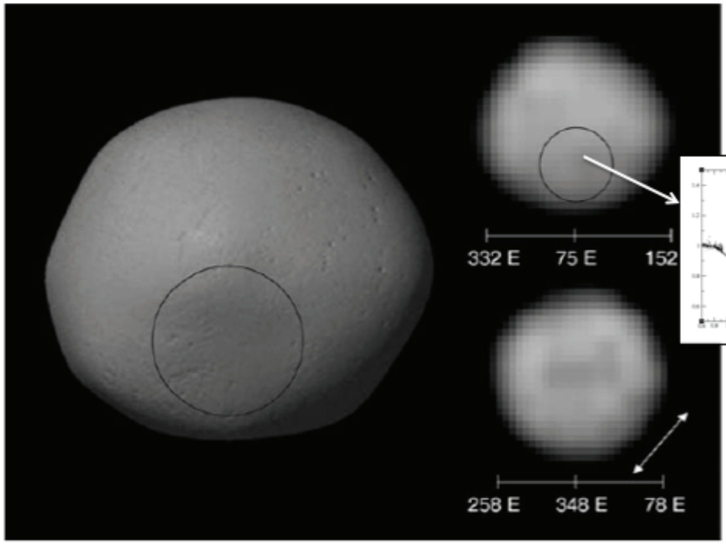
- **Whether Ceres (et al.) have ammoniated minerals is important!**
  - **Hint that it (they?) formed as a TNO and delivered to main belt later?**
- **Mid-IR can distinguish between compositions for Ceres-type asteroids**
- **Will be way too bright for JWST to observe directly with MIRI**
  - **As will the largest few dozen asteroids**
- **GTO project to try to observe scattered light to obtain data**

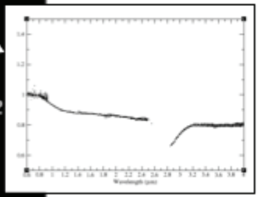


Cohen et al. (1998)

Relevant GTO goals

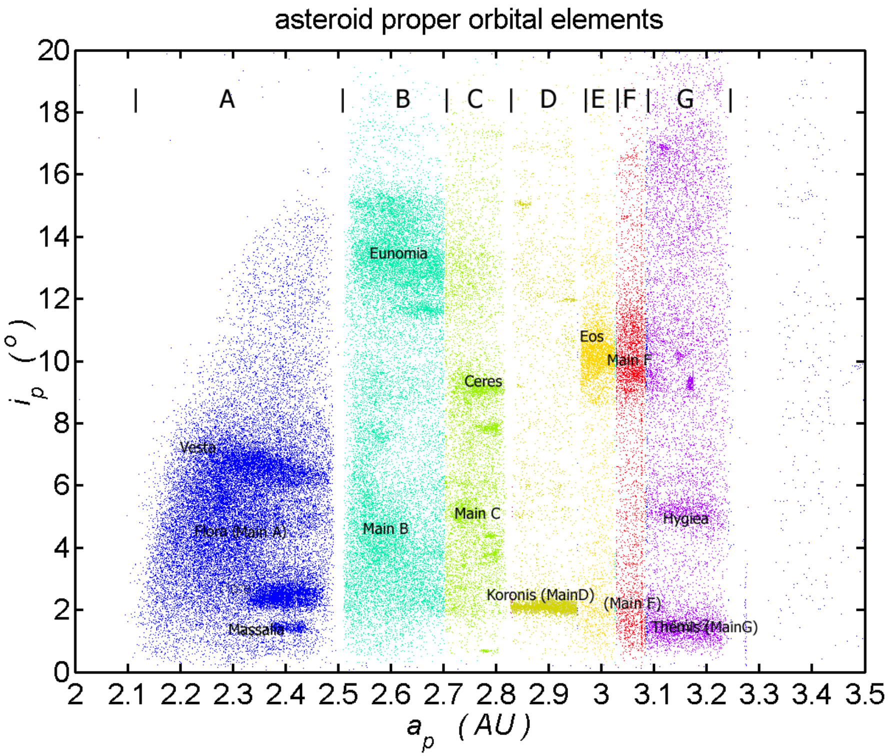
1. **NIRCam imagery of several large asteroids**
   - Complement Dawn data, change detection
   - Extend to unseen objects
   - PSF of NIRCam ~80 km in mid belt, ~45 km at inner belt
2. **NIRSpec resolved spectroscopy of large asteroids**
   - Cover wavelengths unusable from ground
3. **MIRI spectroscopy of scattered light from large asteroids**
   - Demonstrate capability





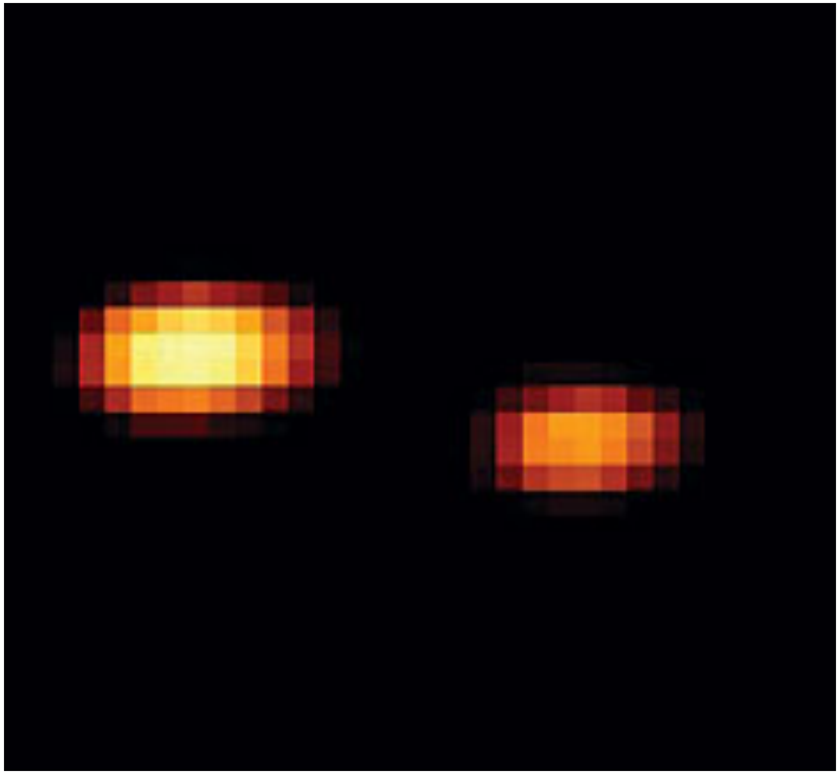
Chips off of Old Blocks

- **Including satellites, families**
- **Recent models of asteroid formation suggest they were "born big"**
  - **Objects ~50 km and smaller originated as part of larger bodies**
- **Ejecta from impacts maintains orbits similar to parent body**
  - **Dozens/hundreds of families and sub families identified**
- **Binary asteroid systems also exist**
  - **Large ones from impact, small ones from "YORP" torque spinup**



Asteroidal Immigrants?

