Space weathering : pandemic in the Solar System

SELECTED CHAPTERS ON ASTROPHYSICS

NOVEMBER 4 AND 11, 2020

KATERINA CHRBOLKOVA

What to expect

General introduction to spectroscopy of minerals

1. What are the most common **minerals** in the airless planetary bodies of the SS?
2. What are their **characteristic spectral features**? + examples from the SS
3. What **effects** influence the spectra?

Some real examples of asteroid mineralogy use

Space weathering

1. What is the **space weathering** and what are its main agents?
2. What are **lunar swirls** and why are they so special?
3. How do we **simulate space weathering** here on the Earth?

Part 1:
Basic minerals in the small bodies

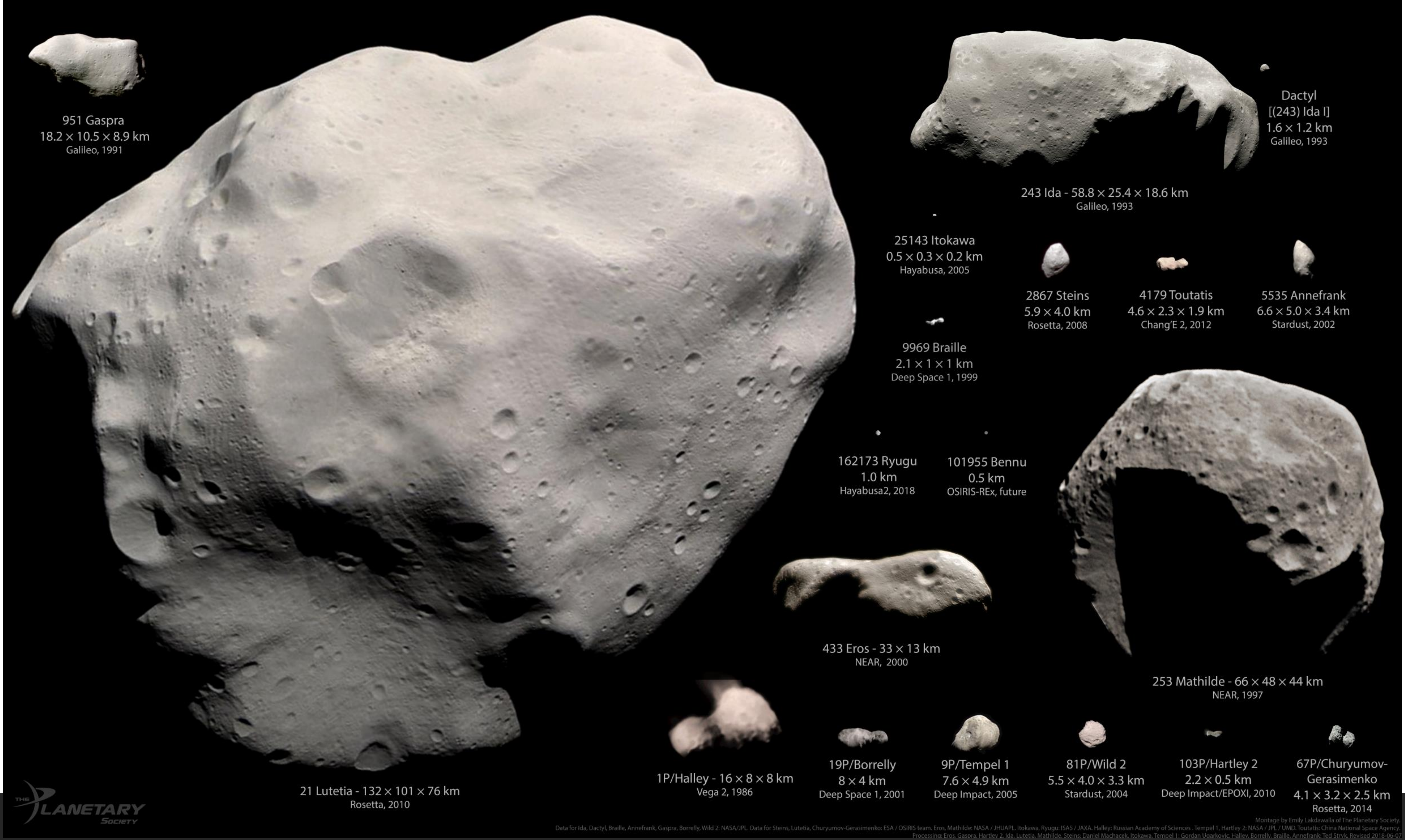
Not a complete overview, aiming onto the most important ones.

First: small bodies of our interest

- Will be mainly about asteroids in the SS and the Moon
- Asteroid population
  - Irregular bodies
  - Sizes up to 1,000 km
  - For the space weathering studies - two main groups:

  1. Near-Earth asteroids
     - Currently: 21 000 bodies
  2. Main-belt asteroids
     - Approx. 10^6
     - Between Mars and Jupiter (2.1-3.3 au)

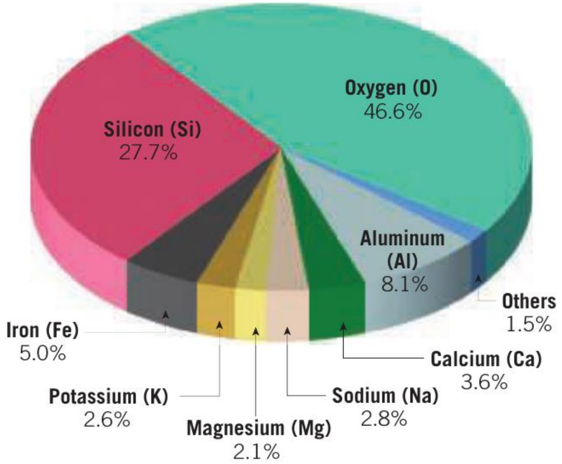
  3. Other groups such as TNOs are beyond our scope



951 Gaspra
18.2 × 10.5 × 8.9 km
Galileo, 1991
Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
4179 Toutatis
4.6 × 2.3 × 1.9 km
Chang'E 2, 2012
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
162173 Ryugu
1.0 km
Hayabusa2, 2018
101955 Bennu
0.5 km
OSIRIS-REx, future
433 Eros - 33 × 13 km
NEAR, 2000
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
21 Lutetia - 132 × 101 × 76 km
Rosetta, 2010
1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004
103P/Hartley 2
2.2 × 0.5 km
Deep Impact/EPOXI, 2010
67P/Churyumov-
Gerasimenko
4.1 × 3.2 × 2.5 km
Rosetta, 2014
THE PLANETARY SOCIETY
Montage by Emily Lakdawalla of The Planetary Society.
Data for Ida, Dactyl, Braille, Annefrank, Gaspra, Borrelly, Wild 2: NASA/JPL. Data for Steins, Lutetia, Churyumov-Gerasimenko: ESA / OSIRIS team. Eros, Mathilde: NASA / JHUAPL. Itokawa, Ryugu: ISAS / JAXA. Halley: Russian Academy of Sciences . Tempel 1, Hartley 2: NASA / JPL / UMD. Toutatis: China National Space Agency.
Processing: Eros, Gaspra, Hartley 2, Ida, Lutetia, Mathilde, Steins: Daniel Machacek. Itokawa, Tempel 1: Gordan Ugarkovic. Halley, Borrelly, Braille, Annefrank: Ted Stryk. Revised 2018-06-07

Typical minerals

- Let's take an example in our Earth:
  - Only 8 elements make up vast majority of minerals:
    - 47% O
    - 28% Si
    - Al, Fe, Ca, Na, K, Mg (5 to 2%)
    - 1.5% all other
- → Si and O are the prime constituents
- → the main group: SILICATES

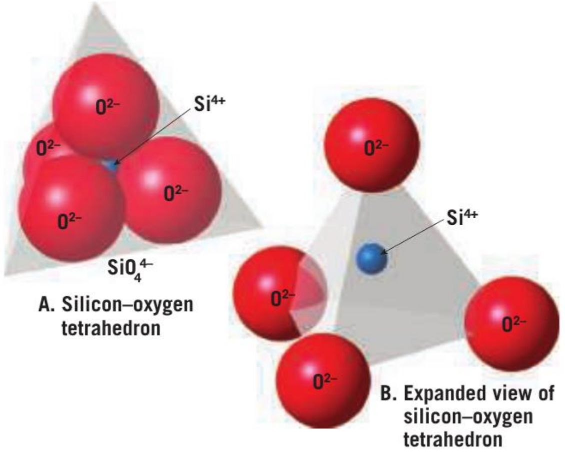


Credit: Tarbuck et al., Earth: An Introduction to Physical Geology (2017)

Silicates

- Building block is the SiO_4 tetrahedron
- Basic division is into the light and dark silicates

1. Light
   - Fe/Mg is missing in the crystalline structure
   - Light colored
   - Smaller density than the dark ones
   - e.g. feldspars (Moon - highlands) or quartz and clays – not so important for us

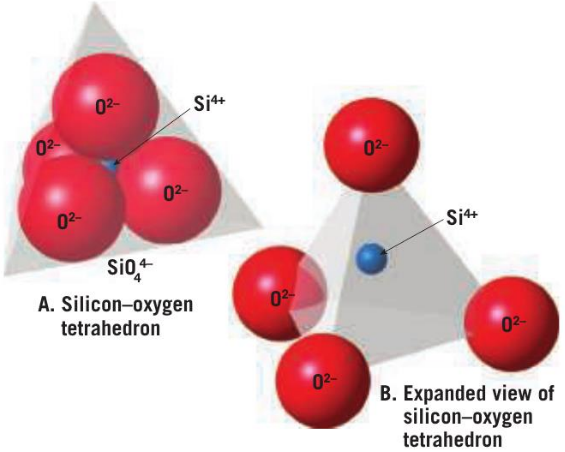


Credit: Tarbuck et al., Earth: An Introduction to Physical Geology (2017)

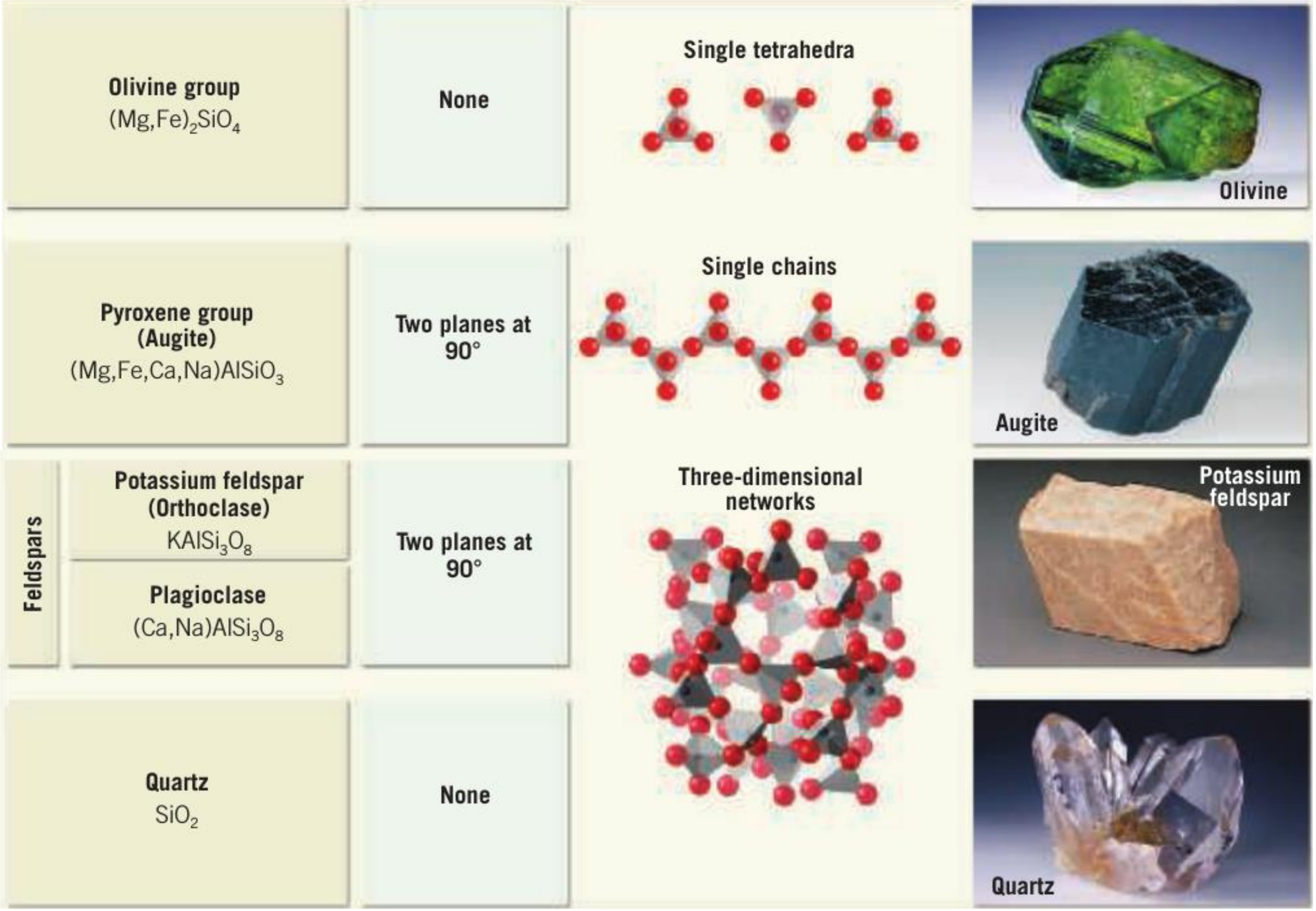
Silicates

- Building block is the SiO_4 tetrahedron
- Basic division is into the light and dark silicates

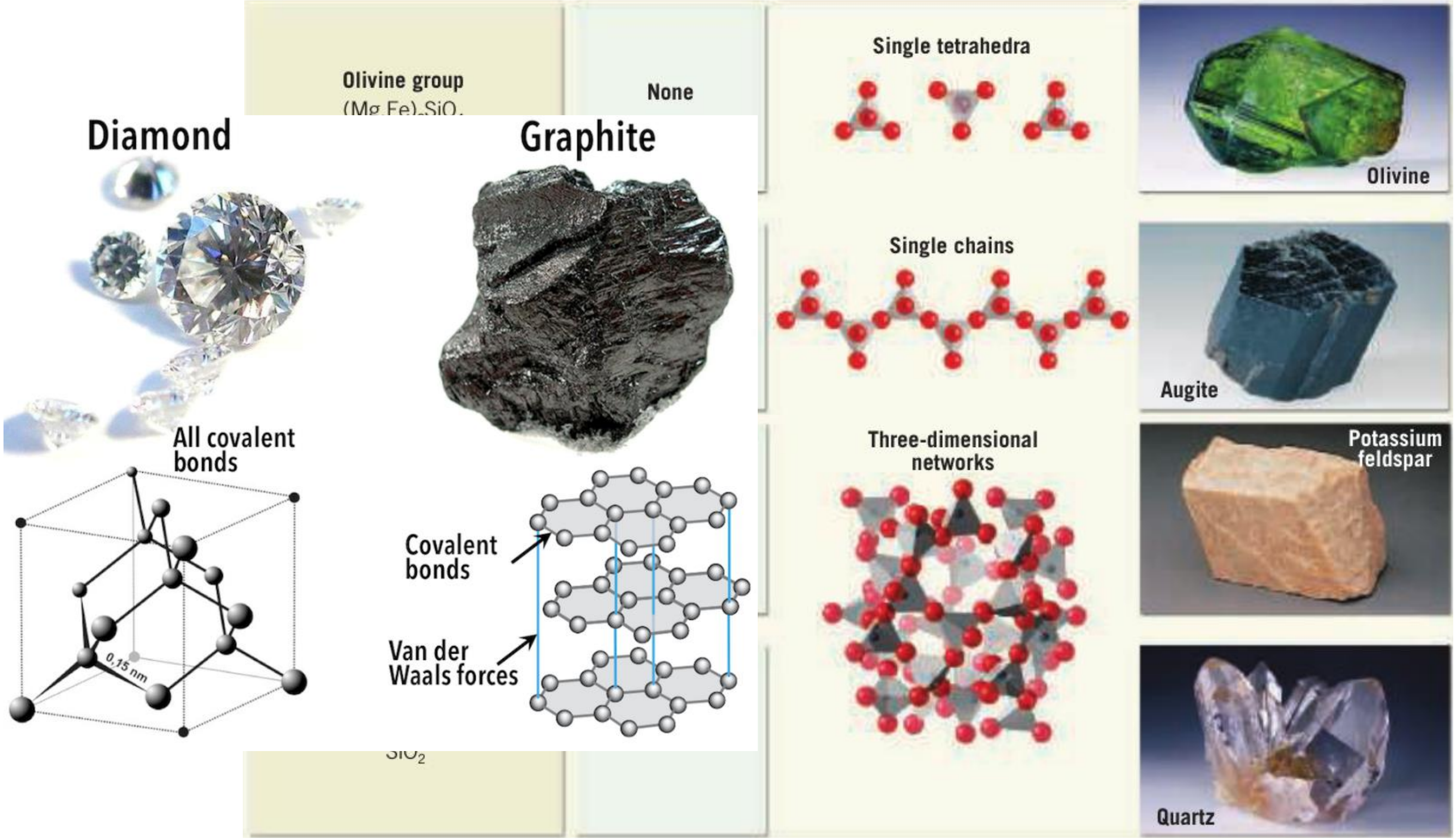
1. Light
2. Dark
   - A more important group
   - Contain Fe and/or Mg , thus are dark and have higher densities
   - e.g. olivines, pyroxenes (garnet – not relevant to us)



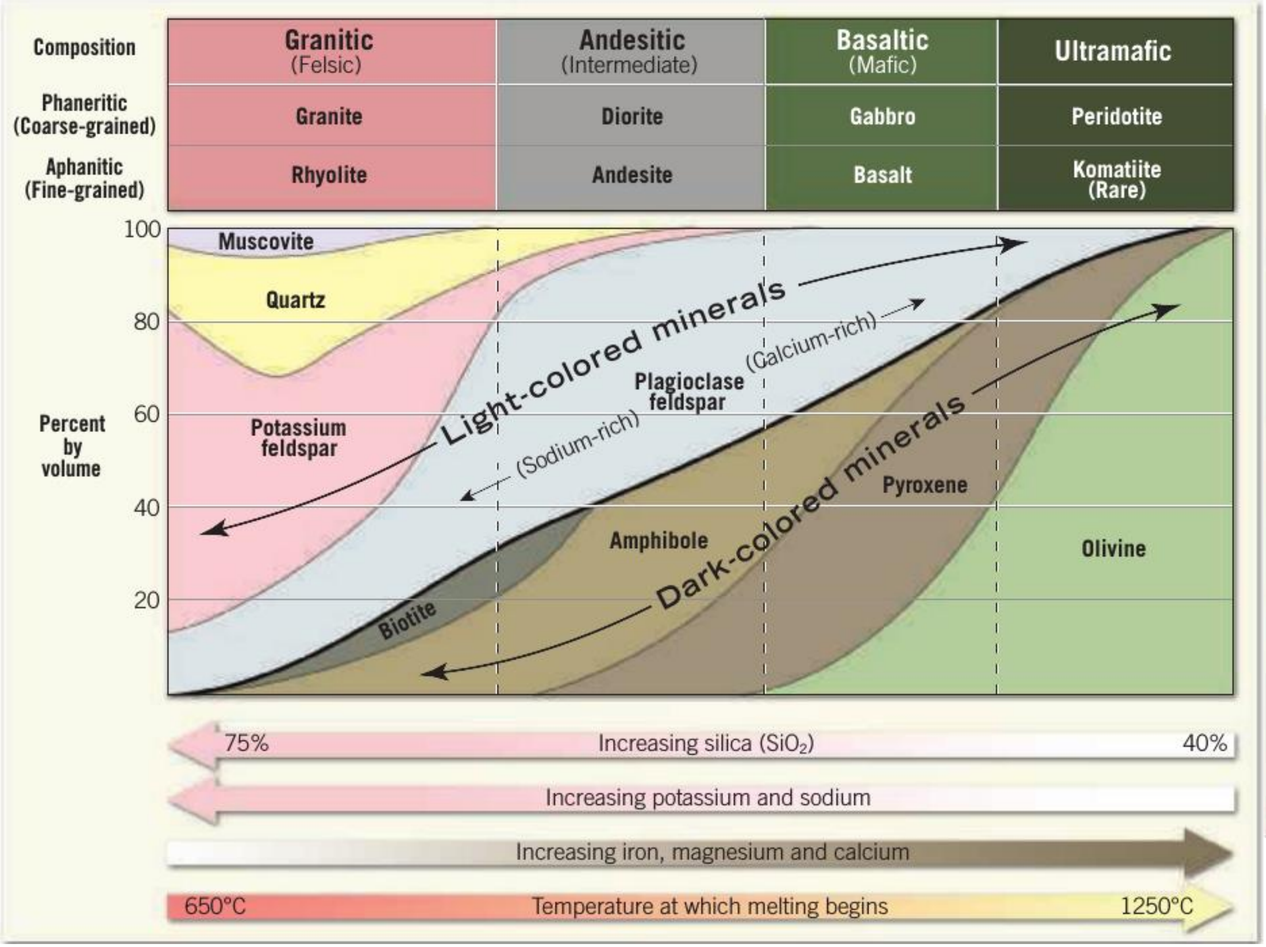
Credit: Tarbuck et al., Earth: An Introduction to Physical Geology (2017)