- Large populations of “Trojan” asteroids lead/trail Jupiter by 60 degrees
  - Distant, low-albedo
  - Expect organics, ice but not verified
  - Spectral data’s kind of ratty overall TBH
- It is thought these were captured by Jupiter from the TNO region during planetary migration
  - But not yet proven
- Trojan exploration given high priority in Planetary Decadal Survey



617 Patroclus system
Marchis et al. (2006)
Separation ~150 mas

Family Affairs

- Many (but not all) of the largest asteroids have dynamical (collisional) families
- Measurements at short wavelengths show spectral homogeneity
  - Not tested beyond ~2.5 μm
- Hydrated asteroid evolution model testable with observations of small family members
- Very limited data on spectral properties of binary components
  - Pluto/Charon different

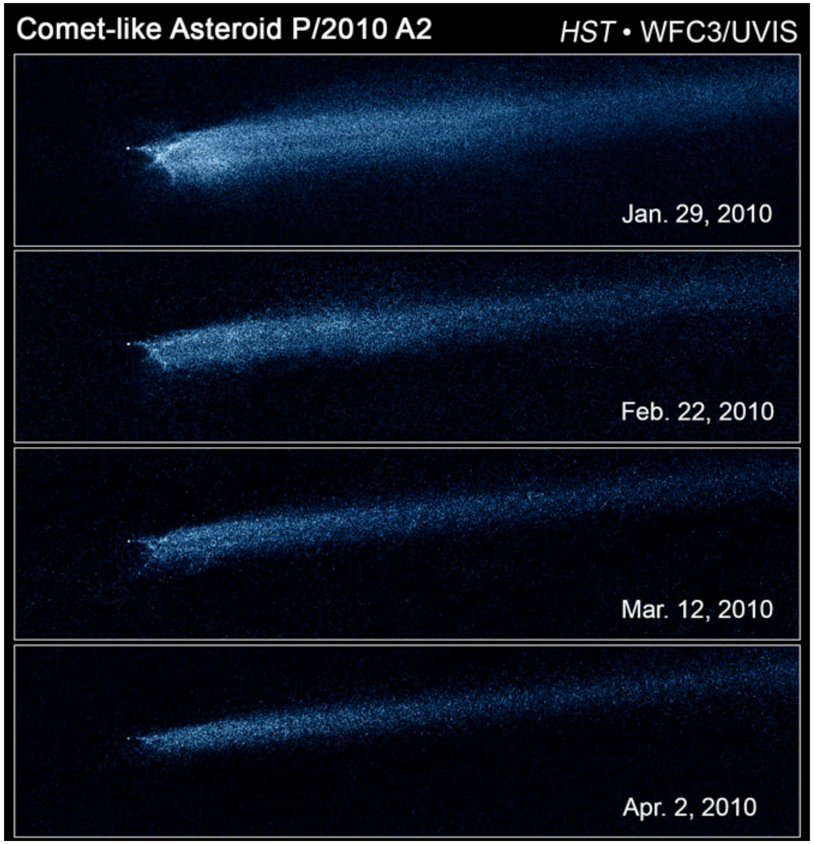
Relevant GTO goals

1. Separate NIRCam, MIRI, and NIRSpec observations of binary asteroid components

Important remaining questions include…

- Do all members of families share the same spectral type?
- How do Trojans/irregular satellites fit into the story?
- Can volatiles be identified on the surfaces of "main belt comets"?

Need to go fainter, need to observe at wavelengths unavailable on the ground!



Jewitt et al.
Most likely not volatile sublimation, but a neat set of images!

Our Next Nearest Neighbors

- Near-Earth Objects (NEOs) are the link from main-belt asteroids to meteorites
- NEO rendezvous and sample returns have only scratched the surface of diversity
  - Follow-up mission targets with wider range of instruments!
- Some objects are consistent with inactive/dormant comets, one "rock comet"?

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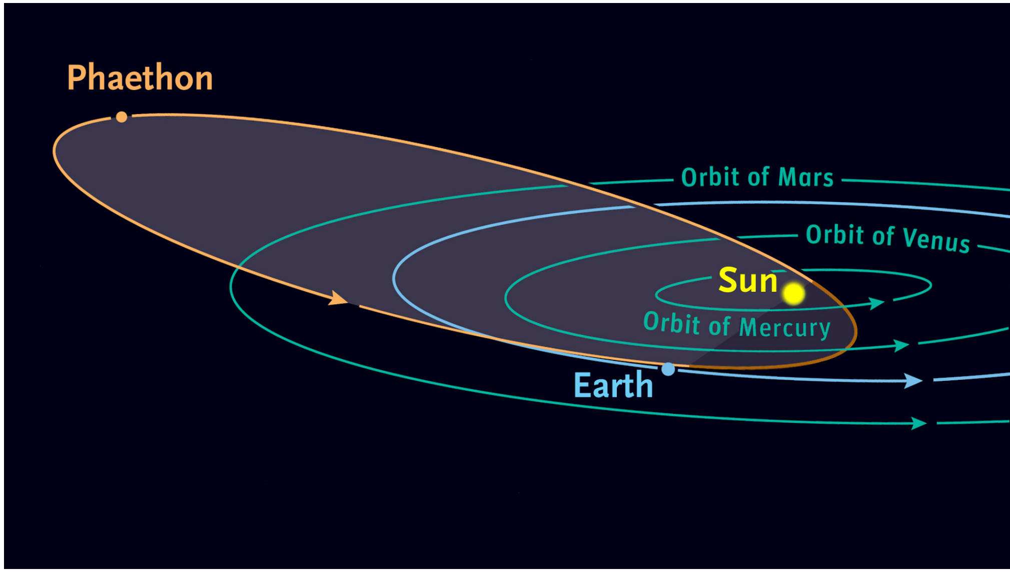