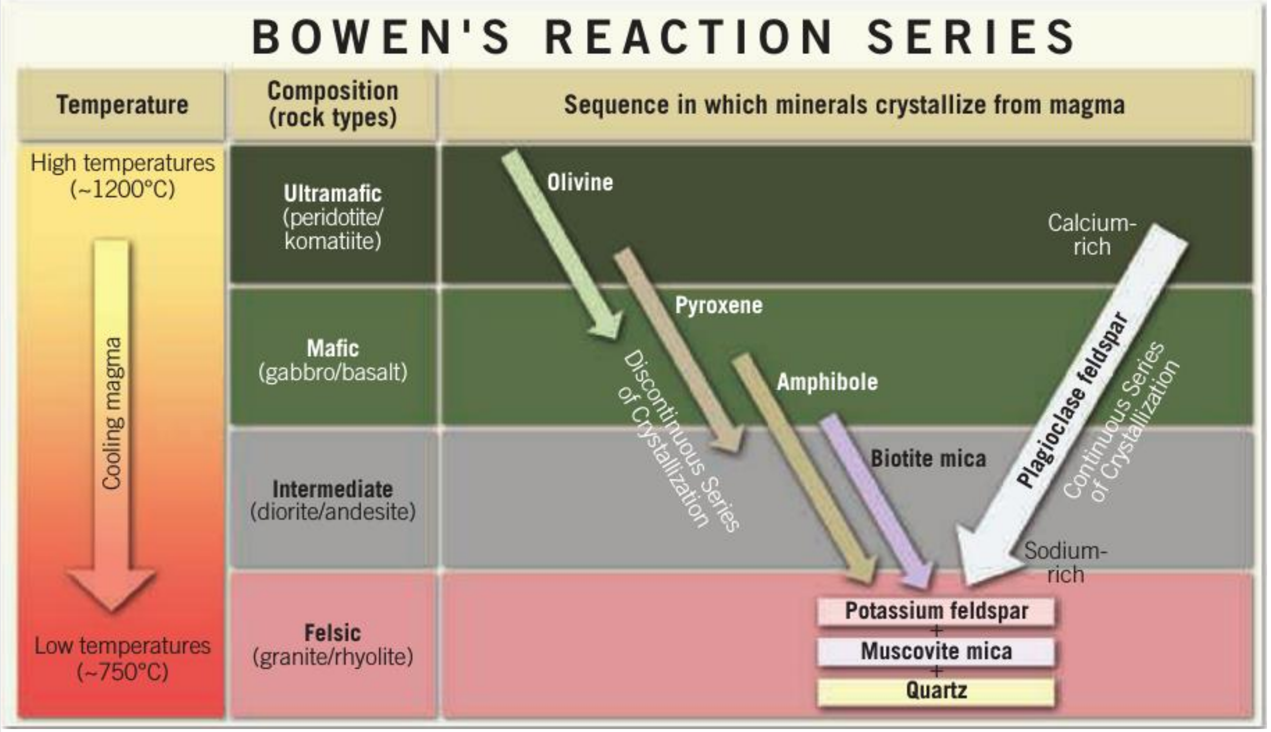


Credit: Tarbuck et al., Earth: An Introduction to Physical Geology (2017) - modified



Credit: K. Panchuk (2018)

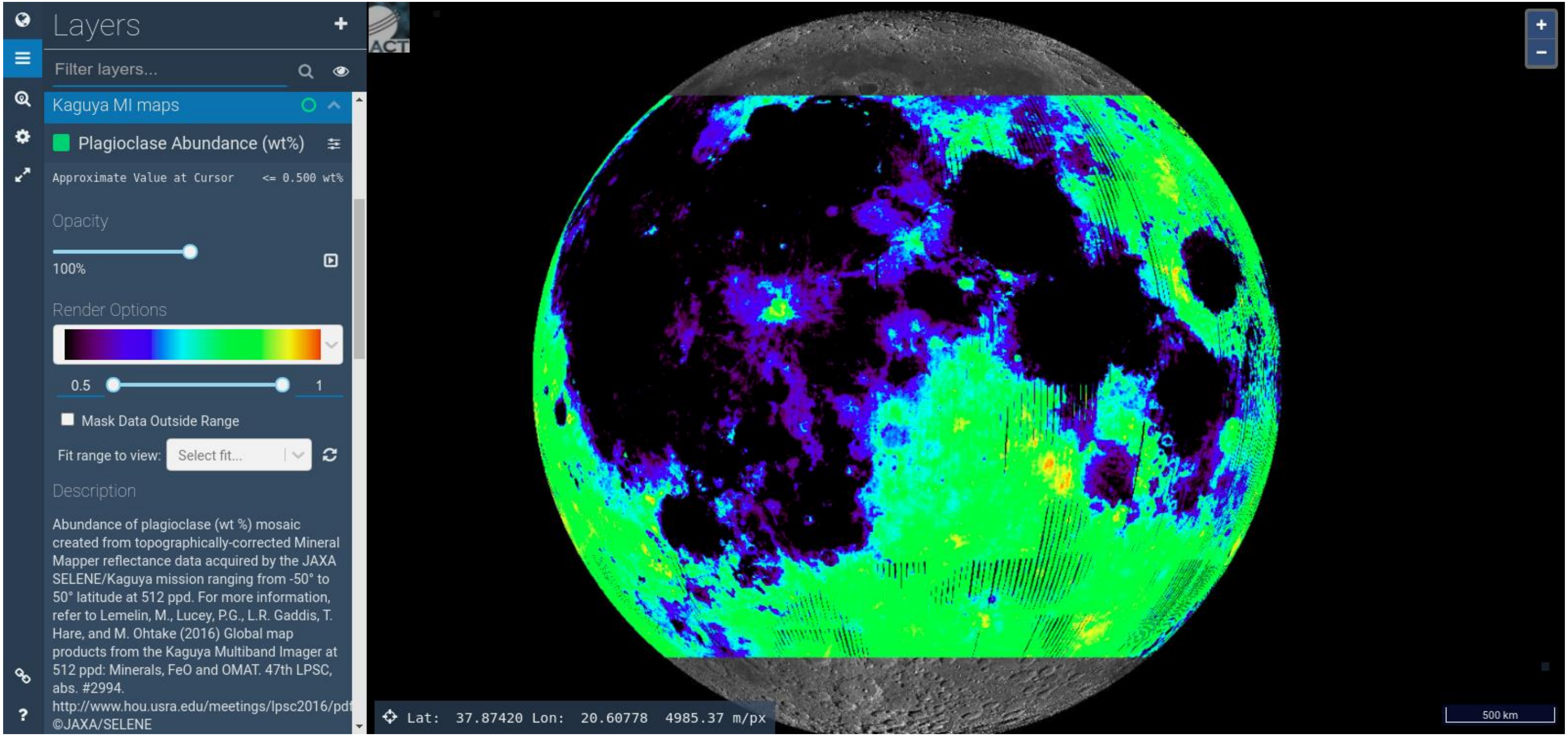




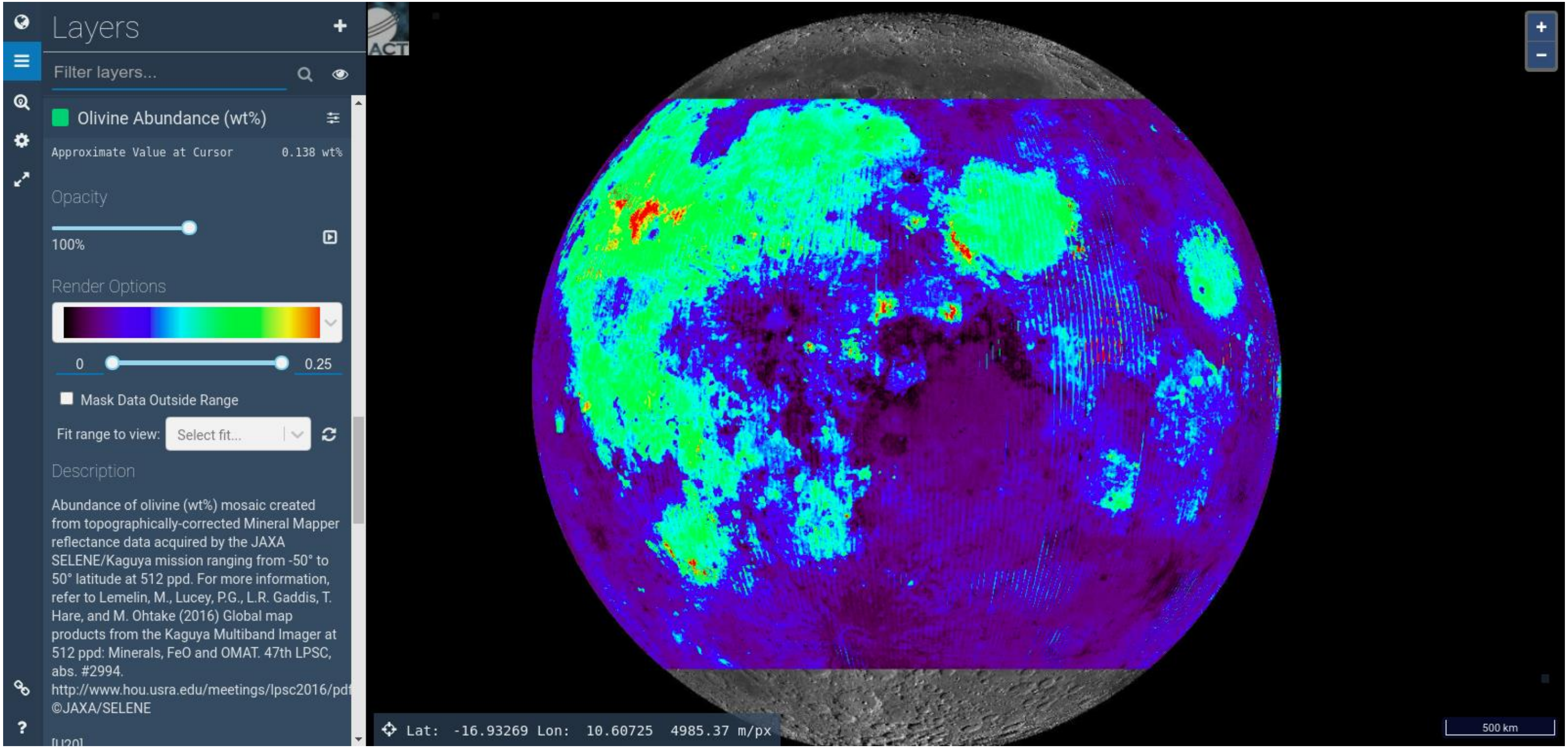
! Small bodies in the Solar system course
-differentiation of planets, larger asteroids

Credit: Tarbuck et al., Earth: An Introduction to Physical Geology (2017)

Credit: LROC Quickmap



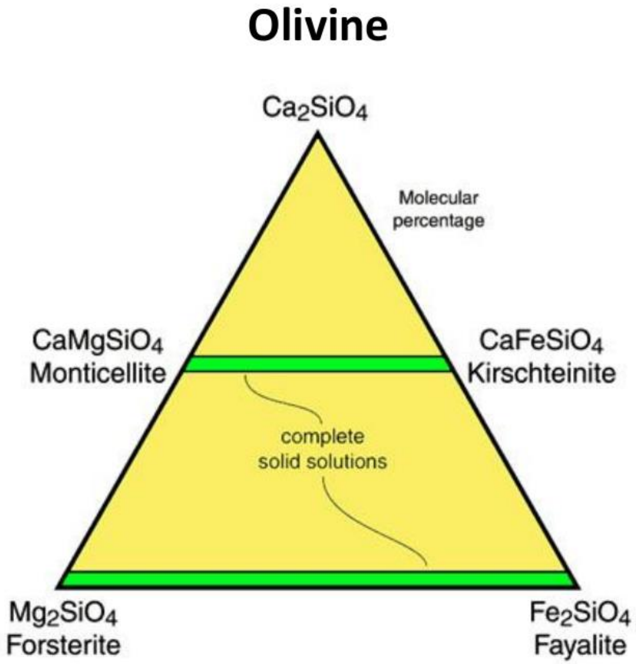
Credit: LROC Quickmap



Credit: LROC Quickmap

Typical minerals - Olivines

- $(Mg,Fe)_2\ SiO_4$
- Black to green color
- As gemstone called peridote
- In Earth's mantle: 50%

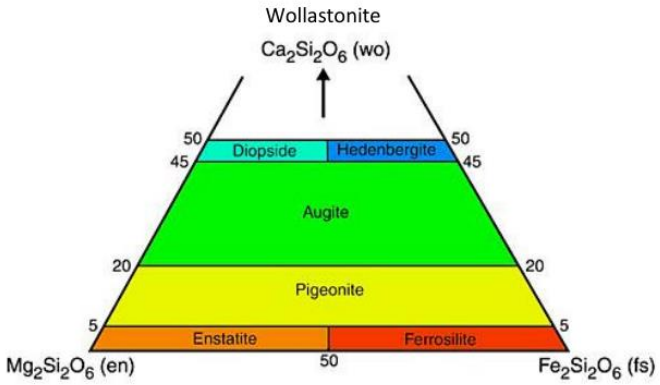


- SS example:
  - asteroids (246) Asporina
  - (1951) Lick
  - Moon

Typical minerals - Pyroxenes

- Don't be scared – just for orientation: three major pyroxenes:
  - Enstatite, Ferrosilite, Wollastonite
- SS example: Moon, (4) Vesta, (25143) Itokawa

Clinopyroxenes (Ca rich)

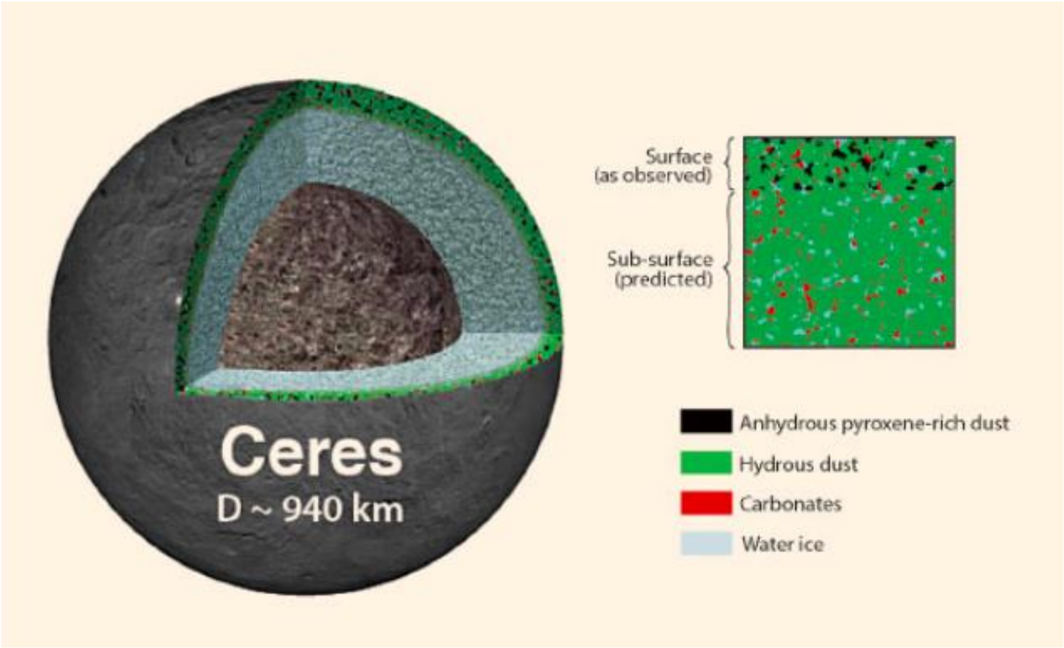


Orthopyroxenes (Ca poor)

Credit: geology.com, mindat.org, e-rocks.com

Non-silicate minerals

- Among the most important groups of non-silicates for the space weathering research are the carbonates
- CO_3^{2-}
- Simpler chains than the silicates
- To be found for example on (1) Ceres



- Other members of this group are not so relevant

  (e.g. sedimentary minerals)

Credit: Vernazza et al. (2017)

Part 2:

Spectra of typical minerals

Spectroscopy

- Clark (1999): "Spectroscopy is the study of light (electromagnetic radiation) as a function of wavelength that has been emitted, reflected, or scattered from a solid, liquid, or gas."

Pros:

- In planetary studies, a very effective tool to study surfaces
- Remote technique
- Reveals info on: mineralogy and physical conditions on the surface
- Is sensitive to small changes in chemical composition and physical state

Spectroscopy

Cons:

- Measured spectra are usually of worser quality than the laboratory ones
  - Lower resolution of the spectrometers
    - Both spatial and spectral
  - When measured from the Earth
    - water absorptions (3000 nm), atmospheric ozone (350 nm), oxygen (760 nm), CO_2 (2000 and 2060 nm)
- Other effects play role and make it uneasy to interpret the spectra (See Parts 3 and 4)

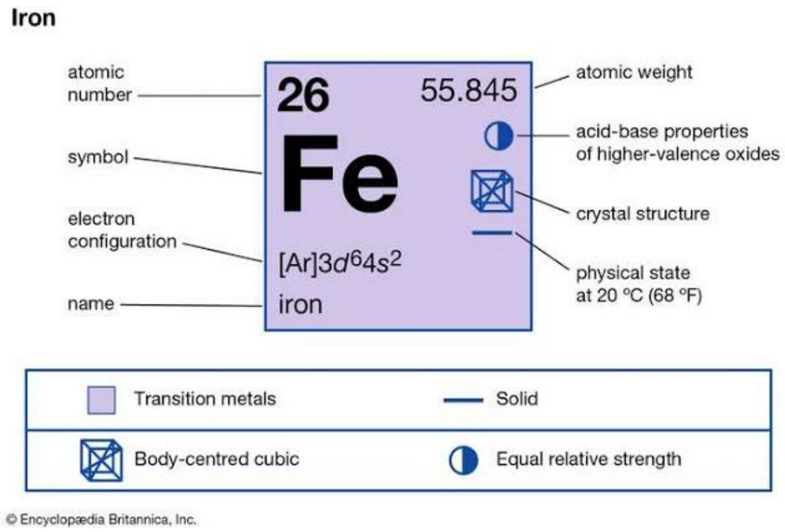
Spectral curves – VIS-NIR

- We are focused onto visible and near-infrared spectra
- Usually measured are wavelengths between 400 and 3000 nm
- These cover the characteristic absorption bands of the most significant minerals
  - Sudden drops in the continuum reflectance
  - Continuum is the overall inclination of the spectral curve
  - When the observed surface consists of more minerals, their absorption bands are all present in the spectra – causes great complexity

Crystalline lattice vs absorptions

- Simple model:
  - Atomic-level
  - A drop in the spectrum is caused by absorption of a photon
  - Consequent de-excitation and reradiation at a slightly different energy

- In crystalline latice, atoms are influenced by each other
  - This causes splitting of energy levels of *3d* orbitals of metal cations
  - Due to presence of oxygen ions



Crystalline lattice vs absorptions

- Depends on the shape of the basic unit
  - Influenced by ligands, symmetry, distortion,…
  - This is how we recognize different compositions
    - Slight shifts to the positions of the bands and their shapes

- Other reasons for creation of the bands:
  - Molecular vibrations in the lattice
  - Conduction bands
  - Transfer of electrons between ions

(a) and (d) pyroxene

(b) and (c) olivine

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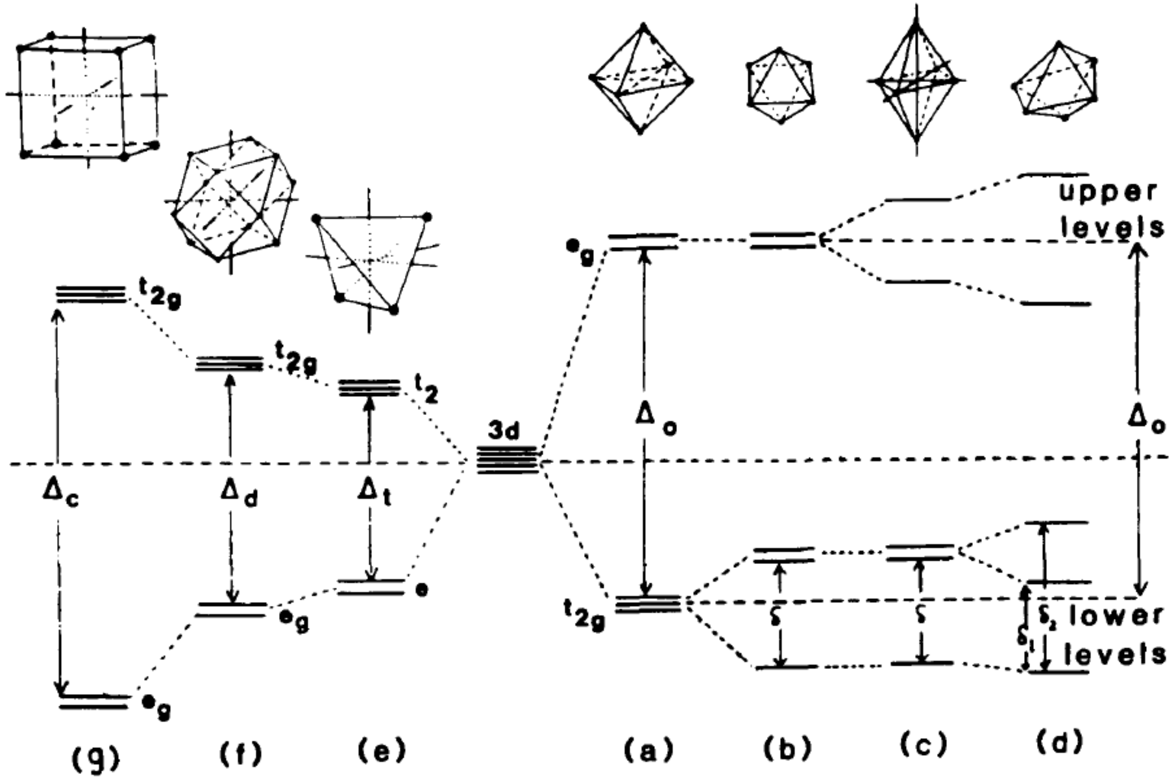


FIG. 1. Relative energies of 3-*d* orbitals of a transition metal ion in different coordination environments (modified from Burns, 1985). (*a*) regular octahedron (e.g. ~pyroxene *M*1 site; basaltic glass); (*b*) trigonally distorted octahedron (e.g. ~olivine *M*2 site; spinel); (*c*) tetragonally distorted octahedron (e.g. ~olivine *M*1 site); (*d*) very distorted six-coordination site (e.g. pyroxene *M*2 site); (*e*) tetrahedral site (e.g. spinel; basaltic glass); (*f*) dodecahedral site (e.g. ~perovskite *A*-site); (*g*) cubic site (e.g. ~garnet). Note that the 3-*d* orbitals are separated into widely spaced energy levels in the pyroxene *M*2 site, and these splittings are responsible for the 1 μm and 2 μm spectral features for Fe^{2+} ions.

Credit: R. Burns (1988)

cavities

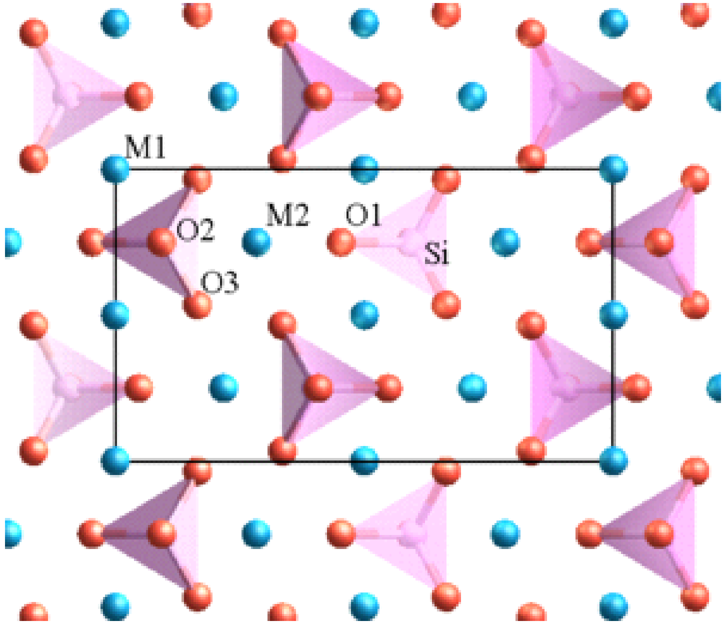
crystal damage

trace amounts of Fe

trace amounts of Mn

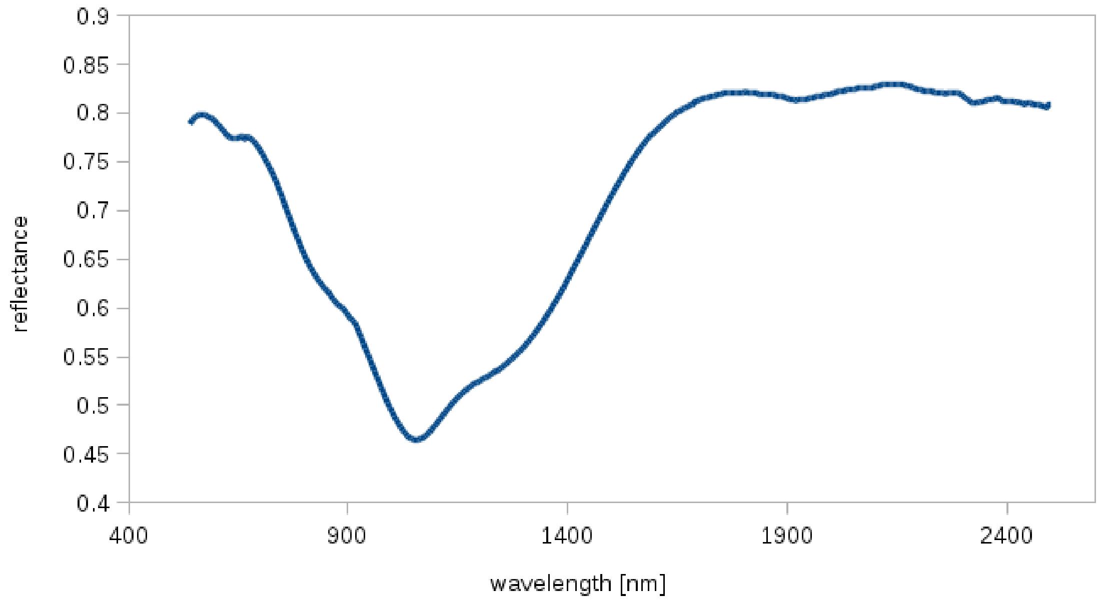
Olivine example

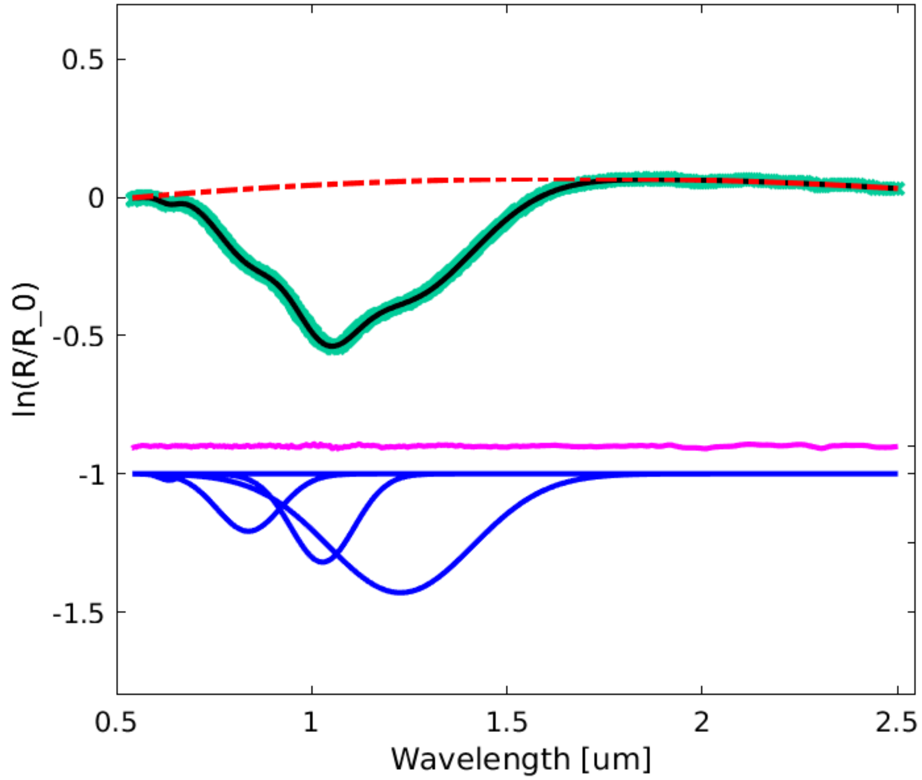
- In olivine, there are two major positions of the transition ion
  - M1 – creates a band at approx. 1 μm
  - M2 – creates two bands at approx. 850 and 1250 nm



Credit: https://www.newworldencyclopedia.org/

Olivine example

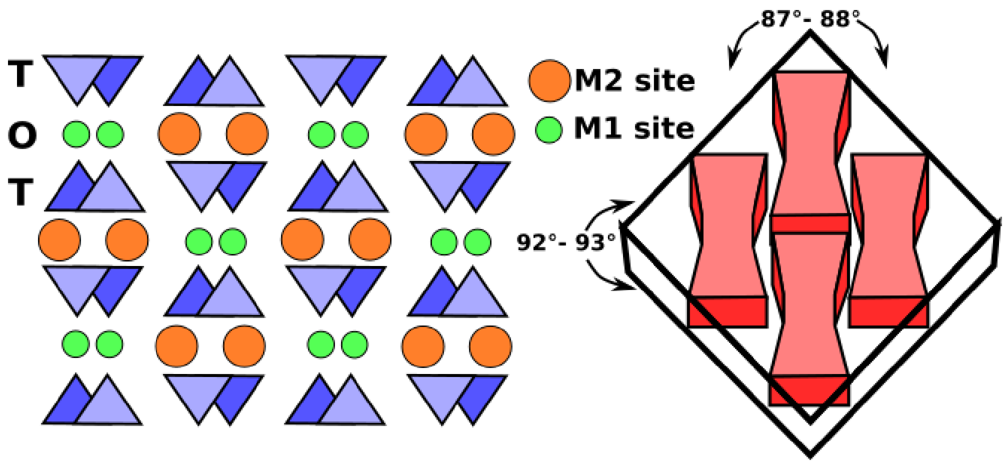




Pyroxene example

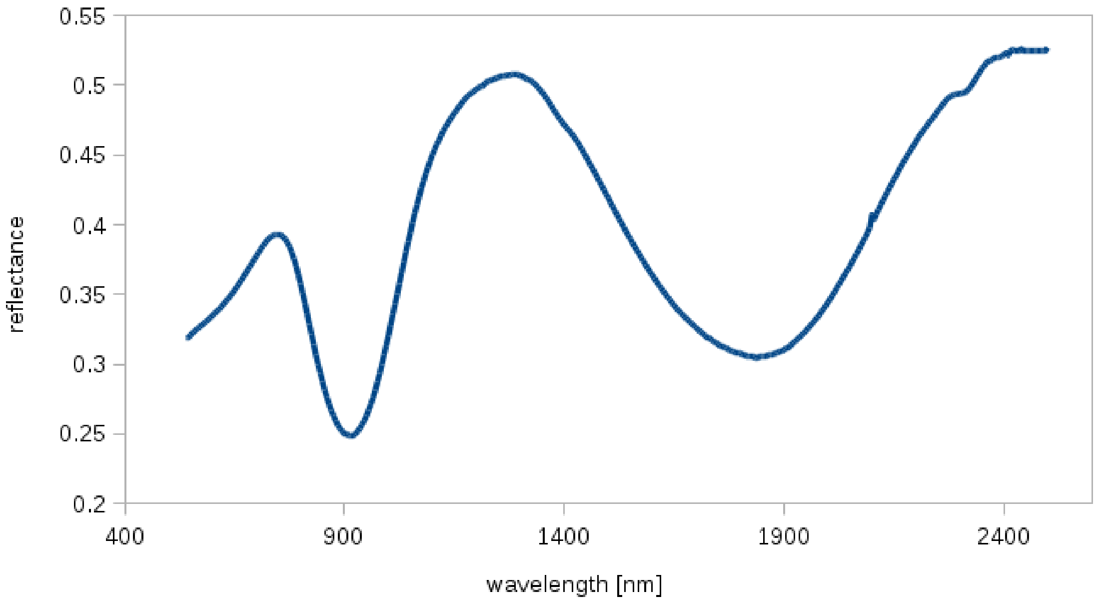
- Pyroxene also shows two sites:
  - M1 is regular octahedron
  - M2 is highly distorted
  - Causes a huge separation of the two bands

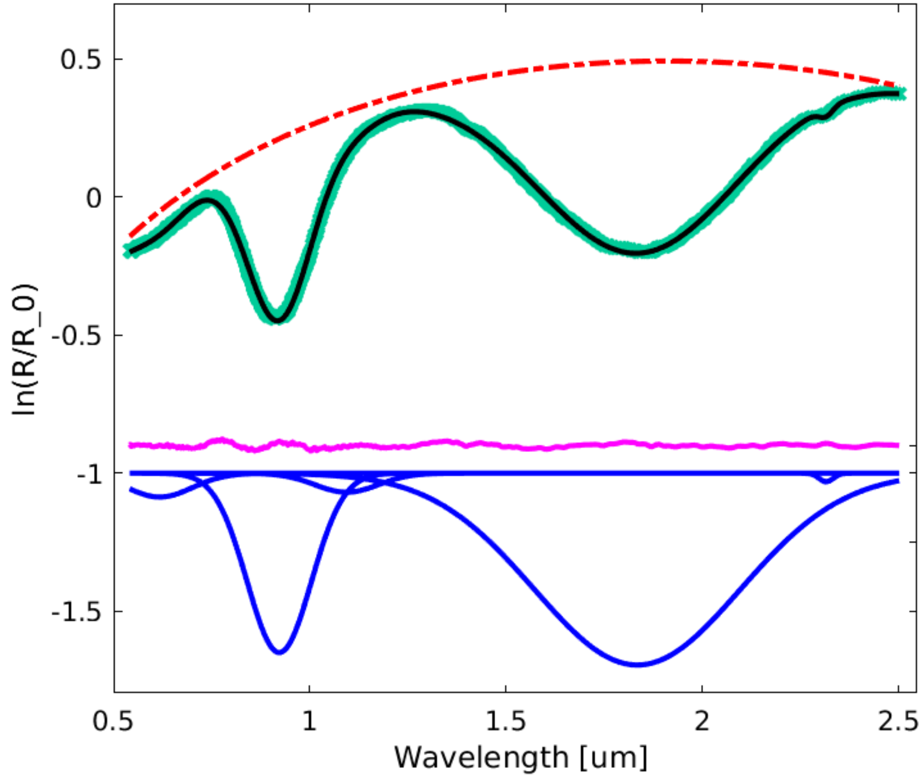
    Not as in the case of olivine



- Especially in the remote sensing data, the 1 μm is easily confused/mixed with the olivine bands, so the 2 μm band is more diagnostic

Pyroxene example



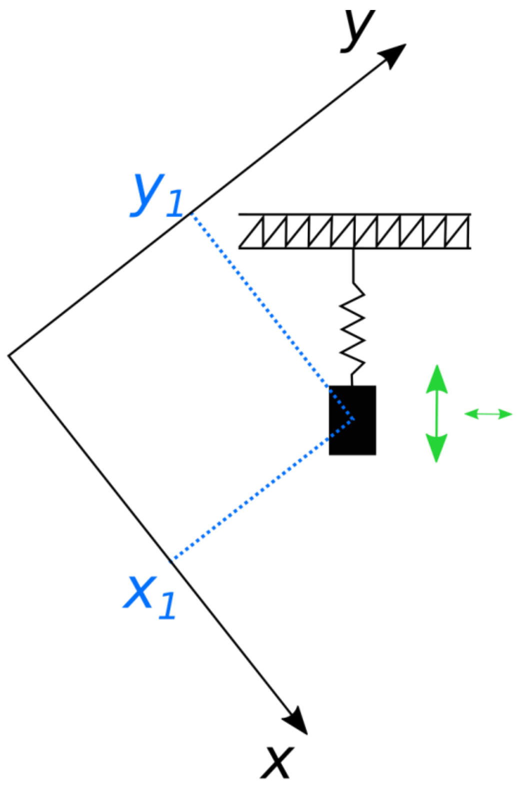


Asteroid spectral types

- Asteroids are composed of minerals
- In majority of cases we have one spectrum representative of the whole asteroid surface
  - i.e. mixture of all the minerals

- Based on the spectra, we divide asteroids into groups/spectral types
  - First attempts already in 60's and 70's
  - Widely used classifications by Thollen (1984) based on the Eight-Color Asteroid Survey
  and by Bus and Binzel (2002) based on SMASSII dataset
  - Nowadays: DeMeo et al. (2009) classification based on principal component analysis of merged SMASSII dataset and more observations

PCA



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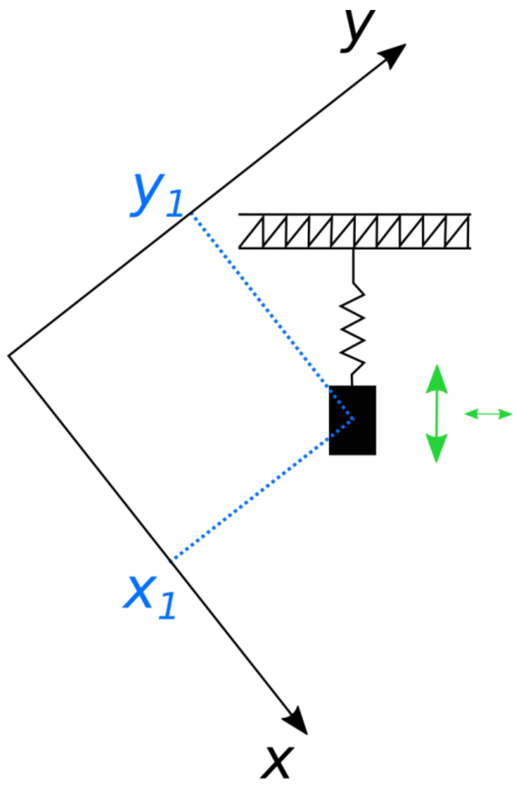
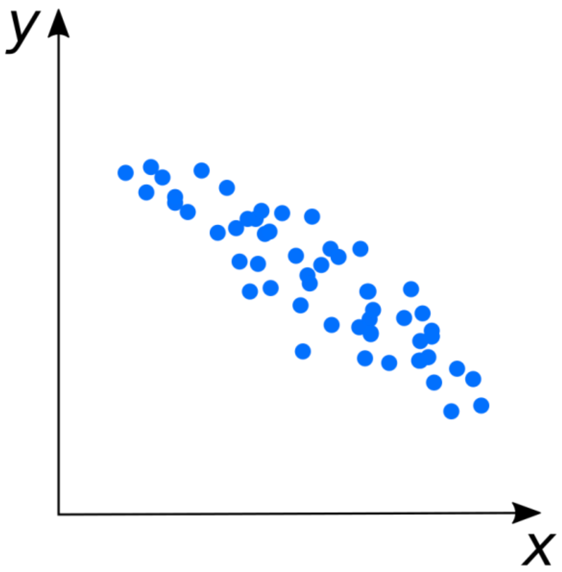
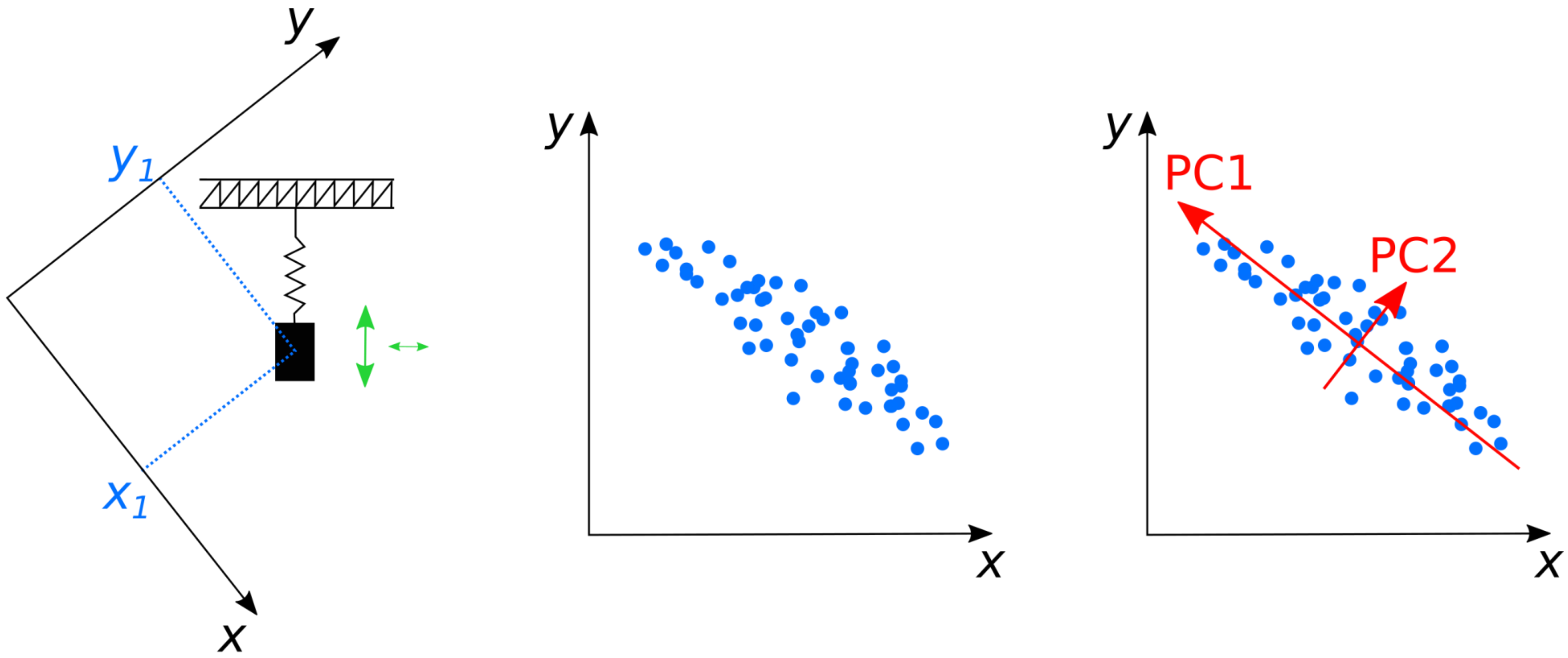
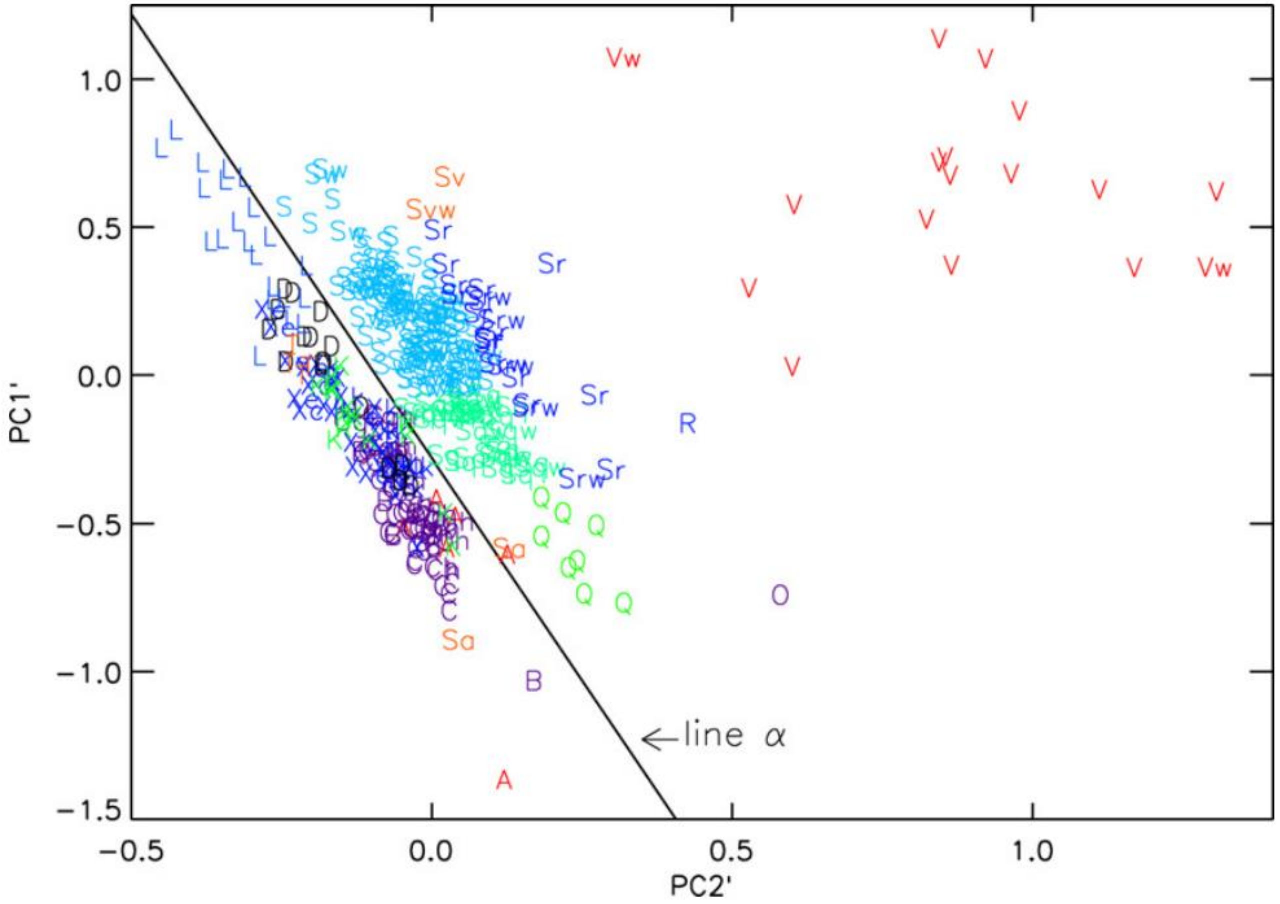