Graphic from Sky and Telescope

Overview of asteroid GTO plans

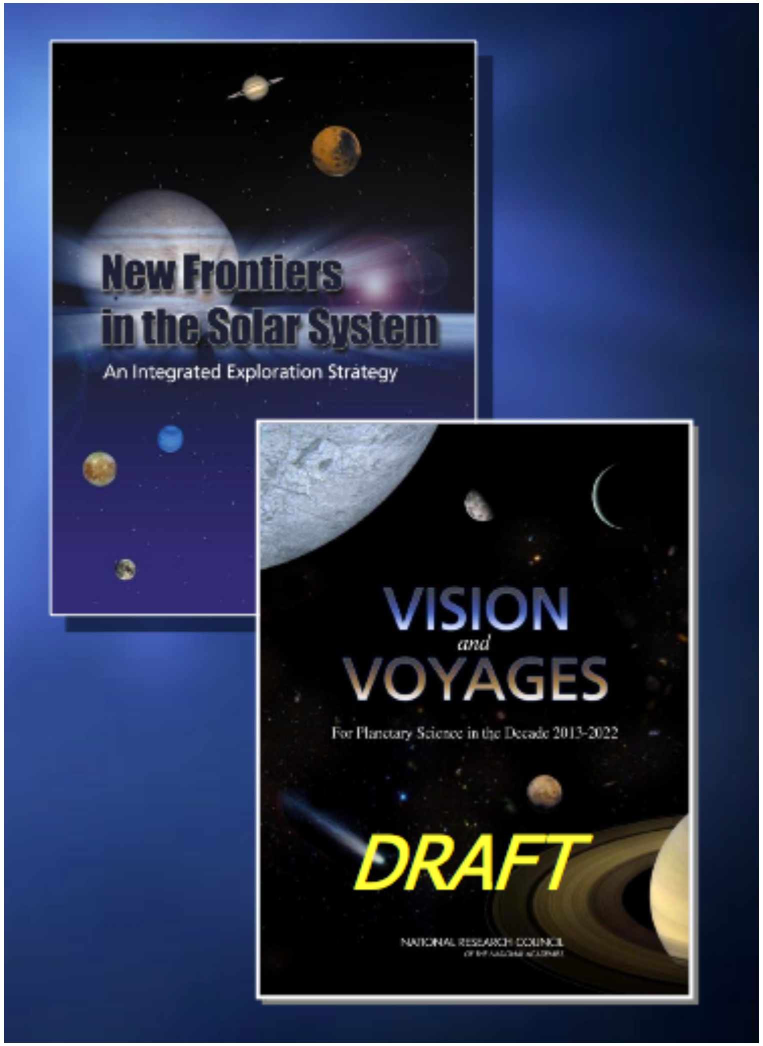
- **Measurements of large, low-albedo asteroids**
  - Develop technique of measuring scattered light with MIRI (in IFU?)
  - Context for Dawn
- **Measurements of Trojan binary components**
  - High community interest
  - Support for Discovery/New Frontiers proposals
- **Measurements of select NEOs**
  - Demonstrate/test limits of tracking
  - Observe objects of community interest
  - Mission support

Summary

- **JWST has the capability to make key measurements of high importance to asteroid science**
- **GTO projects are being designed to make focused observations**
  - **To advance science**
  - **To demonstrate capabilities**
- **We look forward to doing great work together!**

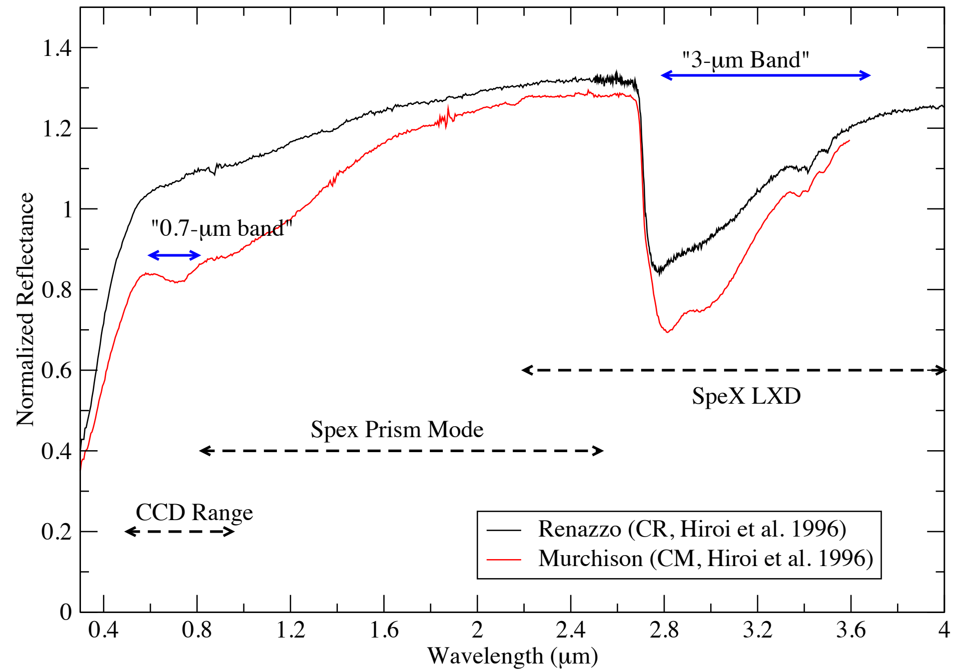
Carbonaceous Chondrites, Hydrated Minerals, and the People Who Love Them

- Carbonaceous chondrite meteorites have H2O, organics
- Important source of same to early earth?
- Sample return from a water/organics-rich C chondrite high scientific priority, in the works for ISAS, NASA. Finalist for ESA.
- Sample return missions are expensive, rare, may fail
- Remote sensing required for reconnaissance, plus data for vast majority of objects



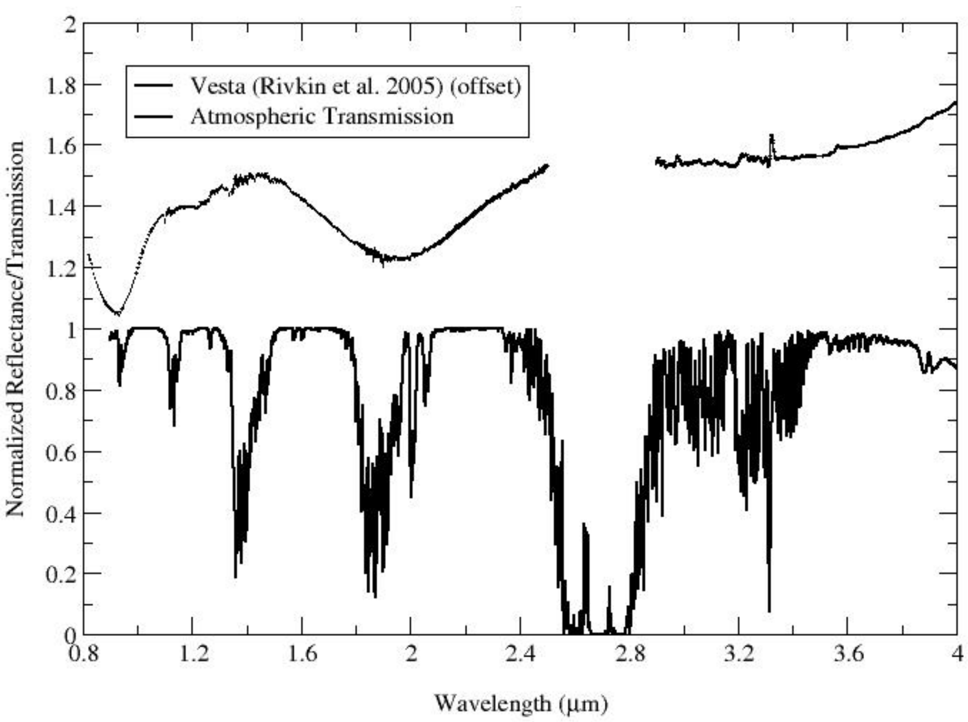
Carbonaceous chondrites among the asteroids

- Largely associated with low-albedo "C complex"
  - With B, C, Cb, Cg, Ch, Cgh classes
- Present throughout asteroid belt, dominate mid/outer belt
- Present in Trojans/irregular satellites as well
- 3-µm spectral region important
  - 2.7 µm OH fundamental
  - ~3.0 µm H_2O overtone
  - Few suitable observing sites
  - Still, lots of work since late 70's!



Observing in the 3-μm Region

- Strong absorptions in 3-μm region from interesting specie
  - OH ~2.7 μm
  - H_2O ~2.9-3.0 μm
  - CH ~3.3-3.4 μm
  - CO_2, CH_4, NH_3, carbonates…
- Earth's atmosphere limits observing sites
- But we do what we can!



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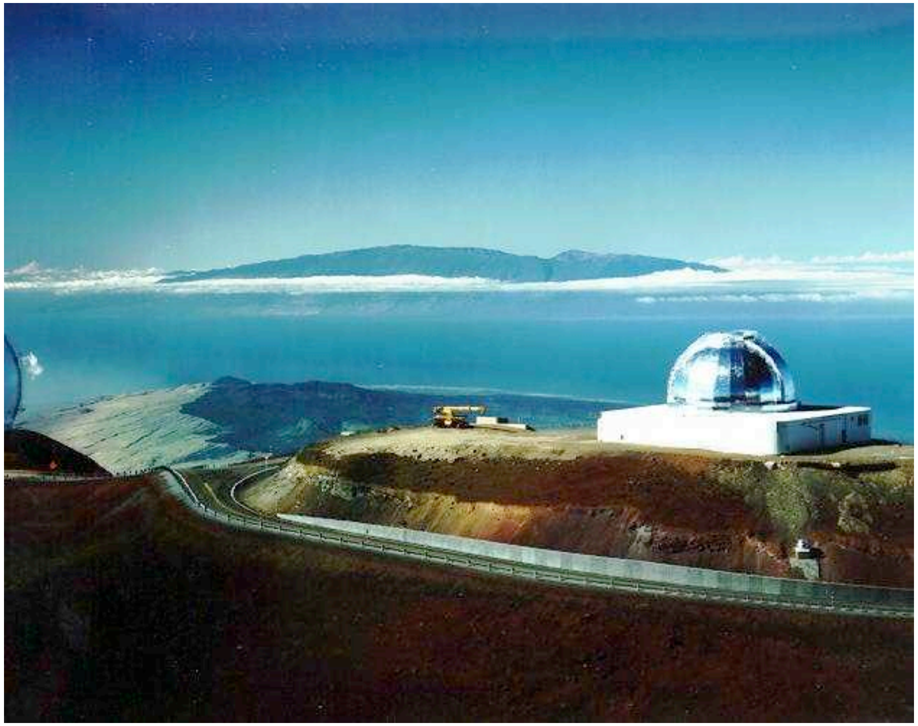
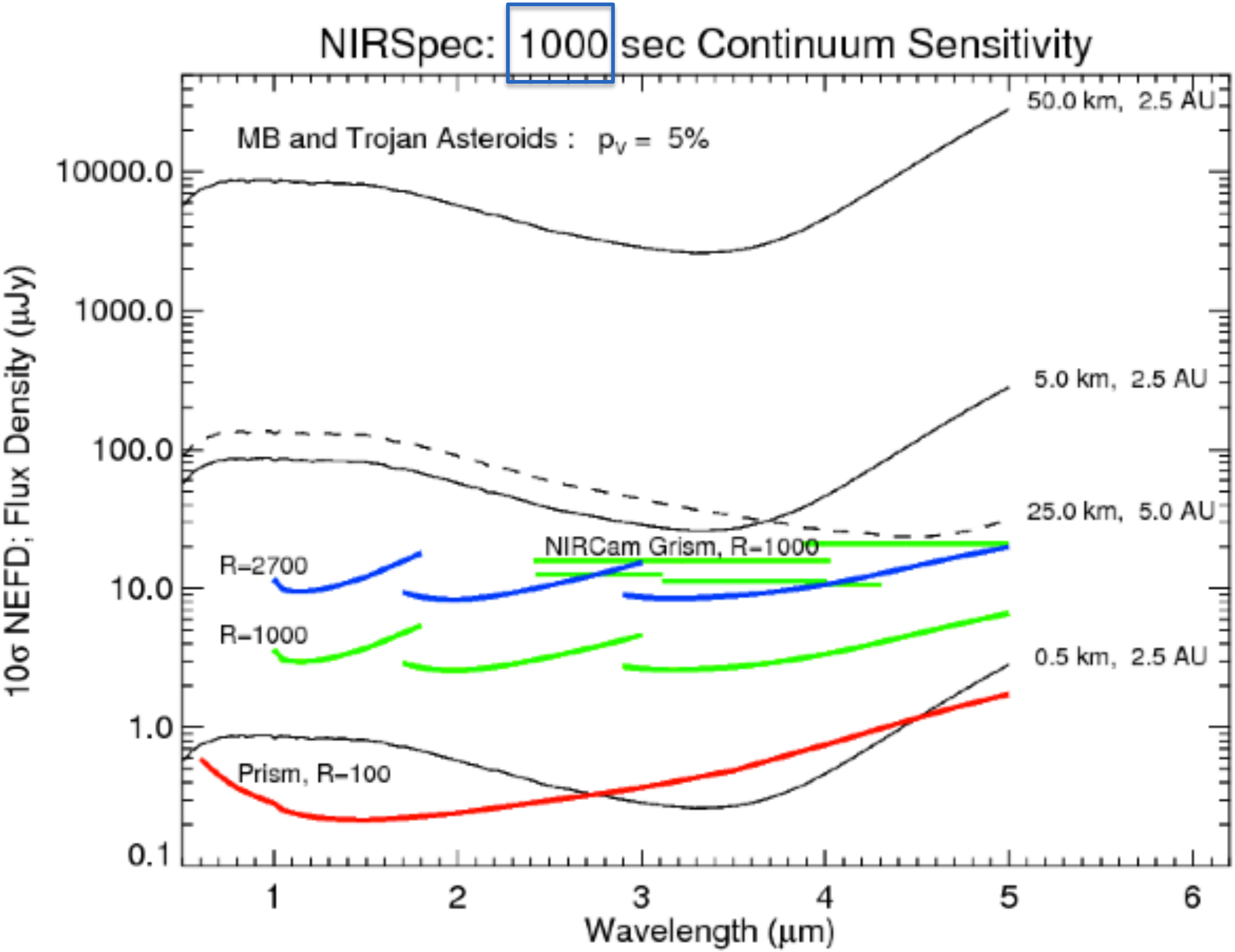
L-band Main-belt/NEO Observing Project (LMNOP)