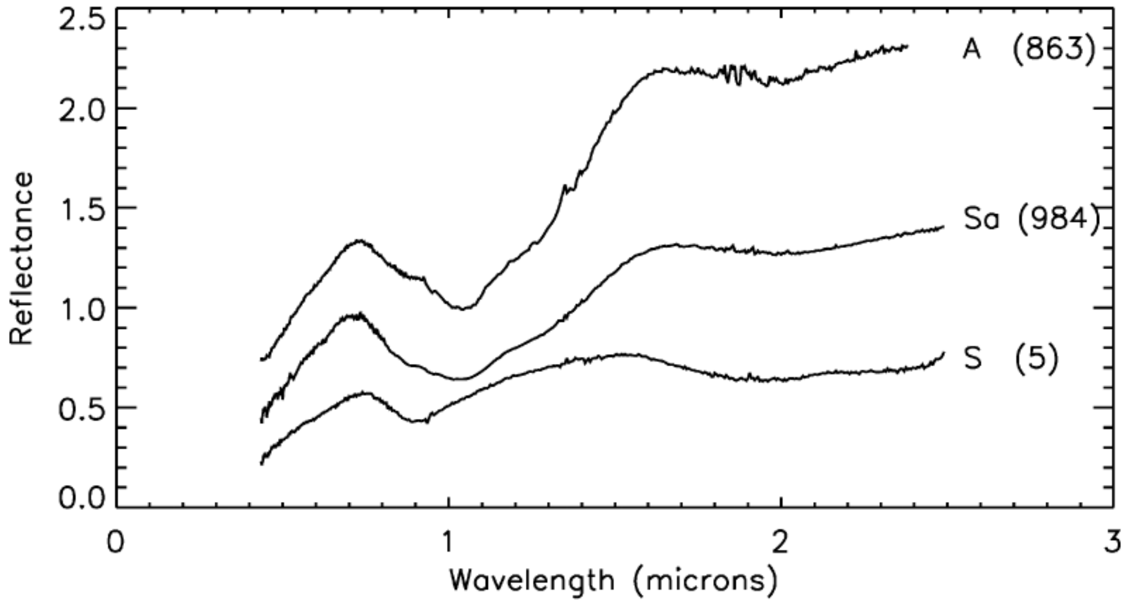


PCA



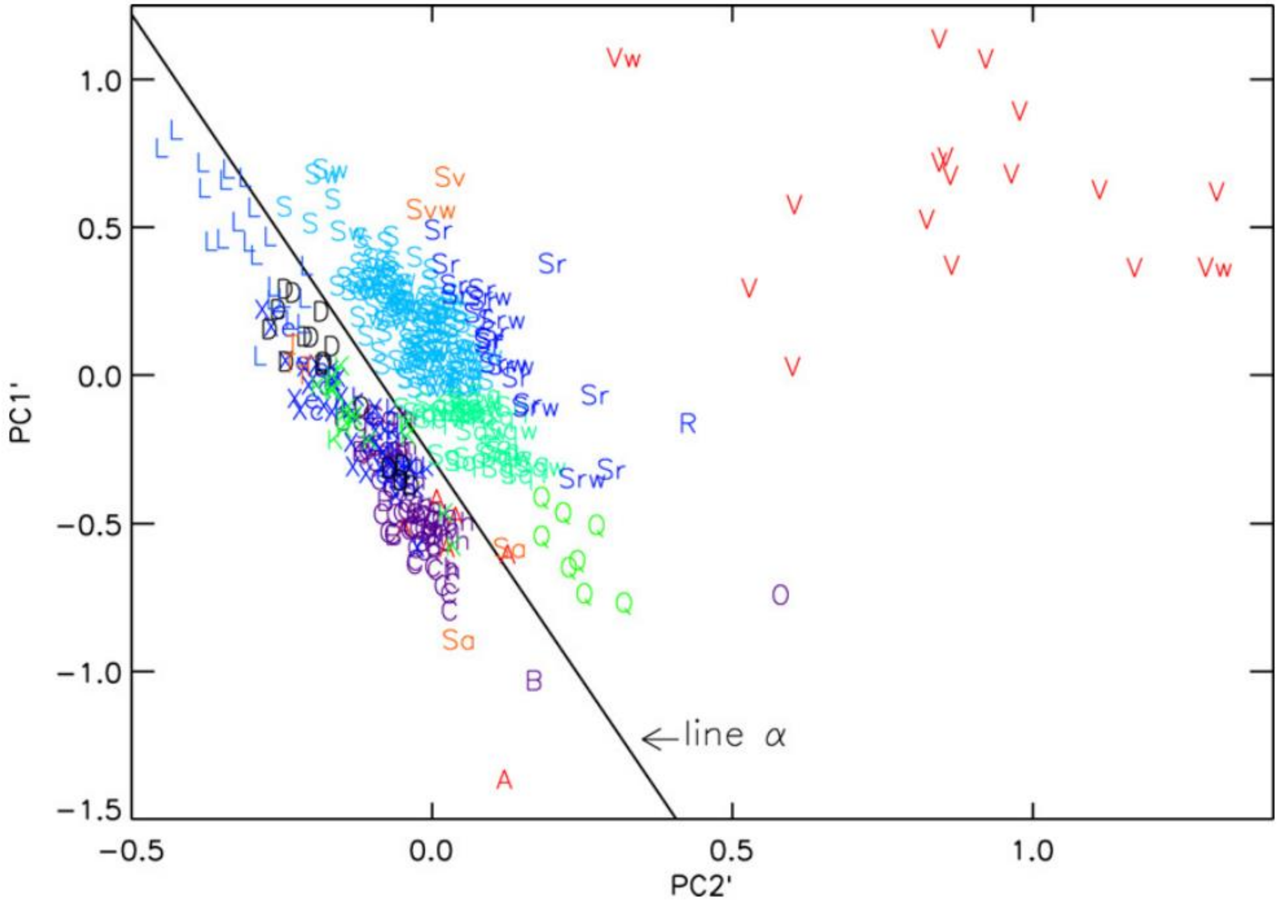
Asteroid spectral types

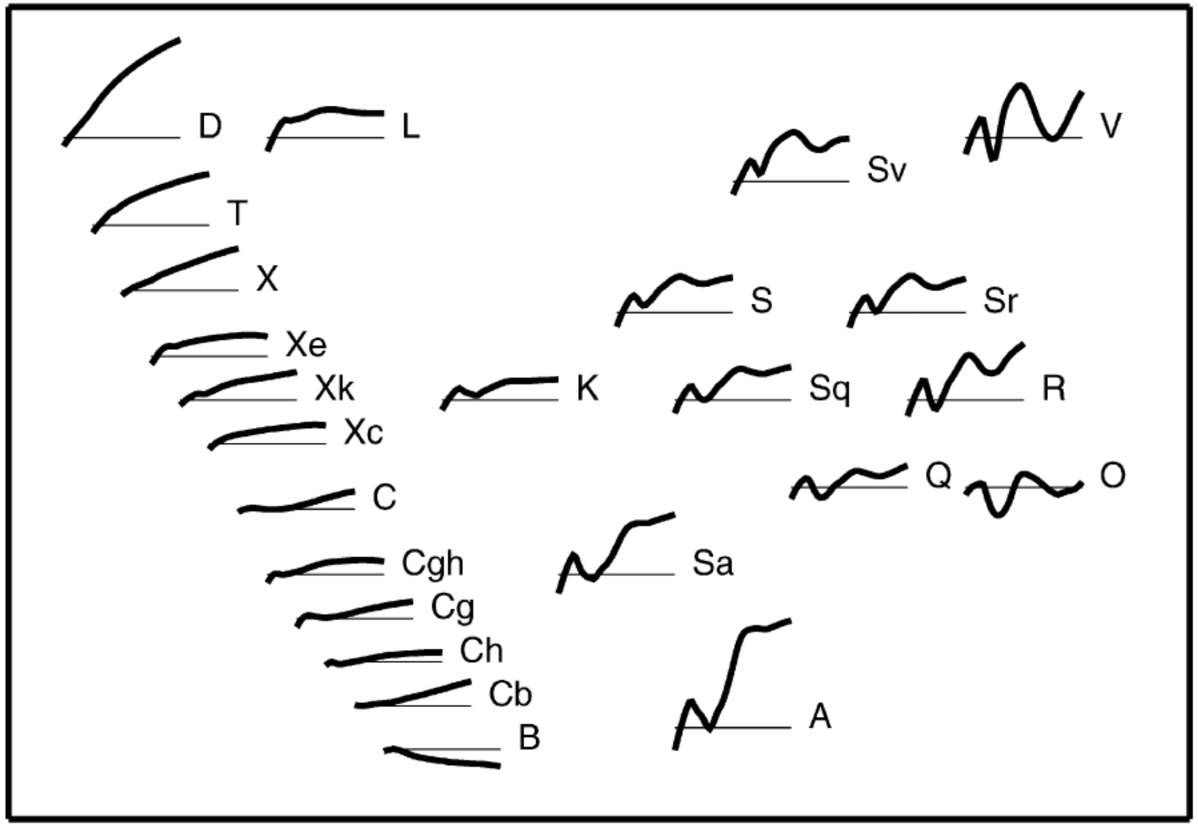




Credit: DeMeo et al. (2009)

Asteroid spectral types

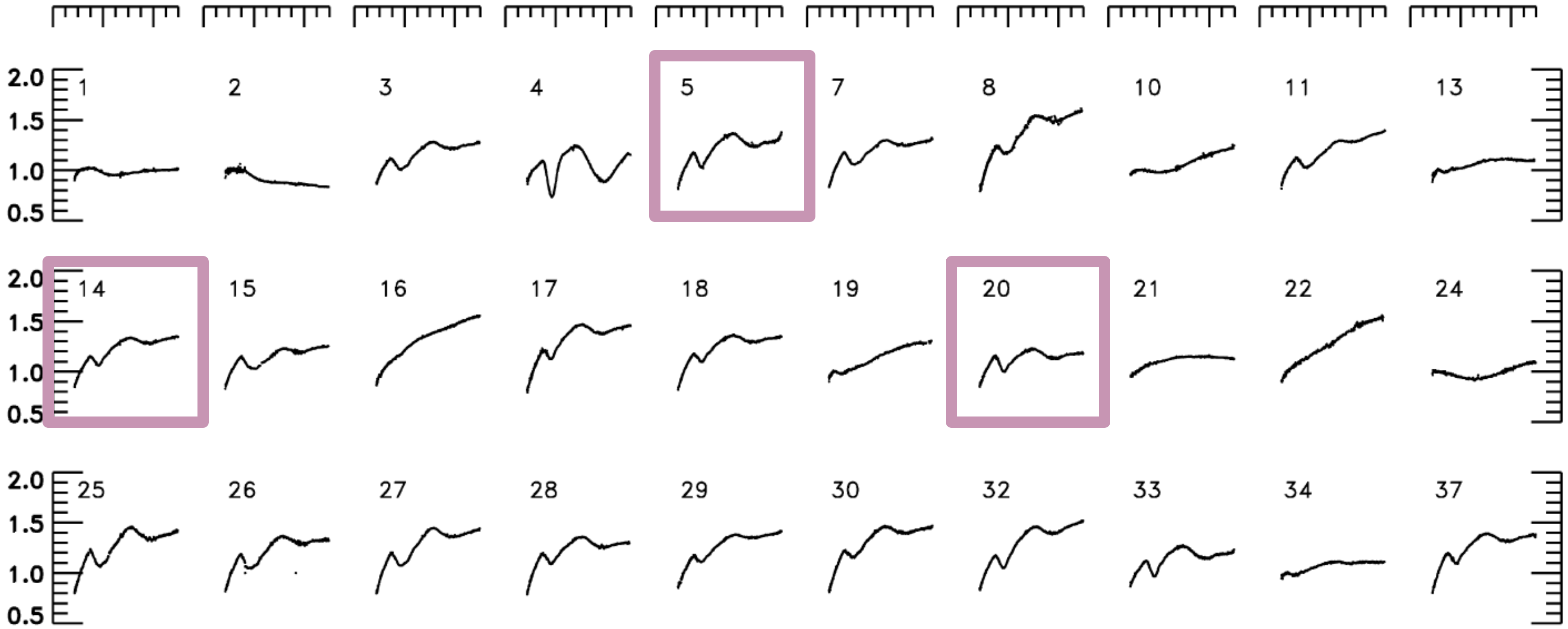




Credit: DeMeo et al. (2009)

Asteroid spectral types – S-types

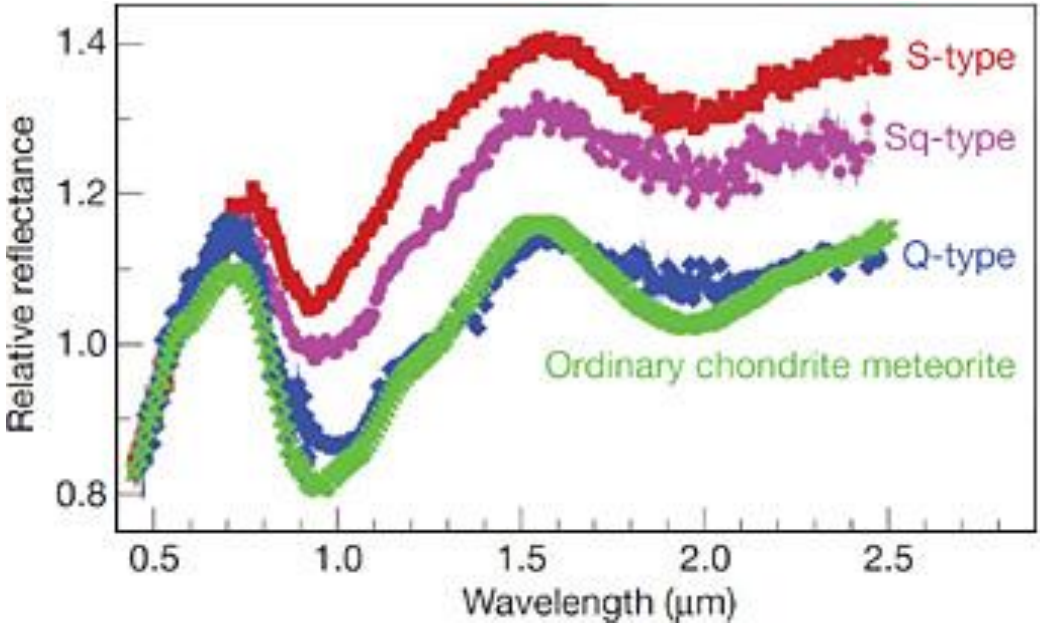
- Asteroids rich in silicates
- Typical 1- and 2-μm bands of moderate depth
- Examples: (5) Astraea, (14) Irene, (20) Massalia, (433) Eros



Credit: DeMeo et al. (2009)

Asteroid spectral types – Q-types

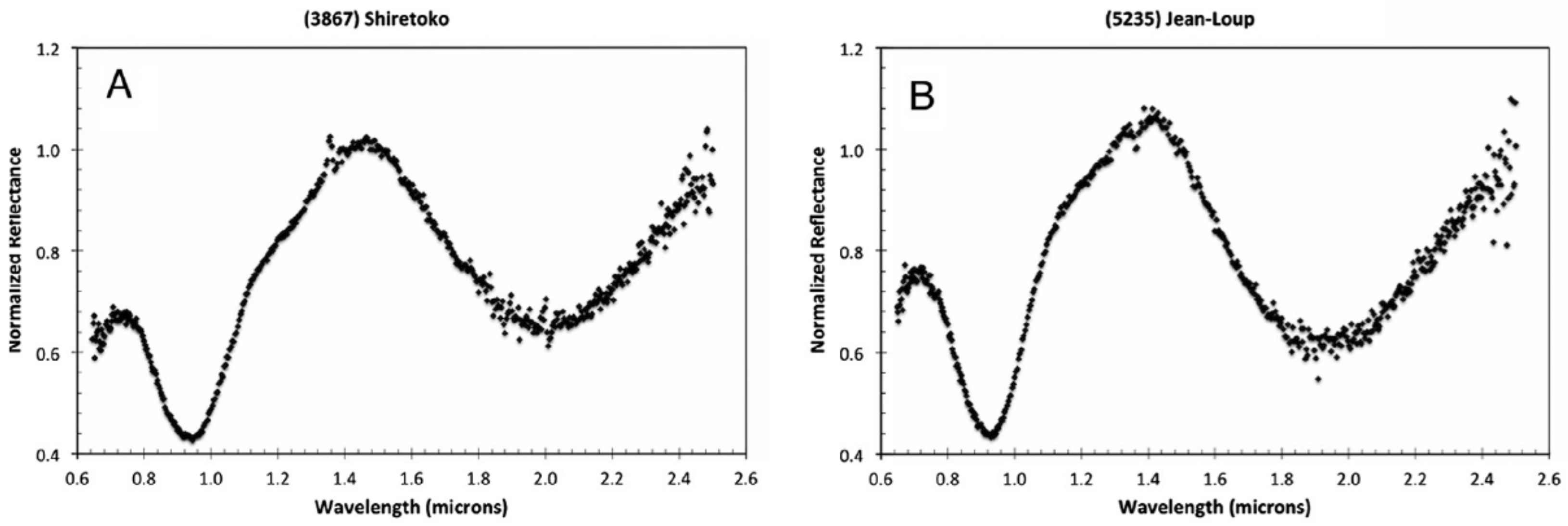
- Very similar to S-types, but with deeper bands and higher albedos, see the discussion next lecture
- Examples: (1862) Apollo or (3753) Cruithne



Credit: R. Binzel

Asteroid spectral types – V-types

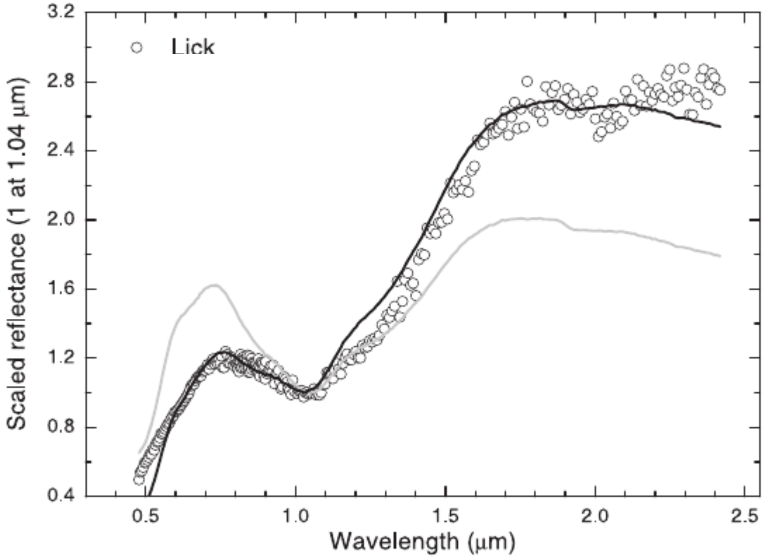
- Asteroids with very strong 1- and 2-μm feature
- Vesta-like, pyroxene-rich
- Examples in the SS: (4) Vesta, (1929) Kollaa



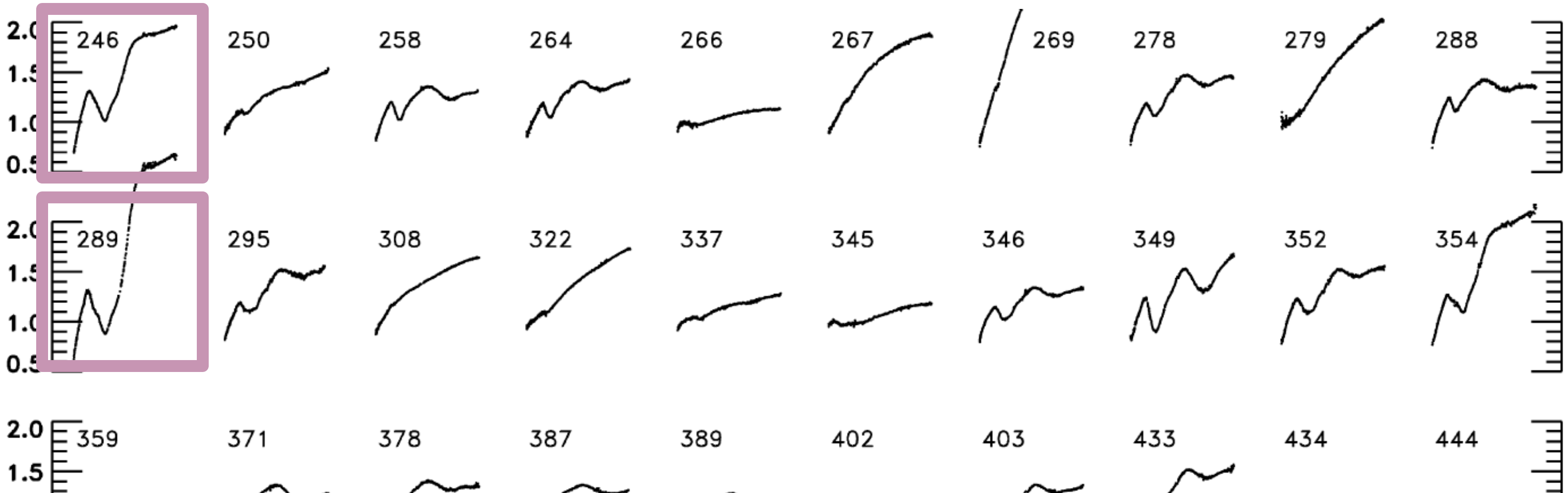
Credit: Hardersen et al. (2014)

Asteroid spectral types – A-types

- Asteroids with very deep absorption at 1 μm, may or may not have shallow absorption at 2 μm
- All with very high slopes
- Olivine-rich
- Example in the SS: (246) Asporina, (289) Nenetta, (1951) Lick