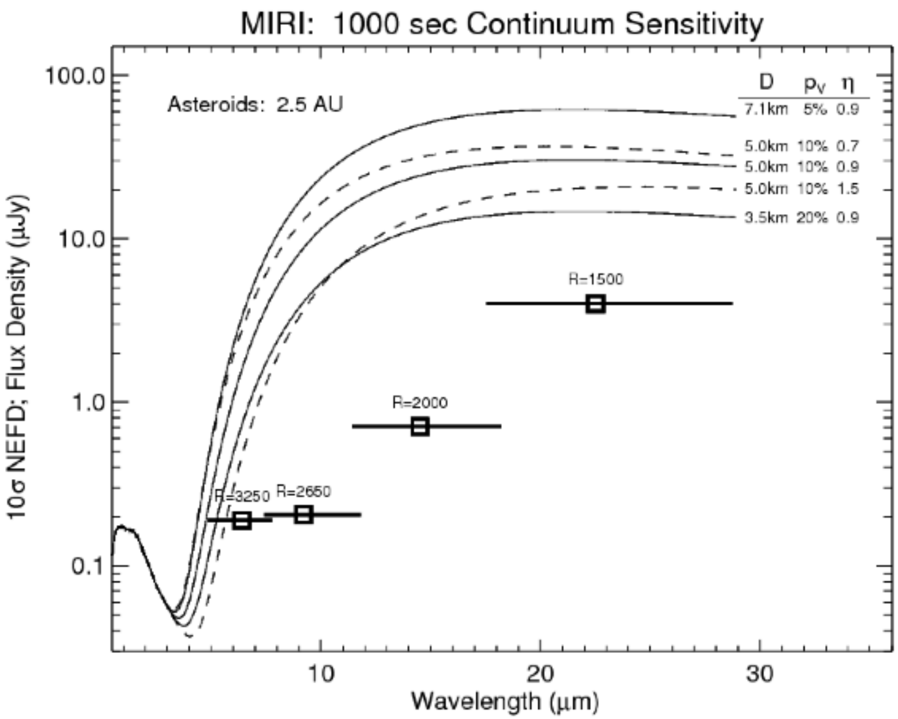
- IRTF (3-m telescope on Mauna Kea), using Spex instrument (2-4 μm)
- 380 observations of 213 objects, 118 C-complex (as of 10/1/13)
- Survey paper in preparation, have been focusing on interesting objects (Ceres, Vesta, Themis, Lutetia…)




NIRSpec: 1000 sec Continuum Sensitivity
MB and Trojan Asteroids : p_V = 5%
50.0 km, 2.5 AU
5.0 km, 2.5 AU
25.0 km, 5.0 AU
0.5 km, 2.5 AU
NIRCam Grism, R~1000
R~2700
R~1000
Prism, R~100
10000.0
1000.0
100.0
10.0
1.0
0.1
1
2
3
4
5
6
Wavelength (μm)
10σ NEFD; Flux Density (μJy)

I don't do mid-IR stuff much, but thought I should include this.

- **Few mid-IR instruments available to asteroid community**
- **Relatively low contrast emission features—need high S/N**
- **Same argument as before: go *fainter*, get wavelengths *blocked by atmosphere***



Summary

- OH- and water-bearing asteroids are of great importance to scientific community
- A variety of hydrated mineralogies are present on asteroids
  - Related to histories
- Ceres-like spectra (brucite+carbonate+clays?) are found on most of the largest asteroids
  - Not represented among meteorites?
  - Largest asteroids all experienced ice-rock differentiation?
- JWST will provide unique, critical data in "water gap"

34

The Appeal of Asteroids

- Preserve evidence of conditions early in solar system history
  - Physical/geochemical
  - Dynamical/positional
- Retain wide variety of compositions
  - Igneous to pristine
  - Water- and organics-poor to -rich
- Cover widest* range of sizes of any astronomical objects sharing a single "category"
  - Experience physical effects not seen in larger objects (cohesion, non-grav forces…)
- (Non-science reasons to be interested, as well)

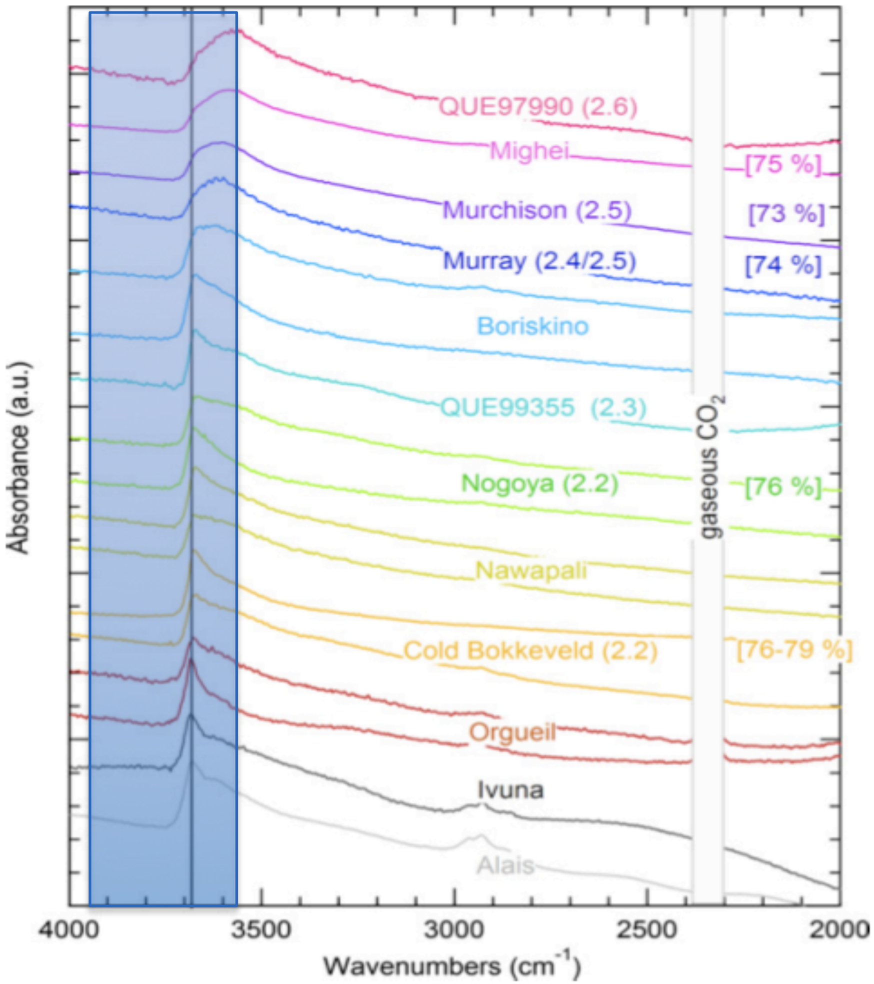
- 10^{-7} – 10^{-5} m: "Dust"
- 10^{-5} – 1 m: Meteoroids*
- 1 – 10^{6} m: asteroids
- 10^{6} – 10^{8} m: planets
- 10^{8} – 10^{12} m: stars/brown dwarfs
- 10^{18} – 10^{21} m: galaxies
- 10^{27} m: observable universe

*Save maybe nebulae? I'm a planetary guy.