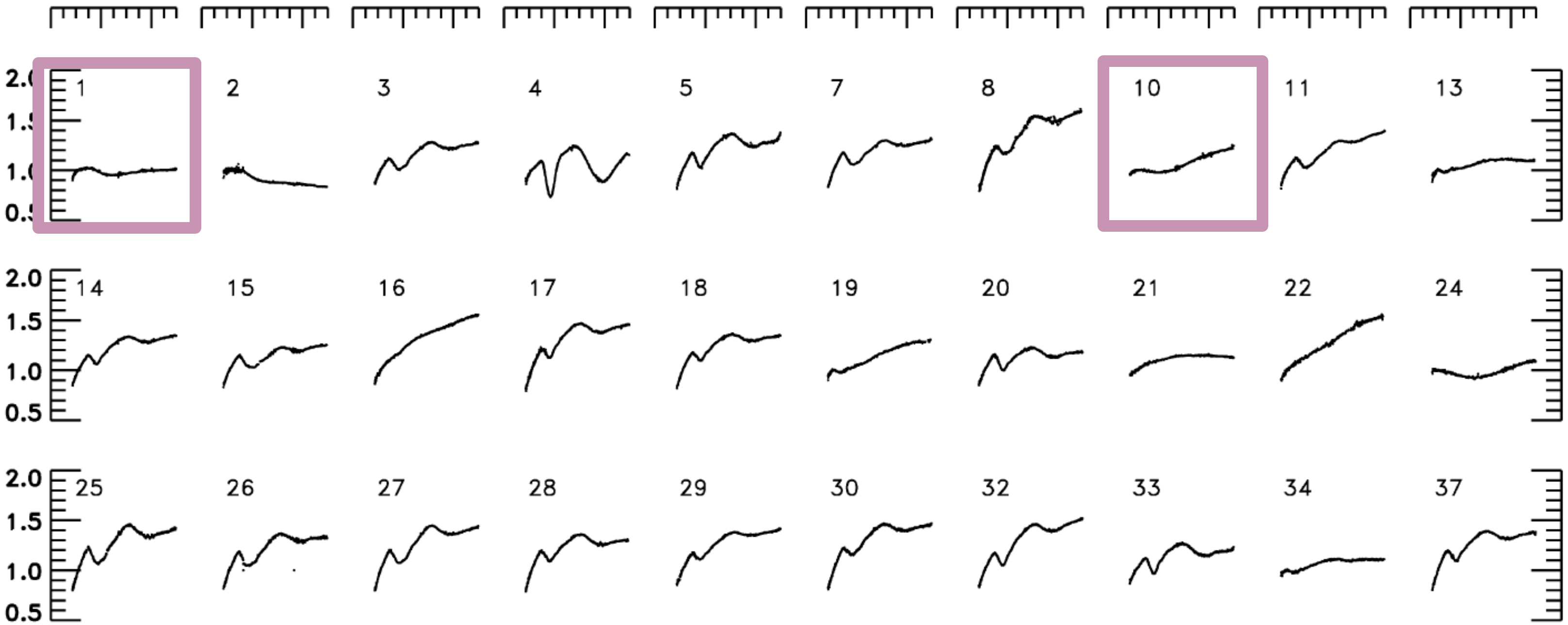
Credit: Brunetto et al. (2007)



Credit: DeMeo et al. (2009)

Asteroid spectral types – C-types

- Nearly feature-less spectra, carbon-rich, primitive
- Linear, neutral slopes with a slight bump around 600 nm
- Examples in the SS: (1) Ceres, (10) Hygiea, (52) Europa, (162173) Ryugu



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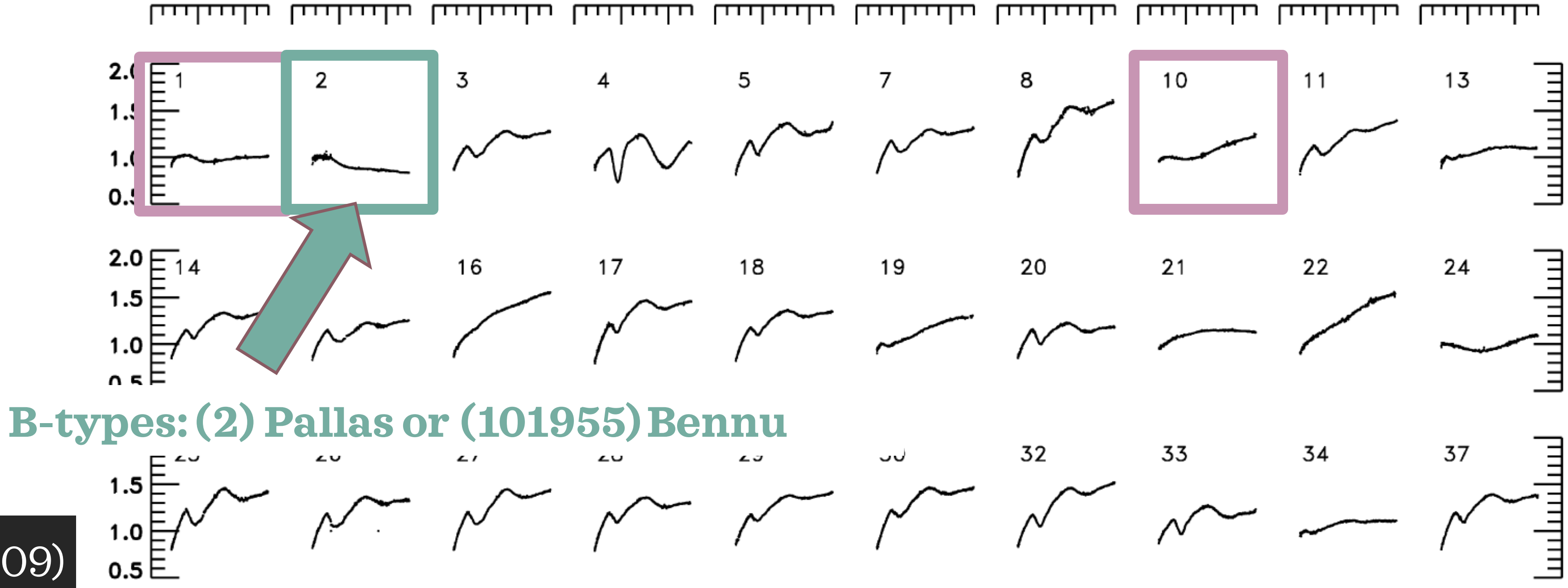


Credit: DeMeo et al. (2009)

Asteroid spectral types – use

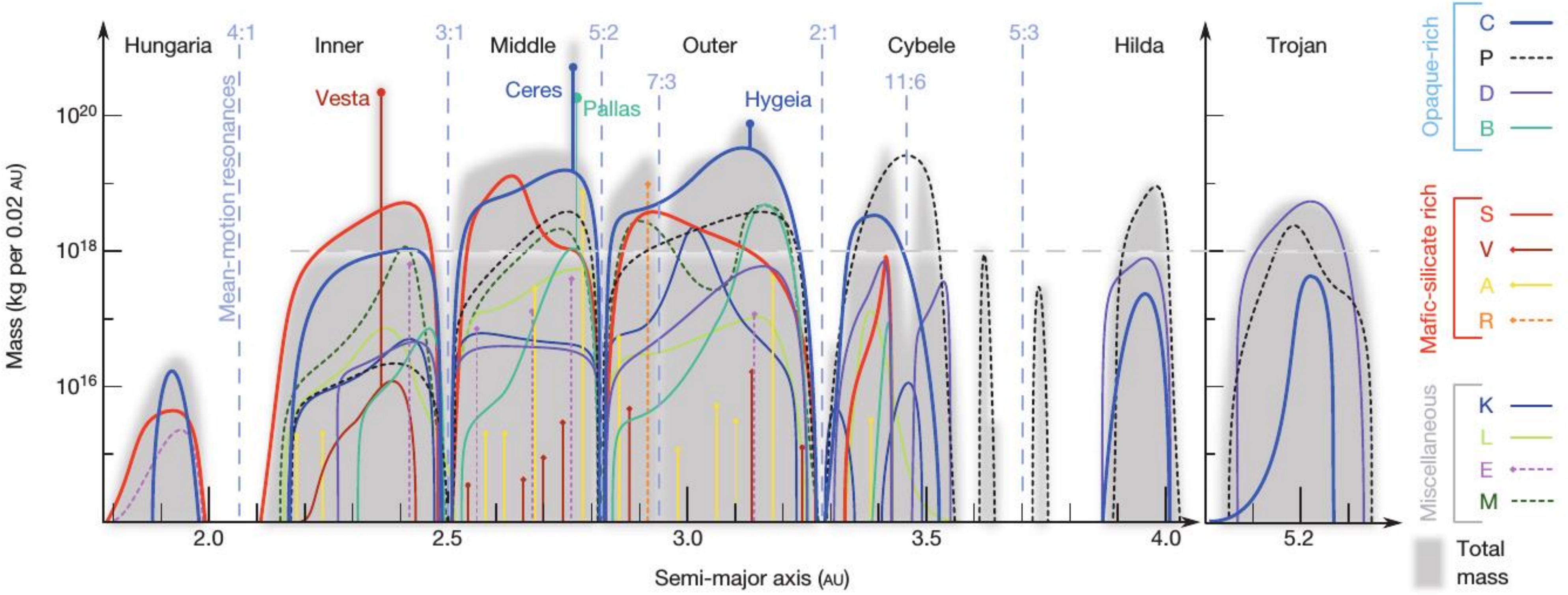
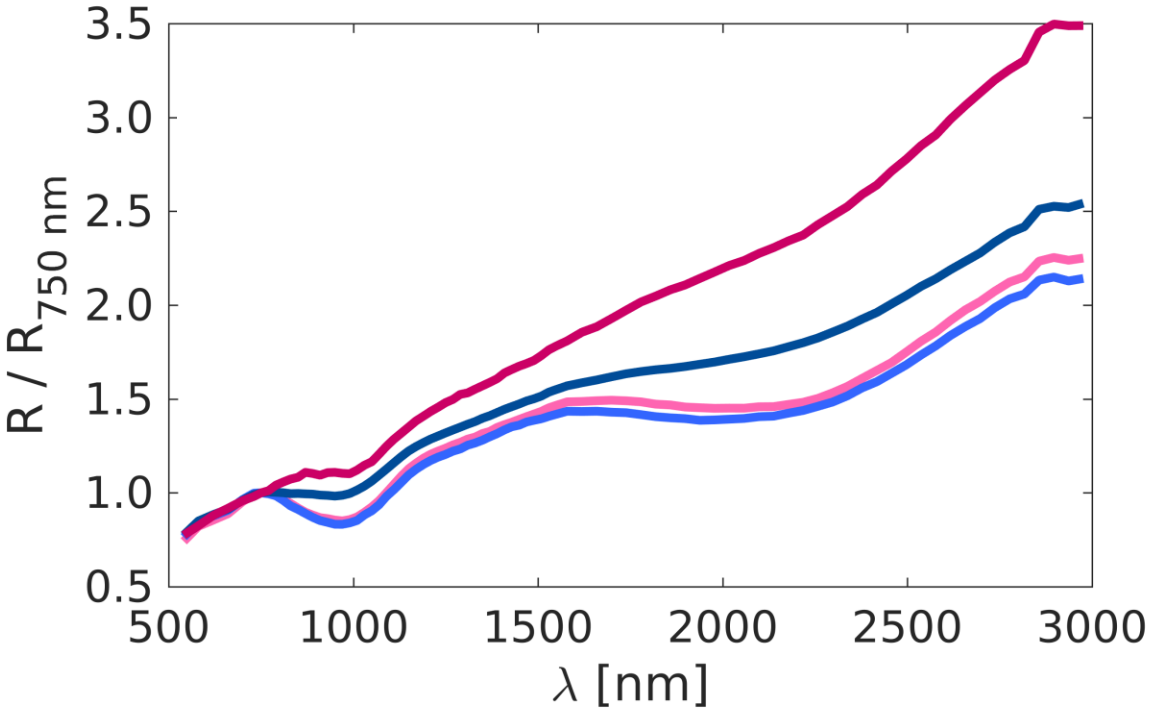


Figure 3 | The compositional mass distribution throughout the asteroid belt out to the Trojans. The grey background is the total mass within each 0.02-AU bin. Each colour represents a unique spectral class of asteroid, denoted by a letter in the key. The horizontal line at 10^{18} kg is the limit of the work from the 1980s[2,8,9]. The upper portion of the plot remains consistent with that work, but immense detail is now revealed at the lower mass range[19].

Credit: DeMeo and Carry (2014)

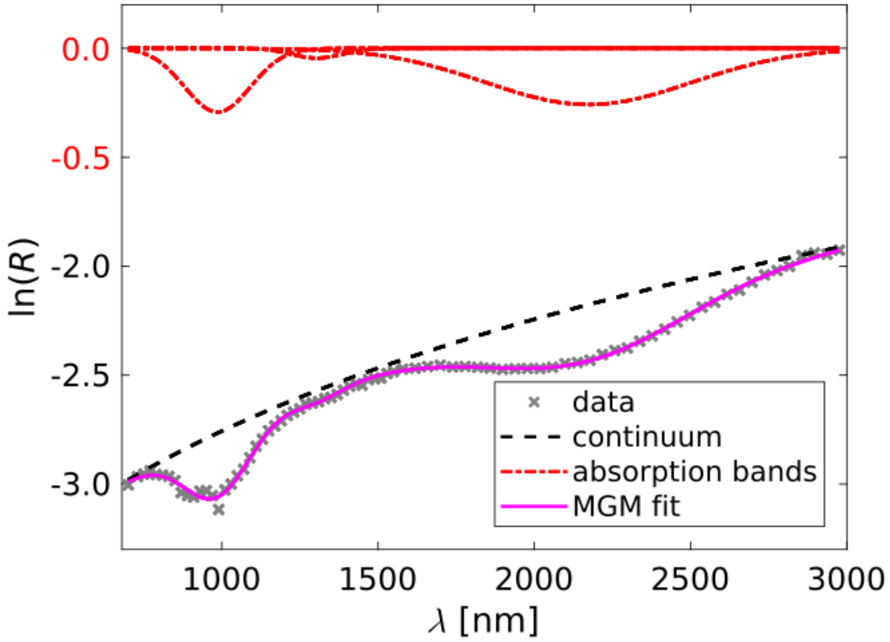
Lunar spectrum

- Moon Mineralogy Mapper – spectrometer onboard Chandrayaan-1 spacecraft
- Example from Oceanus Procellarum



Problematic issues when interpreting

- How to define the continuum?
  - Black body?
  - We still don't understand what are the physical causes
  - Usually thought of as a linear function of energy
- Modelling through logarithm of reflectance
  - Modified Gaussian Model



And other...

Part 3:

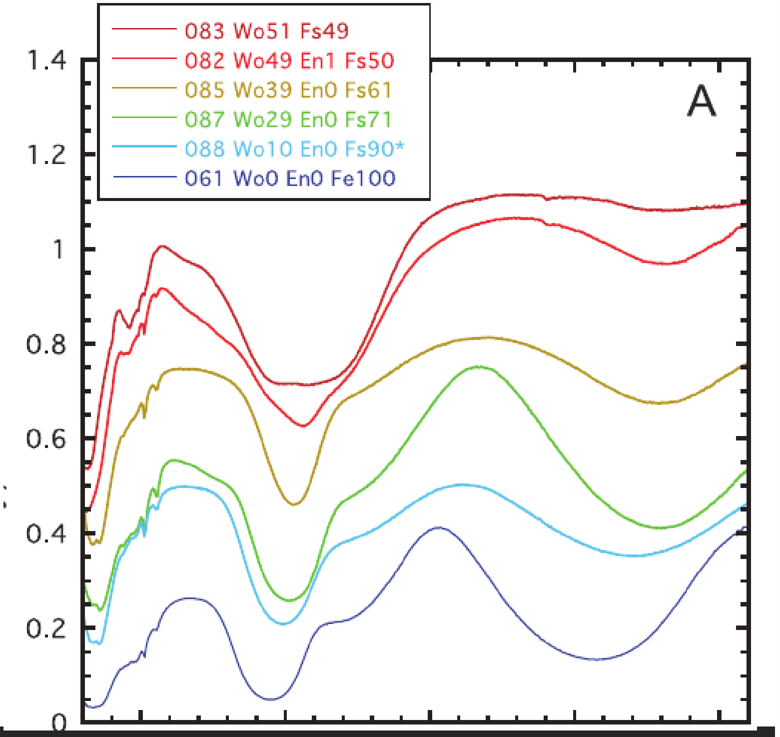
What influences the spectra?

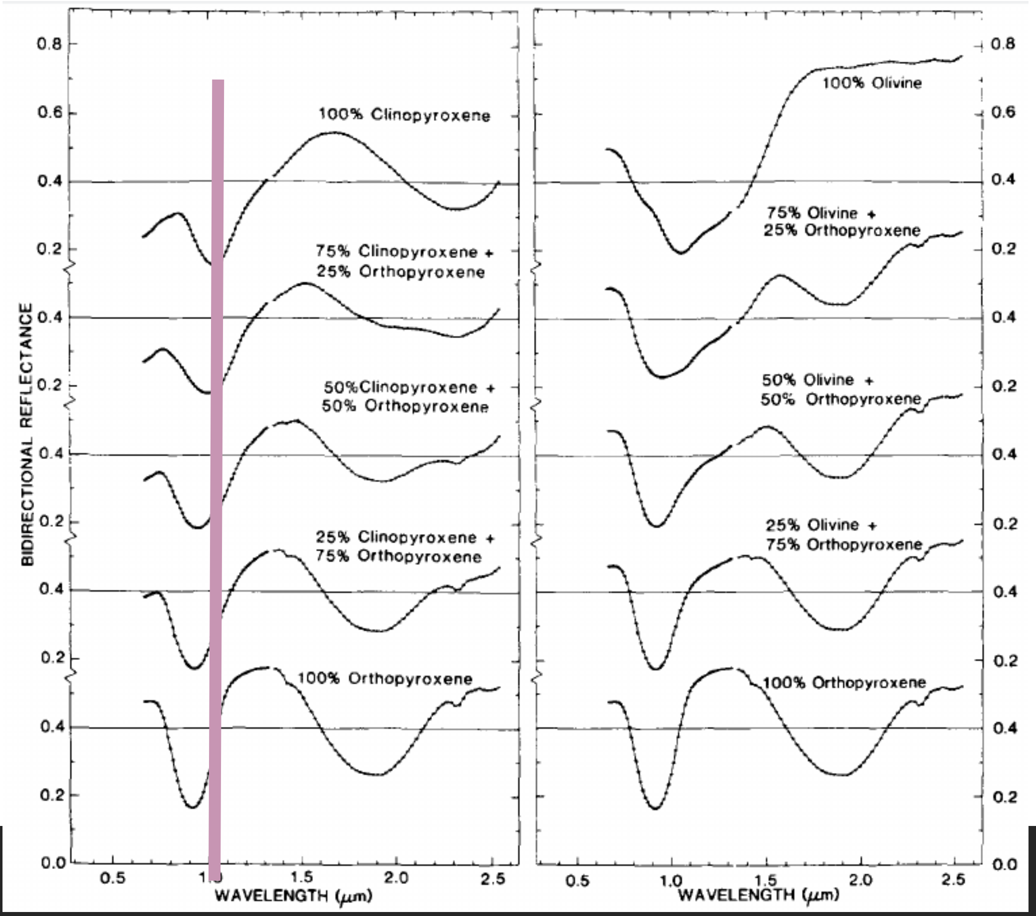
What influences the spectra?

- When we observe a planetary surface, the spectra we get are usually not identical to those, we would measure with the same mineral in the laboratory, as they are affected by several effects.
- Major are:
  1. Sizes of the particles on the surface
  2. Temperature of the surface
  3. Observation geometry
  4. Space weathering

Obviously, mineralogy

- Higher iron content – the lower wavelength of the band's minimum
- Mineral mixtures



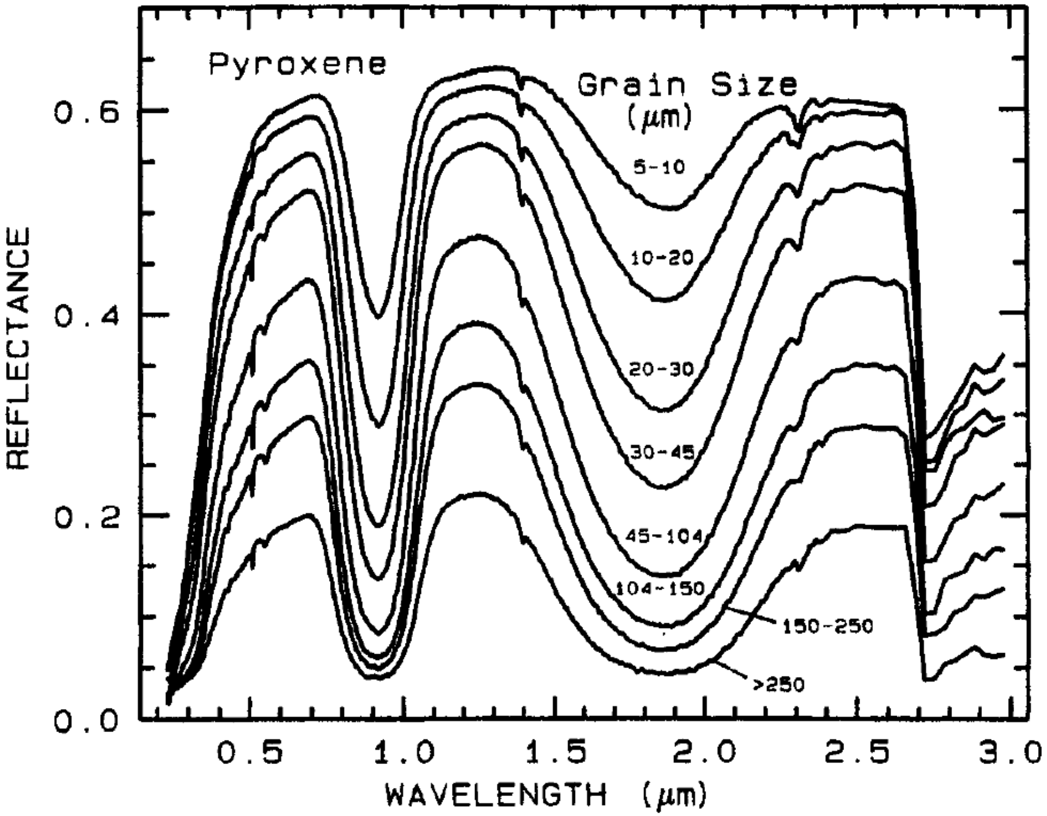


Credit: R. Burns (1988) and Klima et al. (2011)

Particle size

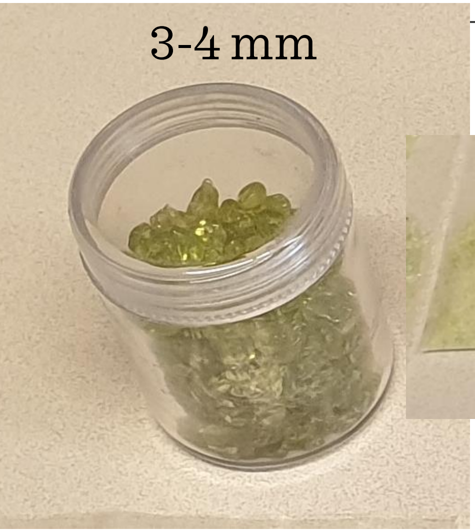
- The larger the particles in the sample
  - The albedo decreases
  - The absorption bands' depths increase
  - The spectral slope is bluer

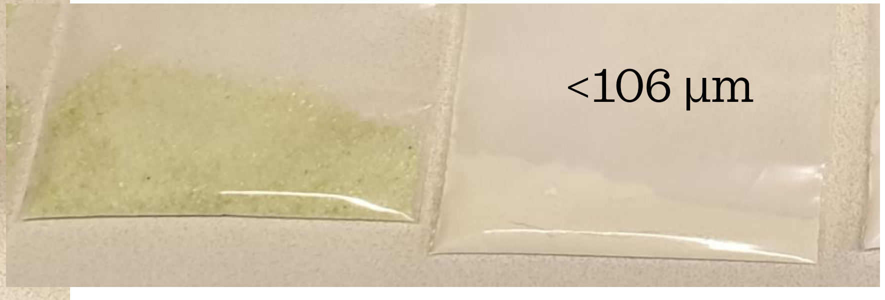
- The reason is a different portion of scattered and absorbed light for different sizes of grains
  - Large grains have greater internal paths, where photons can be absorbed
  - In smaller grains, the surface reflections are the more important, the material is thus brighter

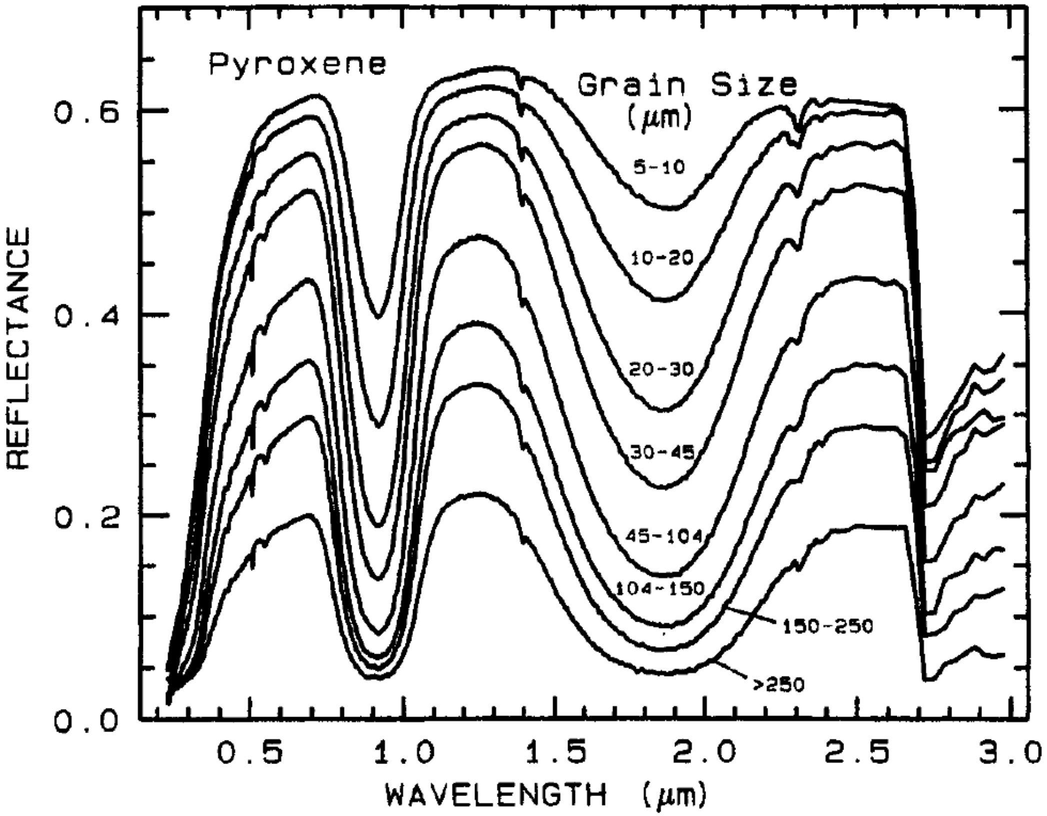


Credit: R. Clark (1999)

Particle size



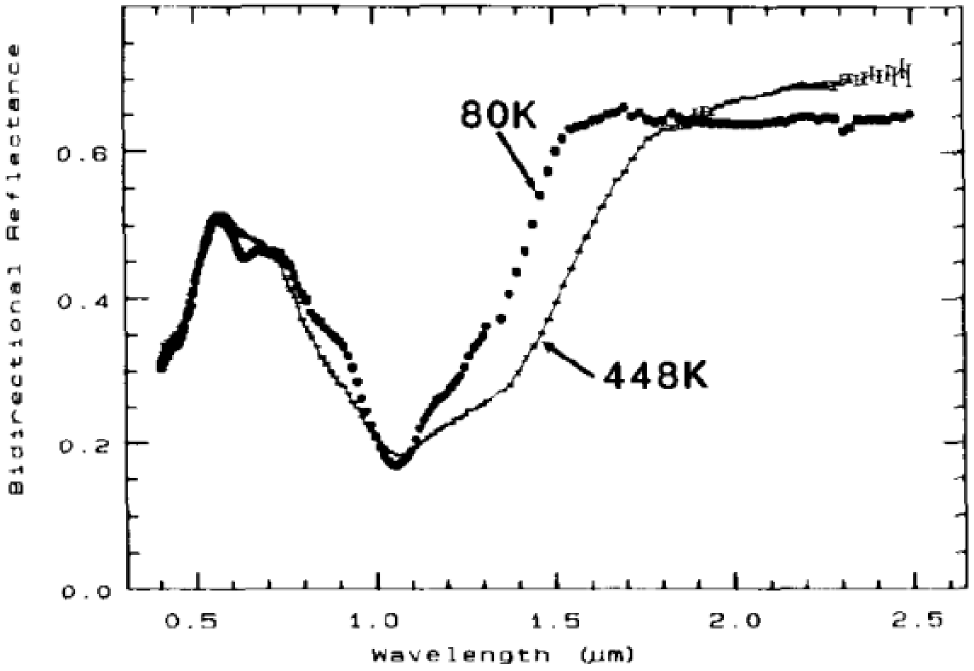




Credit: R. Clark (1999)

Temperature

- Temperature differences:
  - Laboratory: 300 K
  - Asteroid: 140-440 K
- Leads to:
  - Shifts of band's centers (! mineralogy)
  - Changes of band's depths and widths
  - Fe/Ca and band area ratios



Credit: R. Burns (1989)

Temperature

$$T = \left[\frac{(1-A)L_0}{16\eta\varepsilon\sigma\pi r^2} \right]^{1/4}$$

TABLE 1. Calibrations for correcting noncompositional effects.

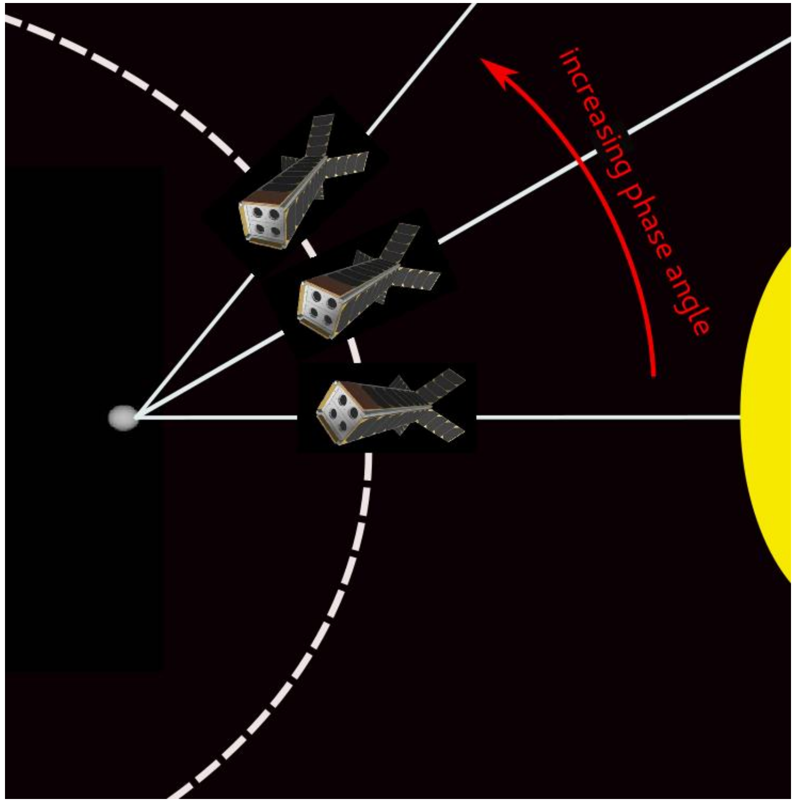
Effect	Analog	Operation	Equation	Equation No.
Temperature	Howardites and eucrites*	Add to Band I Center	$\Delta BI(\mu m) = 0.01656 – 0.0000552 \times T\ (K)$	(2)
		Add to Band II Center	$\Delta BII(\mu m) = 0.05067 – 0.00017 \times T(K)$	(3)
	Diogenites*	Add to Band I Center	$\Delta BI(\mu m) = 1.7 \times 10^{-9} \times T^3\ (K) – 1.26 \times 10^{-6} \times T^2\ (K) + 2.66 \times 10^{-4} \times T\ (K) – 0.0124$	(4)
		Add to Band II Center	$\Delta BII(\mu m) = 0.038544 – 0.000128 \times T\ (K)$	(5)
	Ordinary chondrites†	Add to Band II Center	$\Delta BII(\mu m) = 0.06 – 0.0002 \times T(K)$	(6)
		Add to Band Area Ratio	$\Delta BAR = 0.00075 \times T\ (K) – 0.23$	(7)
	Olivine-rich A-type asteroids‡	Add to Band I Center	$\Delta BI(\mu m) = –(1.18 \times 10^{-7})T^2 + (2.15 \times 10^{-5})T + 0.004$	(8)
		Add to Band I Depth	$BI_{depth\ corr} = 0.0057 \times T\ (K) – 1.71$	(9)

*Reddy et al. (2012c).
†Sanchez et al. (2012).
‡Sanchez et al. (2014).

Credit: Reddy et al. (2015)

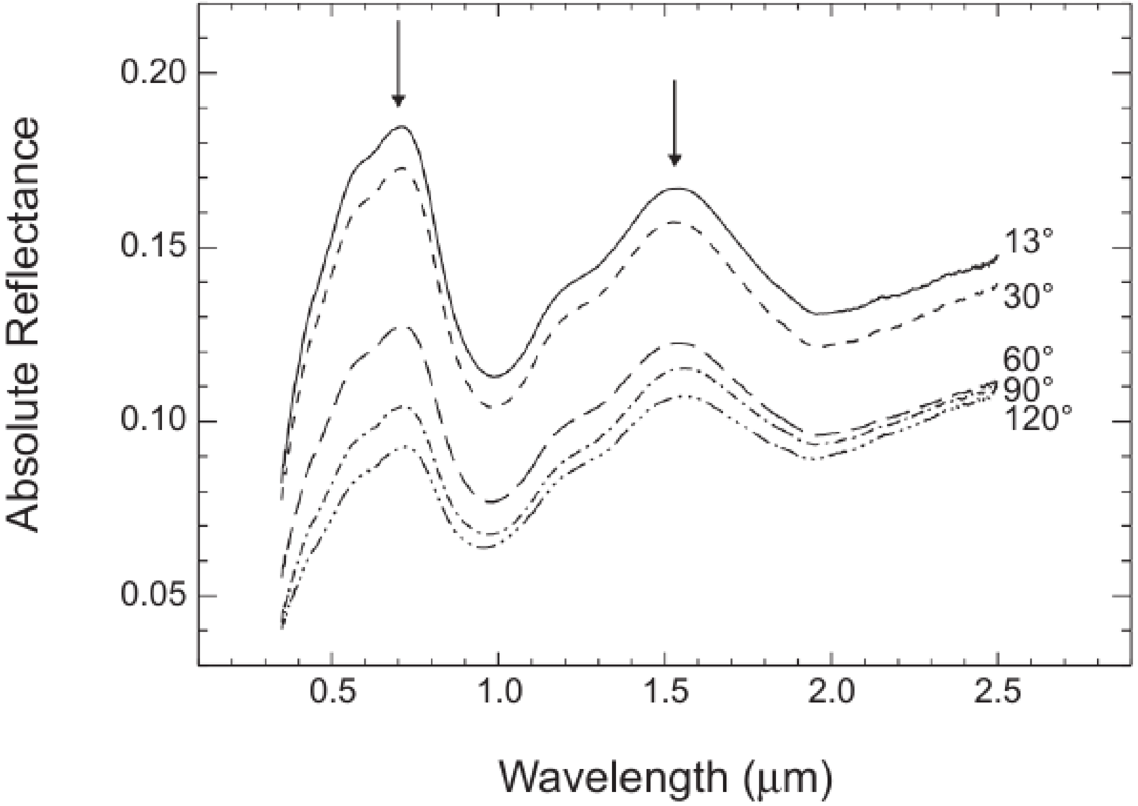
Observation geometry

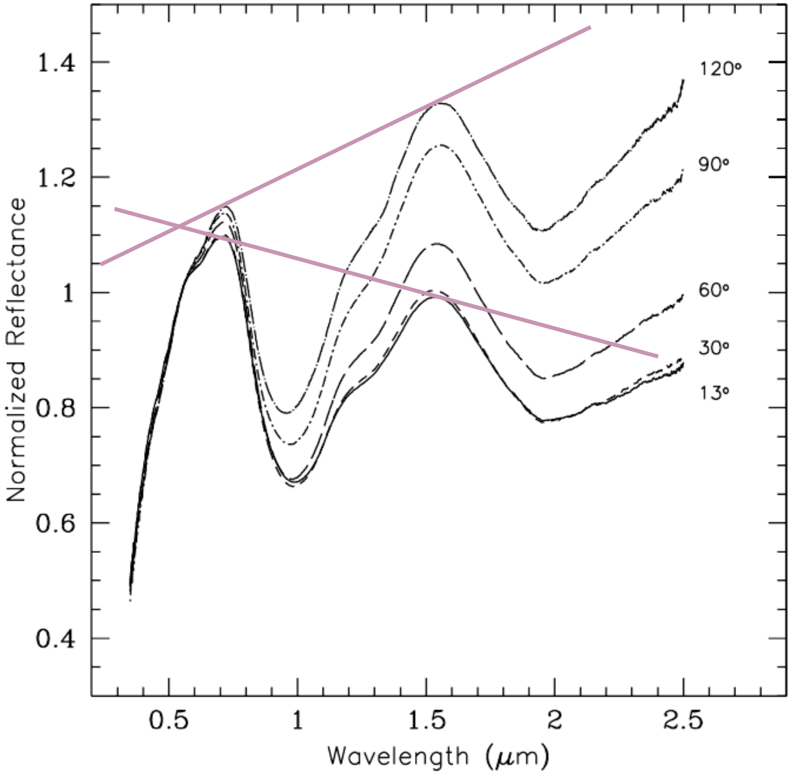
- Phase angle:
  - Angle between the Sun – the body-the probe/spectrometer
  - Typically
    - 0° to 30° for the Main-belt asteroids
    - Higher for the Near-Earth asteroids



- With increasing phase angle:
  - The spectral slope increases for dark, decreases for bright materials
  - Albedo decreases
  - Also alters band depths

Observation geometry





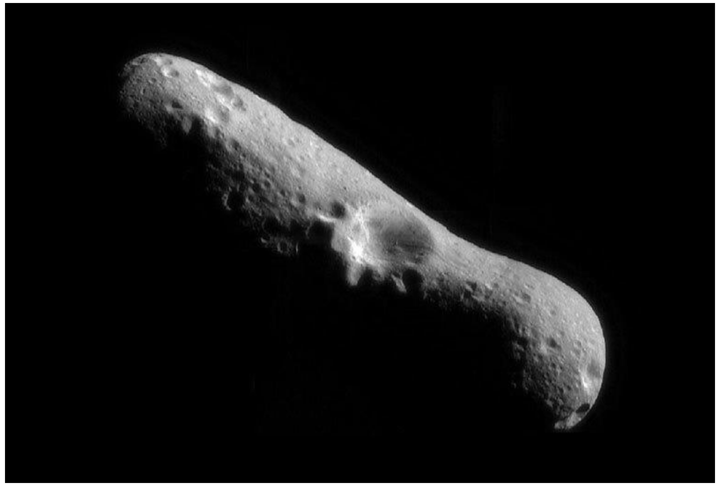
Observation geometry

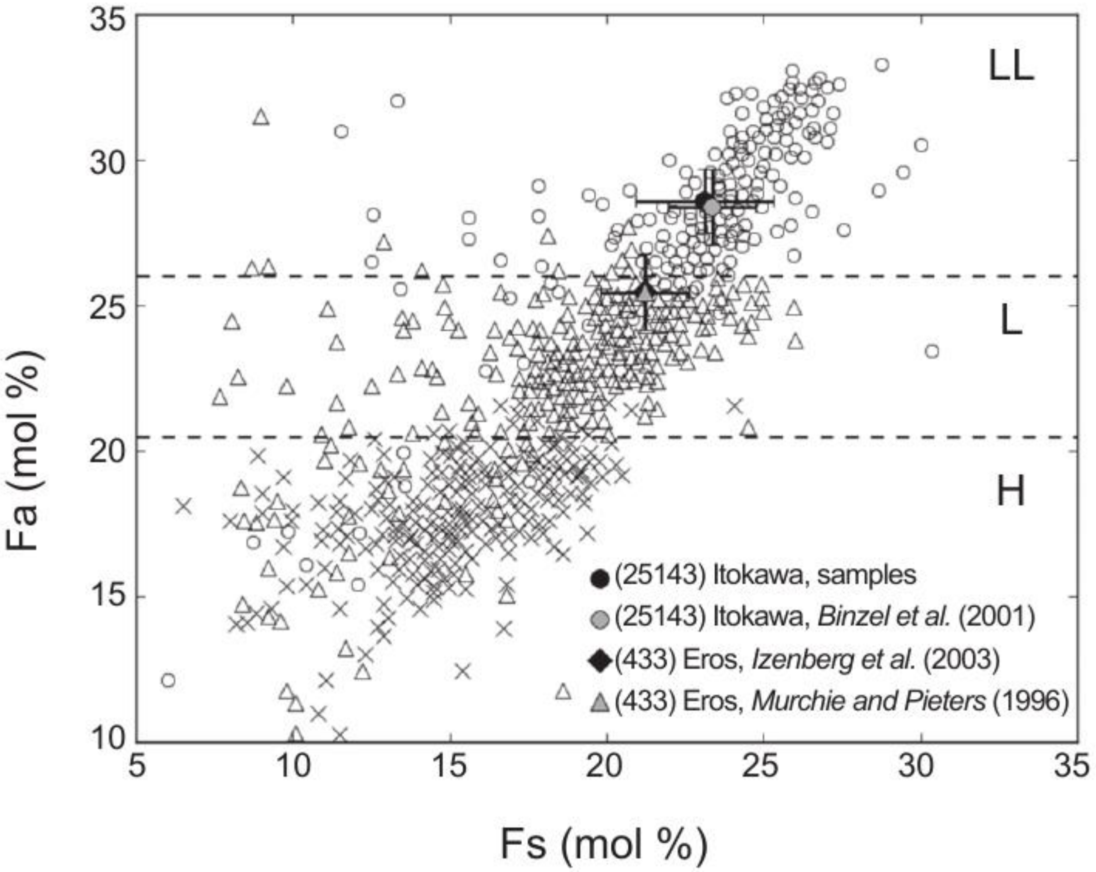
- Dependent also on the shape of the particles and the material, very complex
- Due to wavelength dependence of the single-scattering albedo
- Some correction equation has been developed to recalculate the parameters to the 0° phase angle

Some real examples of asteroid mineralogy use

Eros and Itokawa

- Fs vs Fa abundance can reveal parent bodies of meteorites
- Linking bodies with similar histories



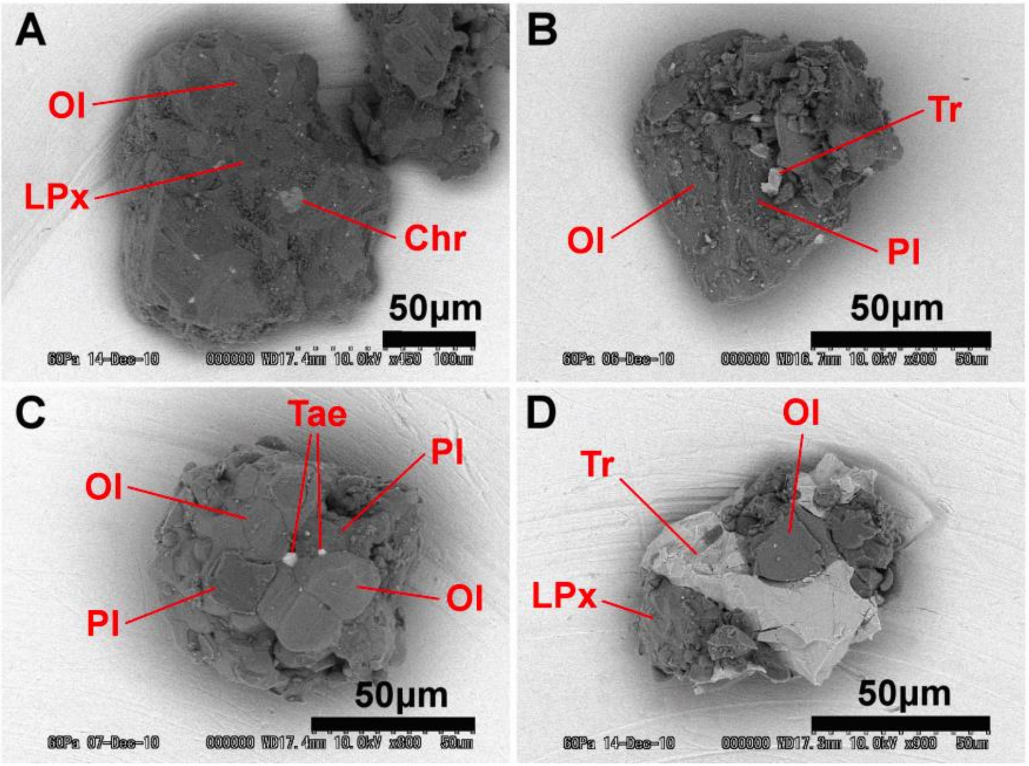


Credit: Reddy et al. (2015) and solarsystem.nasa.gov/ and http://www.meteoriten.com/

Itokawa

- Hayabusa probe
- *"Among the 1534 harvested rocky particles, 1087 are monomineralic, including 580 olivine particles, 126 low-Ca pyroxenes, 56 high-Ca pyroxenes, 186 feldspars (172 plagioclase and 14 K-feldspar), 113 troilites, 13 chromites, 10 Ca phosphates, and 3 Fe-Ni metal grains."*

Nakamura et al. (2011)



- troilite = FeS, chromite = $FeCr_2O_4$, phosphates: PO_4^{3-}

TABLE 3. Mineralogically characterized asteroids.