The Asteroid Life Cycle

JWST observations and how they'll help

- **JWST transmission MUCH better at λ of interest (more like 100% than 0%)**
- **Obtain useable data for first time from majority of "water gap" (shaded)**
- **Allow direct comparisons to lab spectra tying meteorite reflectance to composition**
  - **Best meteorite analog**
  - **Better spectral modeling**
  - **Coexistence of ice and phyllosilicates?**



Beck et al. (2010)

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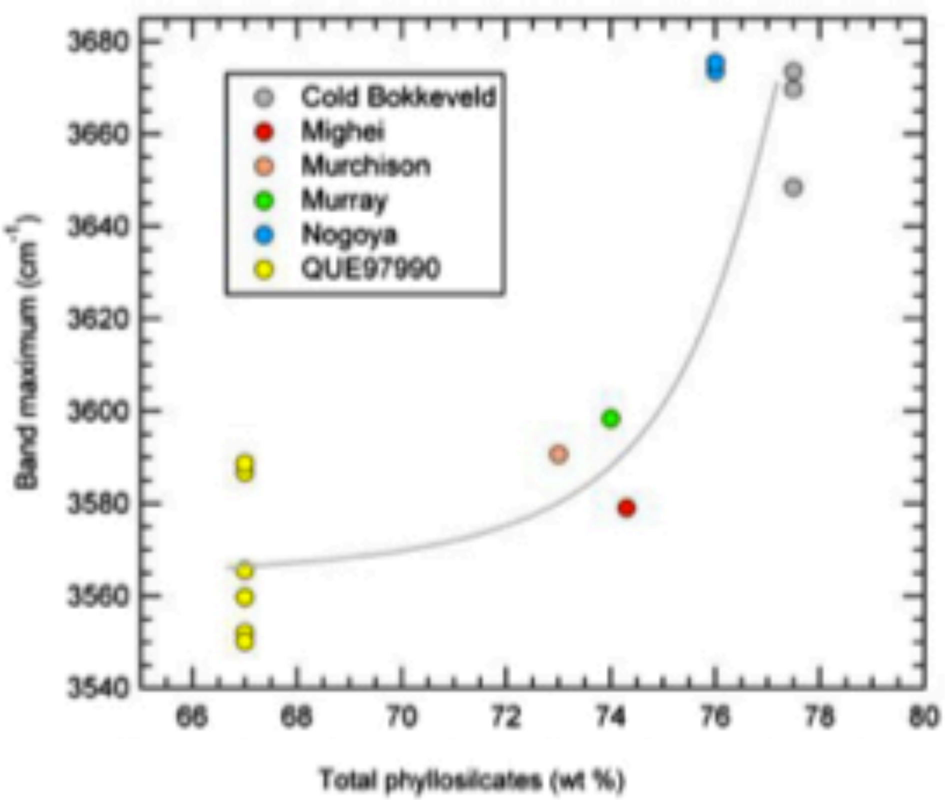


Beck et al. (2010)

10^{-7} — Size of astronomical dust

10^{5} — Diameter of largest asteroids

10^{6} — Diameter of Mercury

10^{8} — Diameter of brown dwarf, diamater of Jupiter

10^{12} — Diameter of largest star

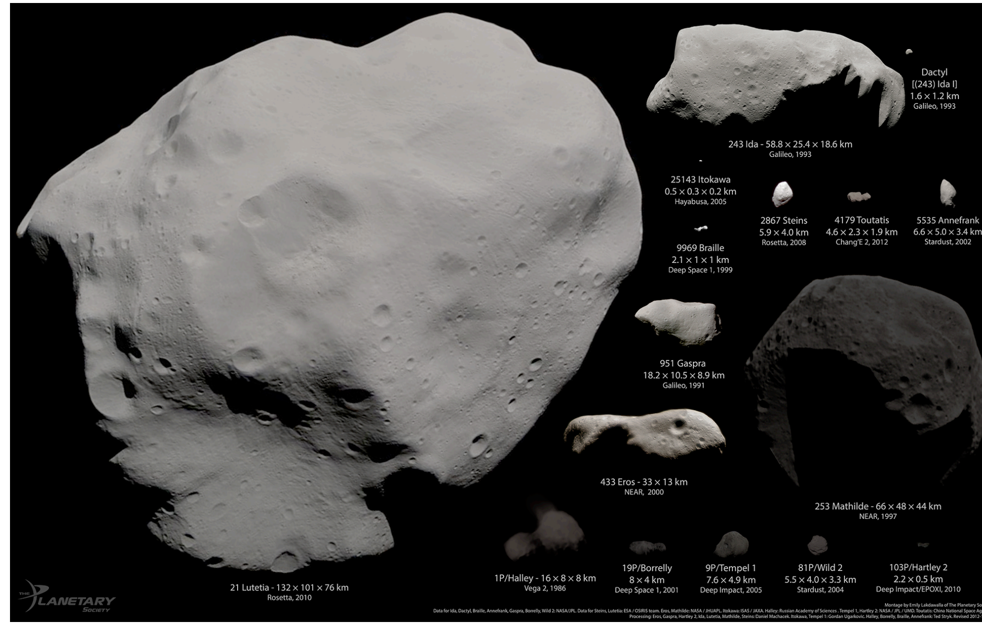
10^{18} — Range from ultracompact dwarf galaxies