Asteroid	Class	Diameter	a (AU)	Family	Predicted Mineralogy (Meteorite Affinity)*	Reference
3 Juno	S(IV)	244	2.670	N	Px/(Ol + Px) ~ 0.30 (possible L chondrite)	1†
4 Vesta	V	~570 × 460	2.362	Y	Pyroxene-plagioclase basalt (HED meteorites)	2
Vesta Family	V/J	—	—	Y	Range of HED lithologies	3,19,20
6 Hebe	S(IV)	185	2.426	N	Px/(Ol + Px) ~ 0.4 and NiFe metal (H chon, IIE irons)	4
7 Iris	S(IV)	203	2.386	N	Px/(Ol + Px) ~ 0.30, Px ~ $Fs_{42}Wo_7$ or Cpx-bearing (possible L chondrite)	1†
8 Flora	S(III)	141	2.201	Y	Px/(Ol + Px) ~ 0.25, NiFe metal, Fe-rich Px and/or Ca-rich Px	5
9 Metis	S(I)	168–210	2.386	Y	Px/(Ol + Px) ~ 0.12 and NiFe metal	6
11 Parthenope	S(IV)	162	2.452	N	Px/(Ol + Px) ~ 0.34	1†
12 Victoria	S(II)?	117	2.334	Y	Px/(Ol + Px) ≤ 0.14 and NiFe metal	1†
15 Eunomia	S(III)	272	2.644	Y	Ol + NiFe + (low-Ca Px) to high-Fe and Ca Px basalt	7
16 Psyche	M	264	2.922	N	NiFe metal	8
17 Thetis	S	93	2.469	N	Px/(Ol + Px) ~ 0.54 or low-Ca Px: Calcic Px ~ 60:40 and Ol <15%	22†
18 Melpomene	S(V)	148	2.296	N	Px/(Ol + Px) ~ 0.47	1†
20 Massalia	S(VI)	151	2.408	Y	Px/(Ol + Px) ~ 0.66, Px ~ $Fs_{26}Wo_4$	1†
25 Phocaea	S(IV)	78	2.400	N	Px/(Ol + Px) ~ 0.30	1†
26 Proserpina	S(II)	99	2.656	N	Px/(Ol + Px) ~ 0.30	1†
27 Euterpe	S(IV)		2.347	N	Px/(Ol + Px) ~ 0.25	1†
37 Fides	S(V)	112	2.642	Y	Px/(Ol + Px) ~ 0.72 ± 0.17	1†
39 Laetitia	S(II)	159	2.769	Y	Px/(Ol + Px) ~ 0.26	1†
40 Harmonia	S(VII)	111	2.267	N	Px/(Ol + Px) ~ 0.89 (0.68–1.0), Px ~ $Fs_{27}Wo_9$	1†
42 Isis	S(I)	107	2.441	Y	Px/(Ol + Px) ~ 0.0 and NiFe metal(?)	1†
43 Ariadne	S(III)	65	2.203	Y	Px/(Ol + Px) ~ 0.13–0.20	1†
44 Nysa	E	73	2.422	Y	Nearly Fe-free enstatite (<Fs_1)	9
63 Ausonia	S(II–III)	108	2.395	Y	Px/(Ol + Px) ~ 0.27 and NiFe metal(?)	1†

Credit: Gaffey et al. (2002)

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44 Nysa	E	73	2.422	Y	Nearly Fe-free enstatite (<Fs_1)	9
63 Ausonia	S(II–III)	108	2.395	Y	Px/(Ol + Px) ~ 0.27 and NiFe metal(?)	1†

Credit: Gaffey et al. (2002)

82 Alkmene	S(VI)	64	2.765	N	Px/(Ol + Px) ~ 0.61 ± 0.16; Px ~ $Fs_{23}Wo_2$	1†
113 Amalthea	S(I–II)	48	2.376	Y	Px/(Ol + Px) ~ 0.13, Px ~ $Fs_{34}Wo_{14}$ and NiFe metal (?)	6,10
115 Thyra	S(III–IV)	84	2.380	Y	Opx + Ca Px assemblage indicated	1‡
215 Kleopatra	M	217 × 94 × 81	2.767	N	NiFe metal	11
246 Asporina	A	64	2.695	N	Olivine + NiFe metal(?) (possible pallasite)	12,13
289 Nenetta	A	42	2.874	N	Olivine + NiFe metal(?); Px/(Ol + Px) < 0.05 (possible pallasite)	1†,13
349 Dembowska	R	140	2.925	Y	Px/(Ol + Px) ~ 0.45; Px ~ $Fs_{25}Wo_{10}$	14
354 Eleonora	S(I)	162	2.796	N	Px/(Ol + Px) ~ 0.05	1†
387 Aquitania	S	106	2.742	Proposed	Spinel (in abundant CAIs?) (CV or CO chondrite)	15
433 Eros	S(IV)	39 × 13 × 13	1.458	N	Px/(Ol + Px) ~ 0.36; Px ~ $Fs_{42}Wo_{18}$ or Cpx-bearing (possible LL chondrite)	16,21
446 Aeternitas	A	43	2.788	Y	Olivine + NiFe metal (?); Px/(Ol + Px) < 0.05 (possible pallasite)	1†,12,13
532 Herculina	S(III)	231	2.772	N	Opx + Ca Px assemblage indicated	1‡
584 Semiramis	S(IV)	56	2.374	Y	Px/(Ol + Px) ~ 0.26 + NiFe metal(?); Px ~ $Fs_{42}Wo_{16}$	1†
674 Rachele	S(VII)	101	2.924	N	Px/(Ol + Px) ~ 0.68–1.0	1†
847 Agnia	S	32	2.783	Y	Low-Ca Px: Calcic Px ~ 60:40; Ol < 15%	22
863 Benkoela	A	32	3.200	N	Olivine + NiFe metal (?) (possible pallasite)	13
980 Anacostia	S	89	2.741	Proposed	Spinel (in abundant CAIs?) (CV or CO chondrites)	15
1036 Ganymed	S(VI–VII)	41	2.662	N	Px/(Ol + Px) ~ 0.64–0.82; Px ~ $Fs_{34}Wo_4$	1†
3103 Eger	E	1.5	1.406	N	Iron-free enstatite	17
1986 DA	M	2.3	2.811	N	NiFe metal	18

*Except where otherwise noted, "Px" indicates a low-Ca orthopyroxene.

†Mineral abundances and compositions using spectral parameters from *Gaffey et al.* (1993a) and equations (2)–(4) and Fig. 4 from the present paper.

‡Olivine-poor or olivine-free two-pyroxene assemblage indicated by test described in text.

References: (1) *Gaffey et al.* (1993a); (2) *Gaffey* (1997); (3) *Binzel and Xu* (1993); (4) *Gaffey and Gilbert* (1998); (5) *Gaffey* (1984); (6) *Kelley and Gaffey* (2000); (7) *Reed et al.* (1997); (8) *Ostro et al.* (1985); (9) *Gaffey et al.* (1993b); (10) *Gaffey* (2002); (11) *Ostro et al.* (2000); (12) *Hiroi et al.* (1993); (13) *Lucey et al.* (1998); (14) *Abell and Gaffey* (2000); (15) *Burbine et al.* (1992); (16) *McFadden et al.* (2001); (17) *Gaffey et al.* (1992); (18) *Ostro et al.* (1991); (19) *Hiroi et al.* (1995); (20) *Vilas et al.* (2000); (21) *McCoy et al.* (2001); (22) *Sunshine et al.* (2002).

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847 Agn					ic Px ~ 60:40; Ol < 15%	22
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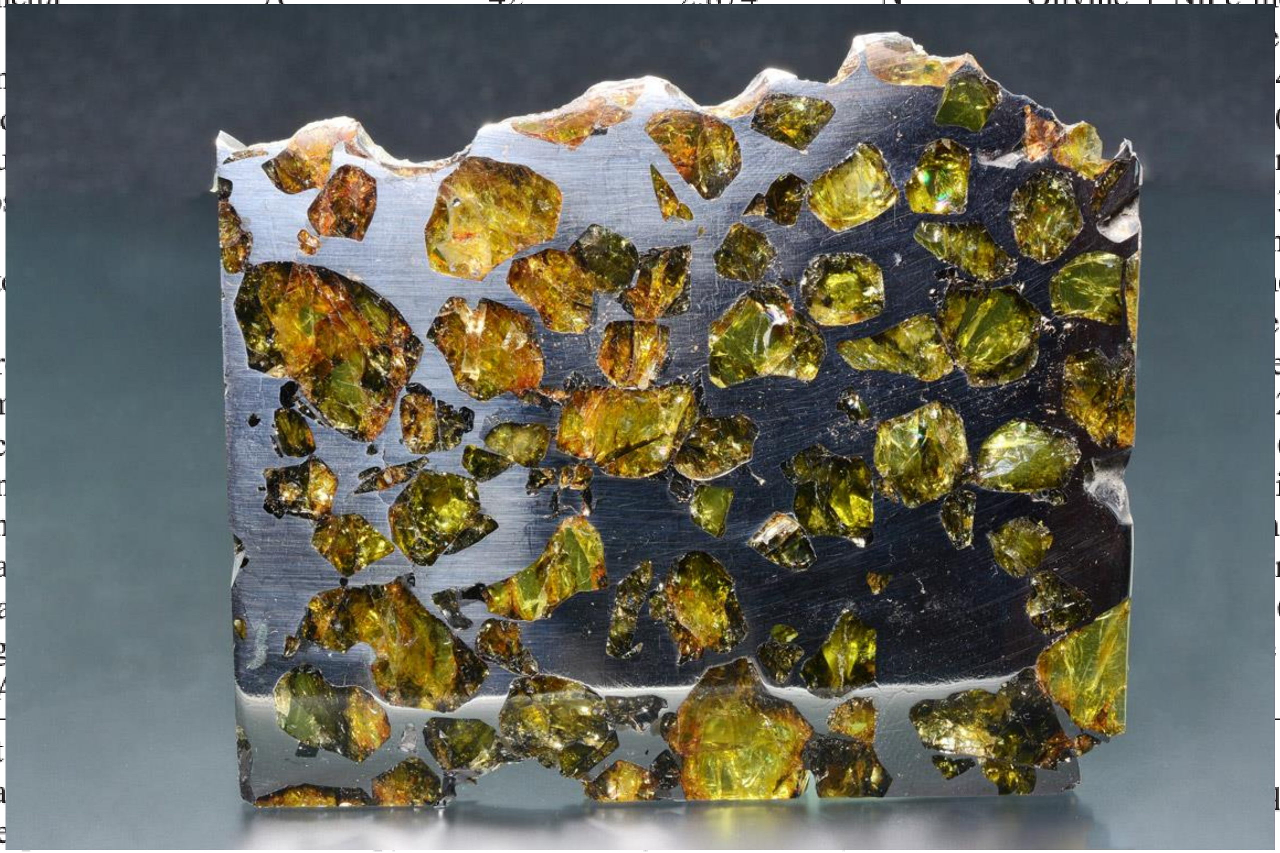
1036 Ga					64–0.82; Px ~ $Fs_{34}Wo_4$	1†
3103 Eg						17
1986 DA						18



*Except

†Minera quations (2)–(4) and Fig. 4 from the present paper.

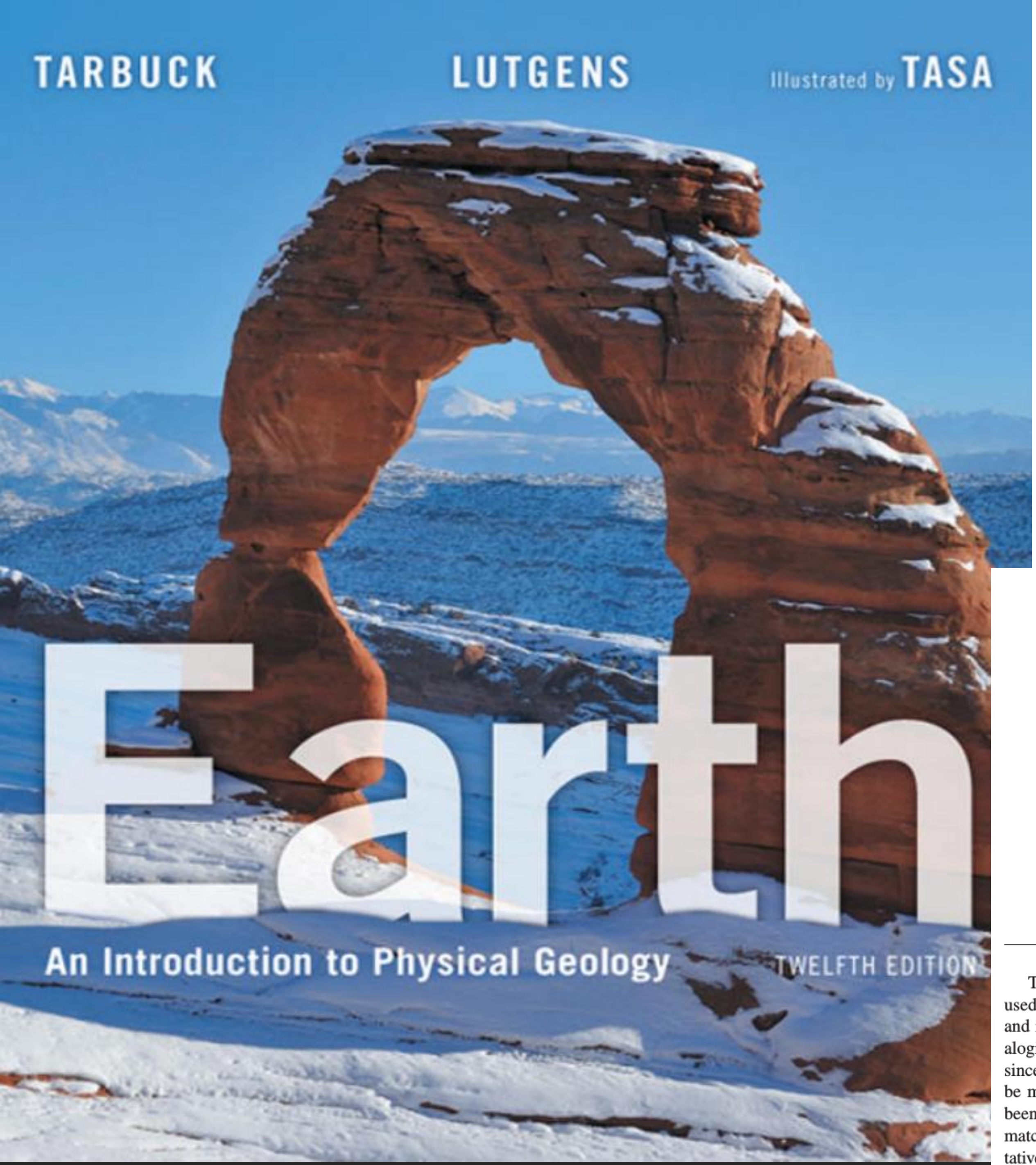
‡Olivine

References: (1) *Gaffey et al.* (1993a); (2) *Gaffey* (1997); (3) *Binzel and Xu* (1993); (4) *Gaffey and Gilbert* (1998); (5) *Gaffey* (1984); (6) *Kelley and Gaffey* (2000); (7) *Reed et al.* (1997); (8) *Ostro et al.* (1985); (9) *Gaffey et al.* (1993b); (10) *Gaffey* (2002); (11) *Ostro et al.* (2000); (12) *Hiroi et al.* (1993); (13) *Lucey et al.* (1998); (14) *Abell and Gaffey* (2000); (15) *Burbine et al.* (1992); (16) *McFadden et al.* (2001); (17) *Gaffey et al.* (1992); (18) *Ostro et al.* (1991); (19) *Hiroi et al.* (1995); (20) *Vilas et al.* (2000); (21) *McCoy et al.* (2001); (22) *Sunshine et al.* (2002).

Credit: Gaffey et al. (2002) and http://www.carionmineraux.com/mineraux/mineraux_mars_2017/

Summary of lesson 1

- Spectroscopy is a powerful tool to evaluate the mineralogy of airless planetary bodies
- Usually, we work in VIS and NIR wavelengths – **characteristic mineral bands**
- Some of very **common minerals** in our scope: olivines, pyroxenes, plagioclase feldspars
- Dark asteroids also contain other (non-silicate minerals)
- Spectral curves help **dividing asteroids into groups**
- One must be cautious, as spectra are **altered by many effects**, such as viewing geometry, temperature, etc.



Reddy V., Dunn T. L., Thomas C. A., Moskovitz N. A., and Burbine T. H. (2015) Mineralogy and surface composition of asteroids. In *Asteroids IV* (P. Michel et al., eds.), pp. 43–63. Univ. of Arizona, Tucson, DOI: 10.2458/azu_uapress_9780816532131-ch003.

Mineralogy and Surface Composition of Asteroids

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Planetary Science Institute

Tasha L. Dunn
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Nicholas A. Moskovitz
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Asteroids III and IV

Methods to constrain the surface mineralogy of asteroids have seen considerable development during the last decade, with advancement in laboratory spectral calibrations and validation of interpretive methodologies by spacecraft rendezvous missions. This has enabled the accurate identification of several meteorite parent bodies in the main asteroid belt and helped constrain the mineral chemistries and abundances in ordinary chondrites and basaltic achondrites. With better quantification of spectral effects due to temperature, phase angle, and grain size, systematic discrepancies due to noncompositional factors can now be virtually eliminated for mafic silicate-bearing asteroids. Interpretation of spectrally featureless asteroids remains a challenge. This chapter presents a review of all mineralogical interpretive tools currently in use and outlines procedures for their application.

Mineralogy of Asteroids

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University of North Dakota

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K. L. Reed
The Space Development Institute

The past decade has seen a significant expansion both in the interpretive methodologies used to extract mineralogical information from asteroid spectra and other remote-sensing data and in the number of asteroids for which mineralogical characterizations exist. Robust mineralogical characterizations now exist for more than 40 asteroids, an order a magnitude increase since *Asteroids II* was published. Such characterizations have allowed significant progress to be made in the identification of meteorite parent bodies. Although considerable progress has been made, most asteroid spectra have still only been analyzed by relatively ambiguous curve-matching techniques. Where appropriate and feasible, such data should be subjected to a quantitative analysis based on diagnostic mineralogical spectral features. The present paper reviews the recent advances in interpretive methodologies and outlines procedures for their application.

Space weathering : pandemic in the Solar System

SELECTED CHAPTERS ON ASTROPHYSICS
NOVEMBER 4 AND 11, 2020
KATERINA CHRBOLKOVA

What to expect

General introduction to spectroscopy of minerals

1. What are the most common **minerals** in the airless planetary bodies of the SS?
2. What are their **characteristic spectral features**? + examples from the SS
3. What **effects** influence the spectra?

Some real examples of asteroid mineralogy use

Space weathering

1. What is the **space weathering** and what are its main agents?
2. What are **lunar swirls** and why are they so special?
3. How do we **simulate space weathering** here on the Earth?