10^{21} — to largest galaxies

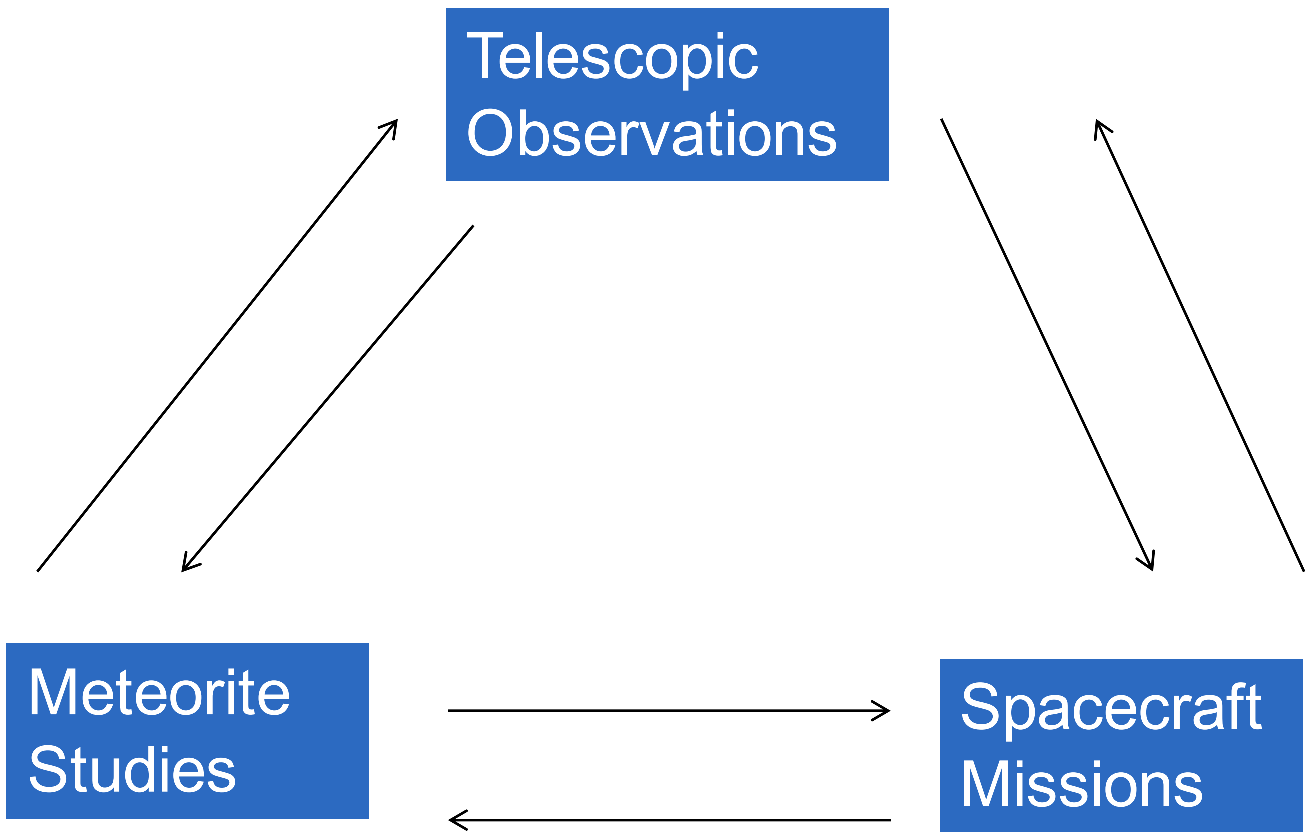
10^{27} — Size of observable universe

Why asteroids?

- **Asteroids represent leftover material not incorporated into the inner planets**
- **Asteroids preserve material largely unaltered (at least compared to the planets)**
- **Meteorites originate on asteroids, giving geochemical context rare in planetary science!**
- **(Impacts, astronauts, mining)**

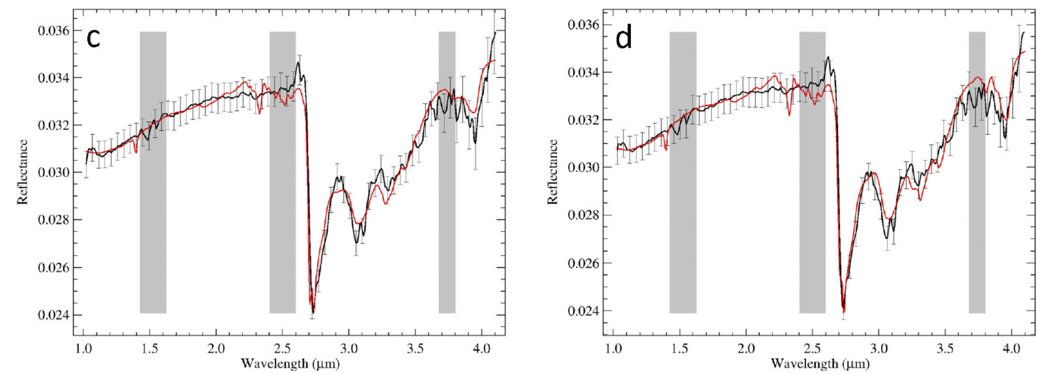


Montage by Emily Lakdawalla, Planetary Society
Image data from NASA, ESA, JAXA…

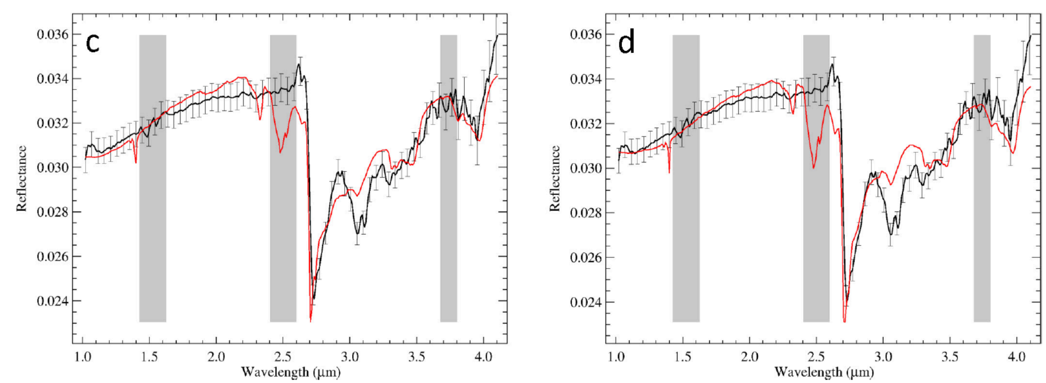

Telescopic Observations
Meteorite Studies
Spacecraft Missions

3-μm Observations

- Most action in the 3-μm region, observed since late 1970s
- Bands at ~3.1, 3.3, 3.9 μm
  - First two consistently seen
  - Last seen when thermal correction done
- First interpreted as ice frost
- Ammoniated phyllosilicates later interpretation
- 2006: Cronstedtite (iron-rich clay), carbonates
- 2009: Carbonates, brucite ($Mg(OH)_2$)
- Frankly, none are perfect.



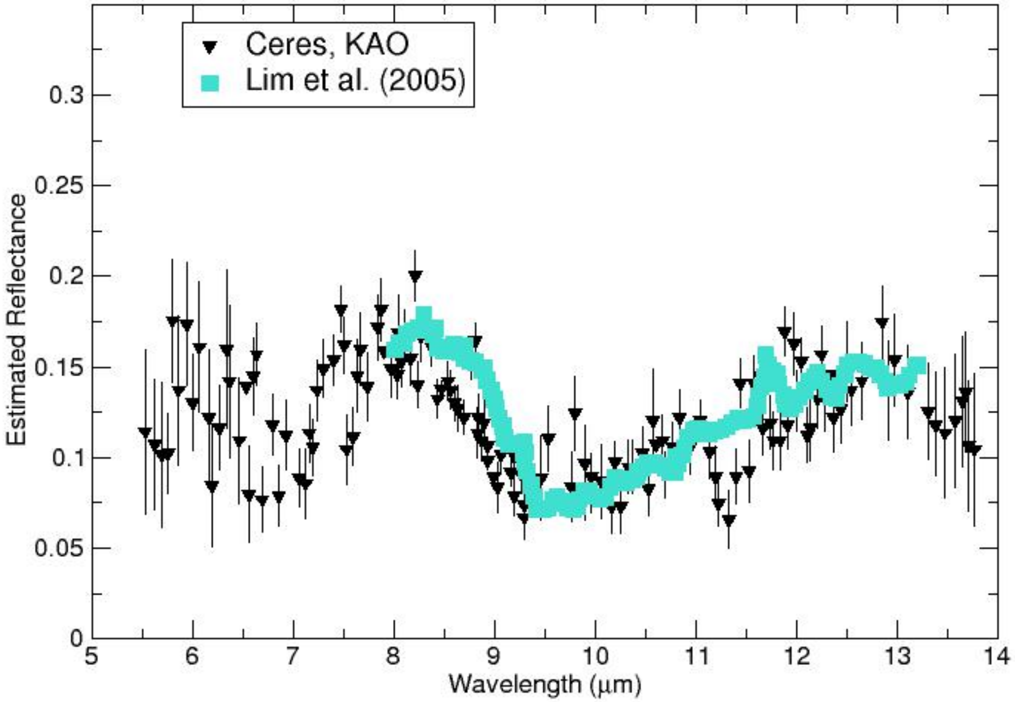
Extended Data Figure 5 | Spectral fit of the spectrum of Ceres including different carbonates. a–d, Results of the spectral fitting model (red curves) using NH_4-annite, antigorite, magnetite and siderite (**a**); NH_4-annite, antigorite, magnetite and calcite (**b**); NH_4-annite, antigorite, magnetite and magnesite (**c**); and NH_4-annite, antigorite, magnetite and dolomite (**d**). Ceres' spectrum is in black. Error bars and vertical grey bars as in Extended Data Fig. 2.



Extended Data Figure 4 | Spectral fit of the spectrum of Ceres including cronstedtite, tochilinite and brucite. a–d, Results of the spectral fitting model (red curves) using tochilinite, cronstedtite, dolomite and magnetite (**a**); antigorite, cronstedtite, dolomite and magnetite (**b**); tochilinite, brucite, dolomite and magnetite (**c**); and antigorite, brucite, dolomite and magnetite (**d**). Ceres's spectrum is in black. Error bars and vertical grey bars as in Extended Data Fig. 2.

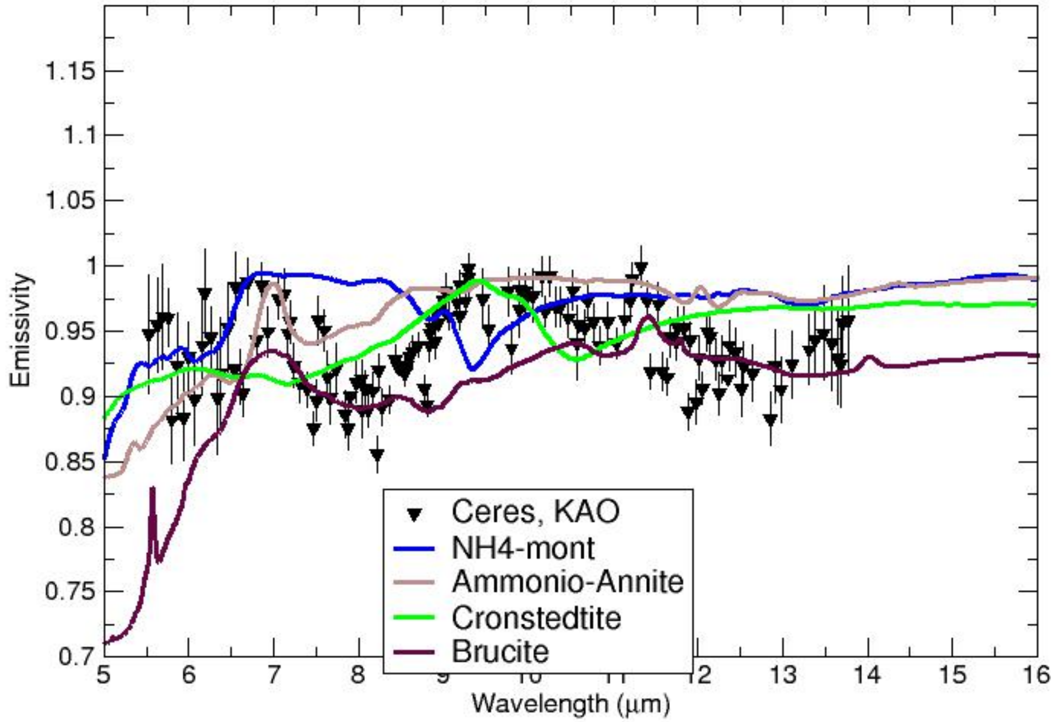
Mid-IR

- **Can distinguish between compositions for Ceres-type asteroids**
- **Relatively limited mid-IR data for Ceres**
  - **Too bright for Spitzer**
  - **Will be way too bright for JWST to observe directly**



Mid-IR

- **Relatively limited mid-IR data for Ceres**
  - **Too bright for Spitzer**
  - **Will be way too bright for JWST**
- **KAO data from Cohen et al.**
- **Palomar data from Lim et al.**
- **Some ISO data (in prep)**
- **Some additional data with Lim as PI (in prep)**
- **SOFIA data (Vernazza?)**
- **Not clear that data matches much of anything, but field of mid-IR asteroid study maturing quickly!**



Some initial findings

- **Three of the 4 largest C-complex asteroids are Ceres-types**
  - **Similar histories to Ceres as well?**
  - **Similar interiors as Ceres?**
- **Few large asteroids have 3-µm spectra like meteorites**

Object	SMASS class	3-µm type
1 Ceres	C	Ceres
2 Pallas	B	Pallas
10 Hygiea	C	Ceres
704 Interamnia	B	Ceres
52 Europa	C	Ceres?
511 Davida	C	Pallas
31 Euphrosyne	Cb	Themis/Cybele
88 Thisbe	B	Themis/Cybele ?
324 Bamberga	CP (Tholen)	Themis/Cybele
451 Patientia	C (Tholen)	Ceres

Ten largest C-complex asteroids