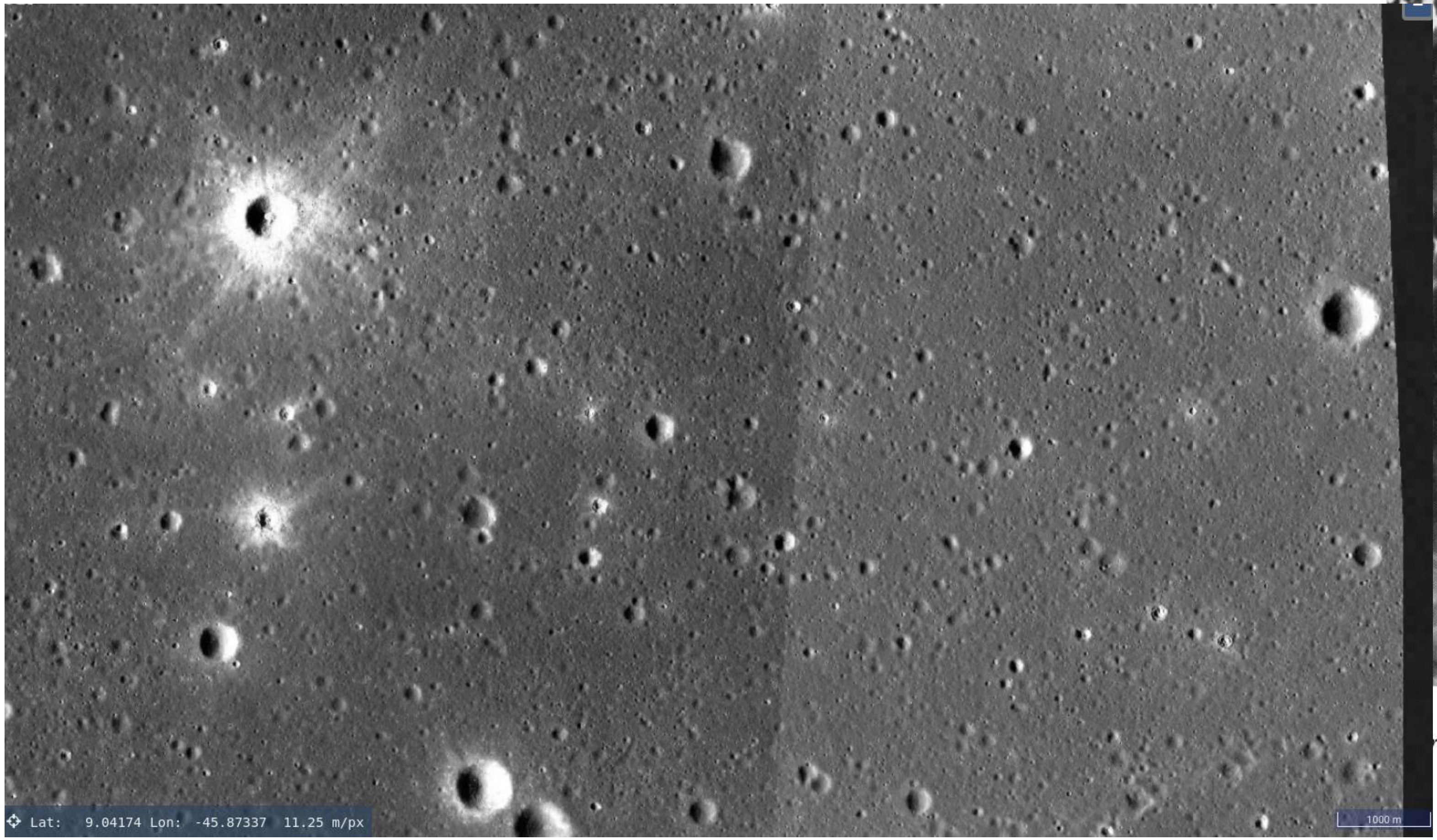
Part 4:
Space weathering

Beginnings

- One of the first: Gold (1955) - young lunar craters are bright, erosion of the lunar surface

Region around Copernicus, showing craters possessing a central peak and a pit within that. 100-inch Mount Wilson.

Beginnings



round Copernicus, *showing craters possessing a central peak and a pit within that.*
100-*inch Mount Wilson.*

Credit: Gold (1955) and LROC Quickmap

Beginnings

- One of the first: Gold (1955) - young lunar craters are bright, erosion of the lunar surface

- Great advances during the Apollo era
  - Apollo 11 – samples back to Earth
  - Pulverized rocks are darker than lunar soil of the same composition
  - Conel and Nash (1970), Gold et al. (1970), Hapke et al. (1970)

Region around Copernicus, showing craters possessing a central peak and a pit within that. 100-inch Mount Wilson.

Credit: Gold (1955)

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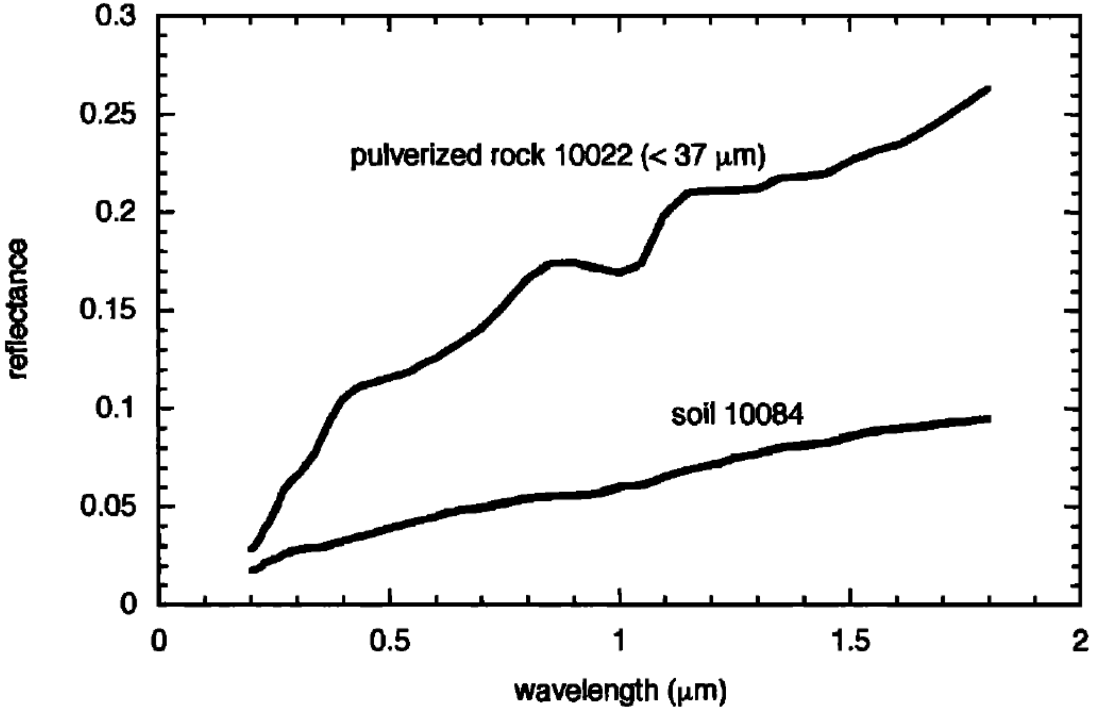

Figure 2. Bidirectional reflectance spectra ($i = e = 30°$, $g = 60°$, where i is the incidence angle, e is the viewing angle and g is the phase angle), relative to a MgO standard, of Apollo 11 lunar soil sample 10084 and lunar rock 10022 pulverized to < 37 µm.

Credit: Gold (1955) and Hapke (2001)

What is space weathering?

- Chemical and physical alteration of the surfaces of the airless planetary bodies (asteroids, moons)
- Happens as a consequence of interaction with the space environmnet:
  - Solar wind irradiation
  - Particles of galaxy radiation
  - Micrometeoroids' impacts
- Influences:
  - Chemical state of the surface
  - Surface structure
  - **Spectral curves!**

How are spectra affected?

- When considering bright asteroids (S-, Q-, V-, A-types) or the Moon and the VIS-NIR spectra:
  - As the surface weathers:
    - The albedo (reflectance at certain wavelength) decreases
    - Spectral slope increases (we call it reddening)
    - Characteristic mineral bands are being subdued

How are spectra affected?

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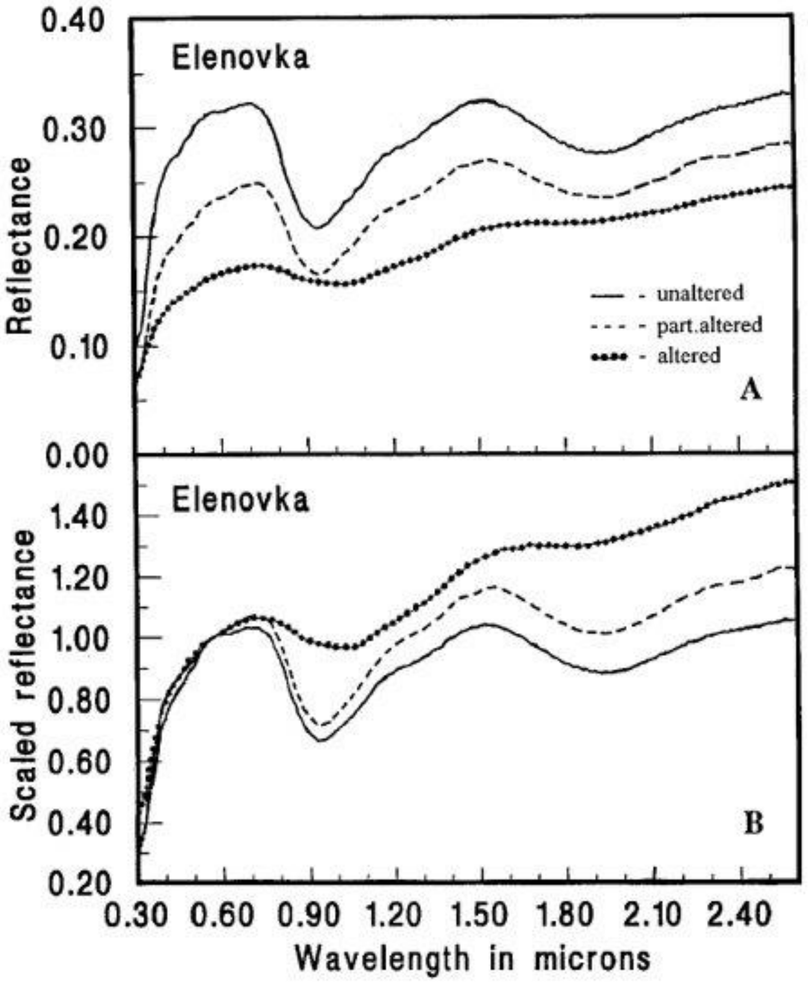

FIG. 4. Absolute VNIR reflectance spectra (A) and normalized VNIR reflectance spectra (B) of powdered Elenovka samples. The spectra in (B) have been scaled to 1.0 at 0.56 μm. Line types are consistent between (A) and (B).

Credit: Moroz et al. (1996)

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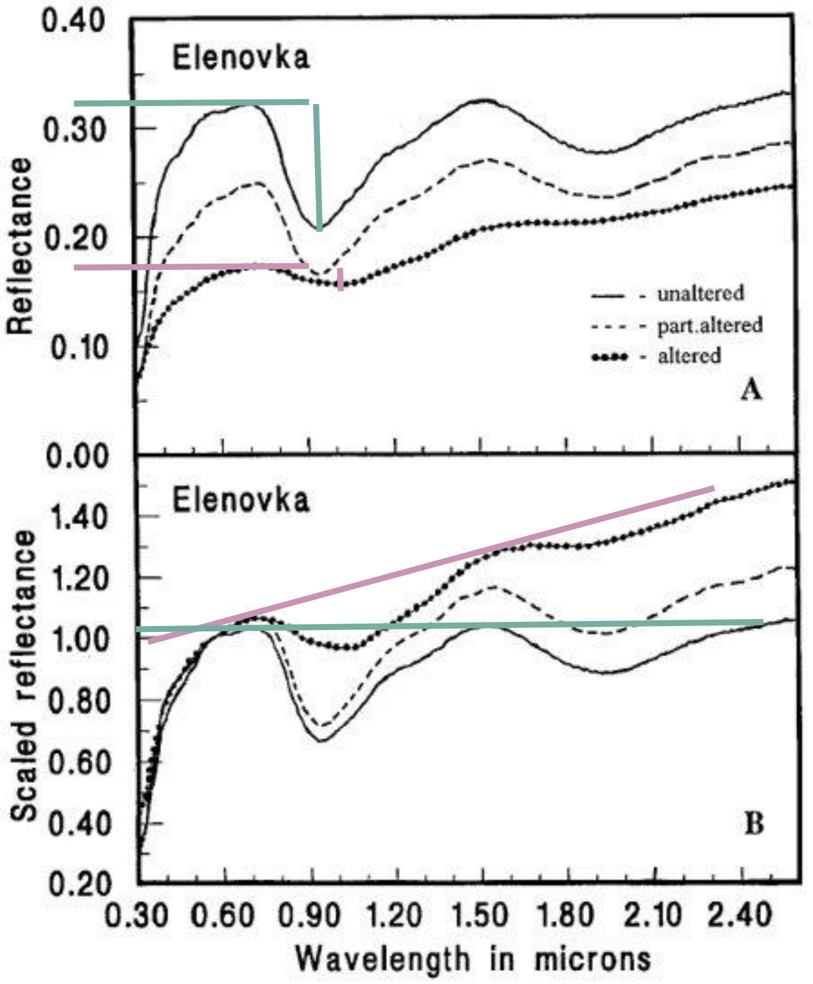

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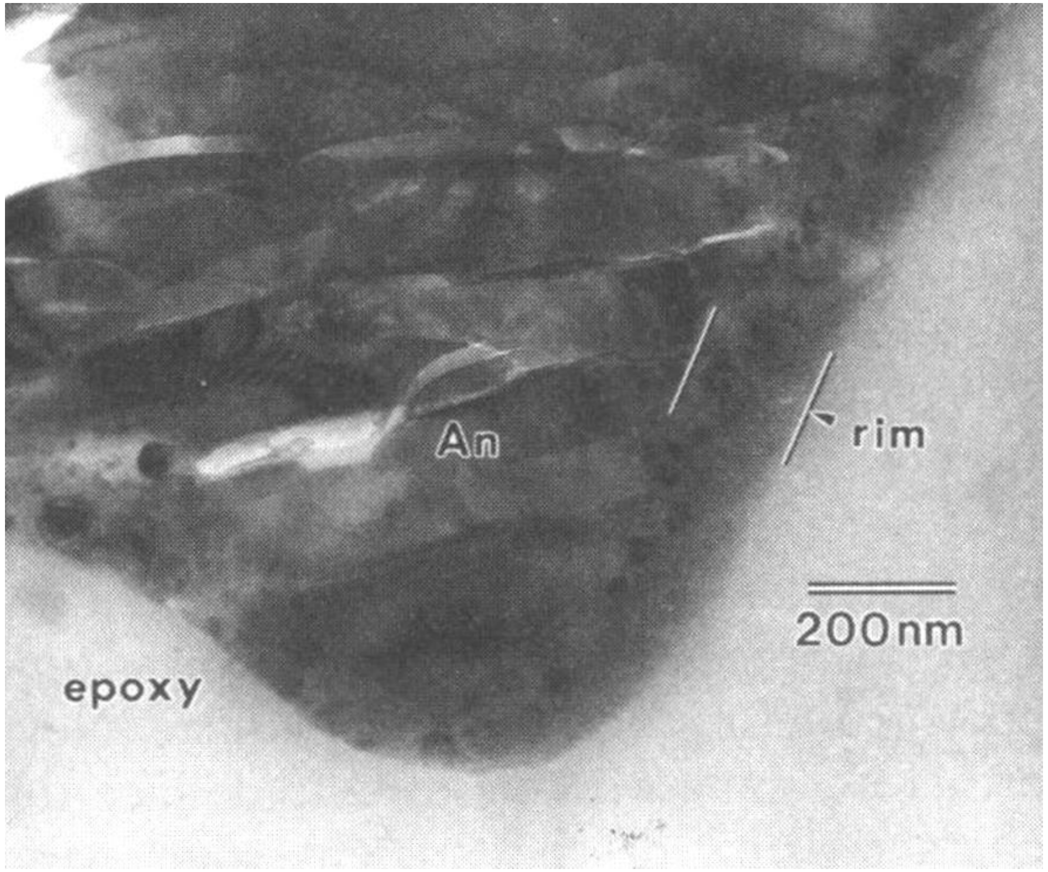
Why? - nanophase iron

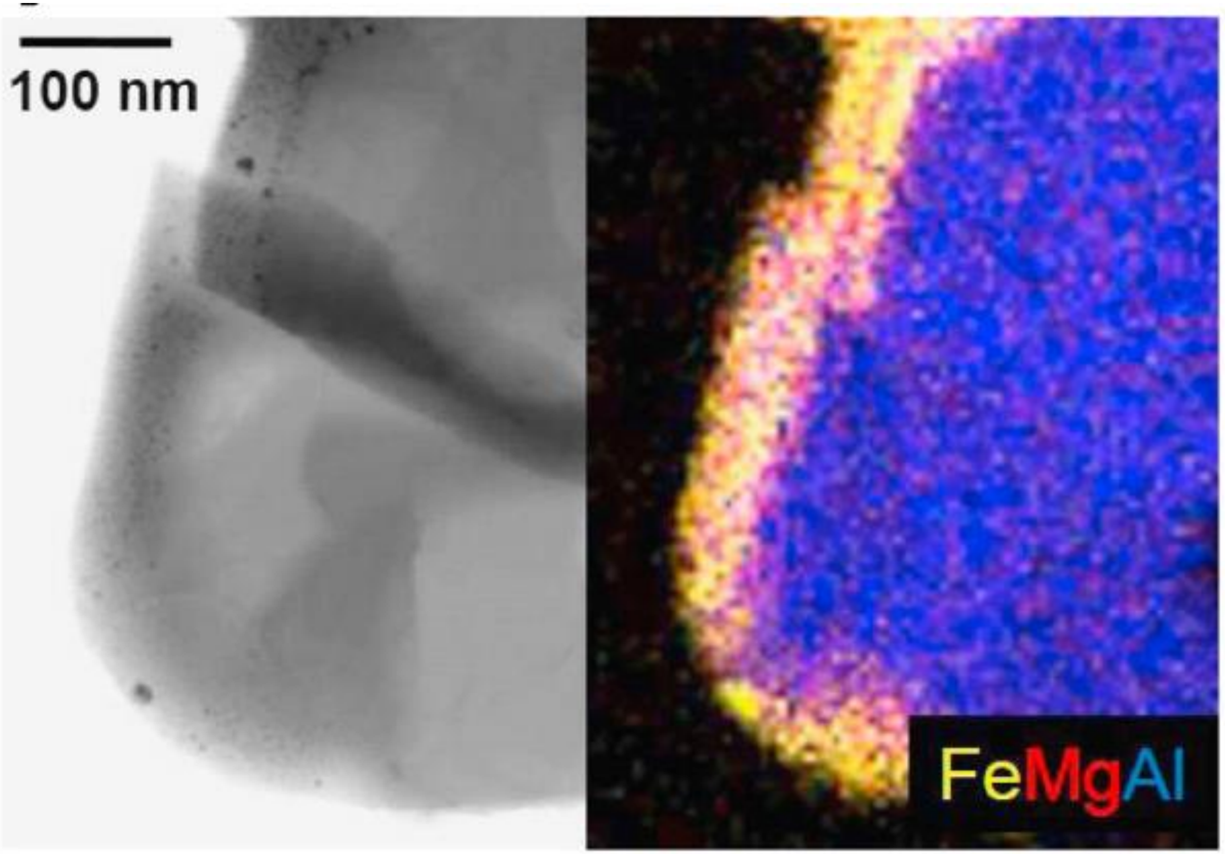
- First thoughts: dark amorphous glasses → now: not the prime reason
- Metallic iron particles tens of nm in diameter: "nanophase iron $npFe^0$"
  - Affect more the short wavelengths
  - Causing mainly reddening with small portion of darkening
  - In thin rims below the surface, 100 nm
- Larger: "submicroscopic iron SMFe"
  - Causing mainly darkening
  - More probably dispersed throughout the matrix

Why? - agglutinates

- If the processes continue → merging into larger and larger structures
  - Agglutinates
  - Lunar soil welded by glass
  - Iron particles up to hundreds of nm in diameter
- Causing mainly darkening of the spectra

Why?

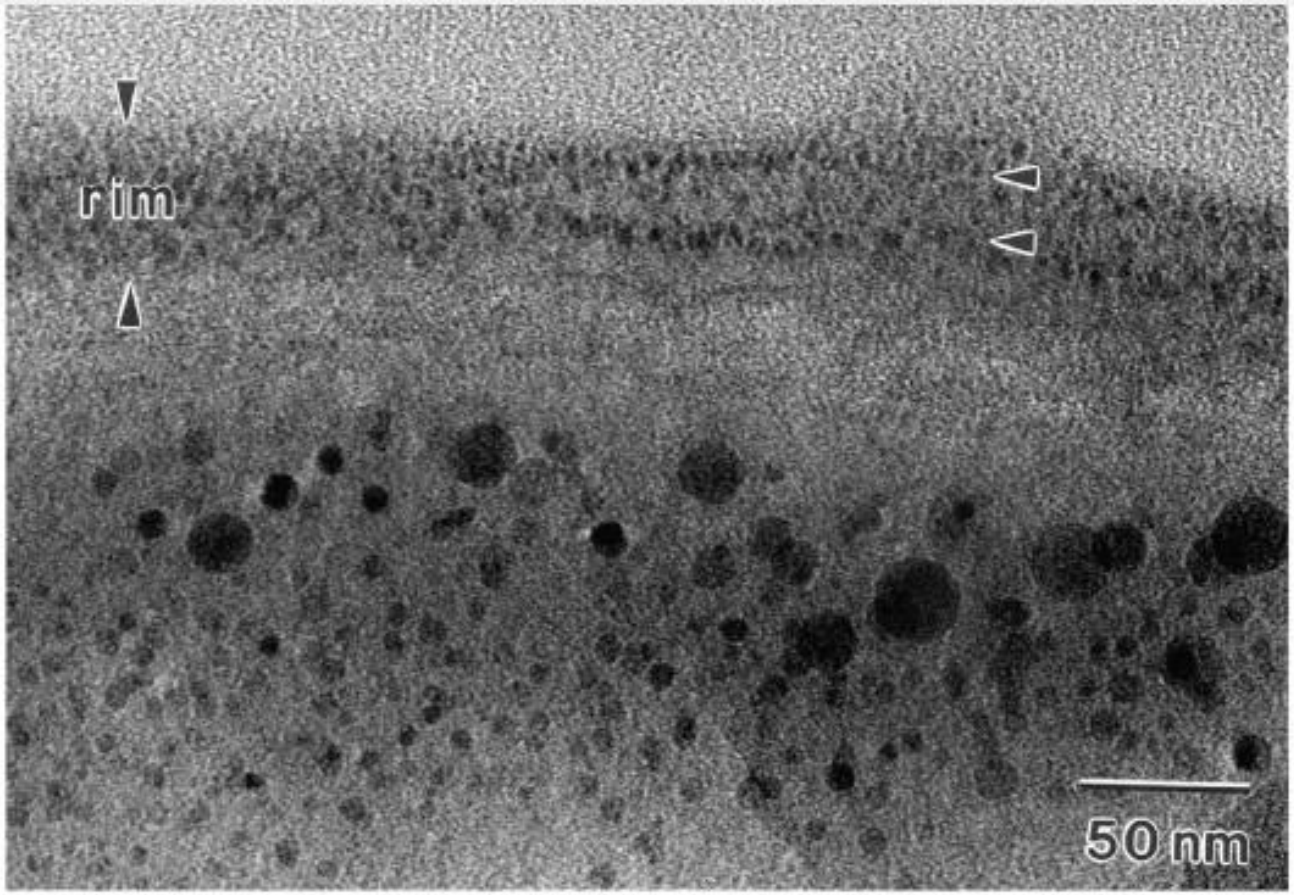




An = anorthosite (Plg feldspar + small amount of mafic)

Credit: Keller and McKay (1993) and Pieters et al. (2016)

Why?

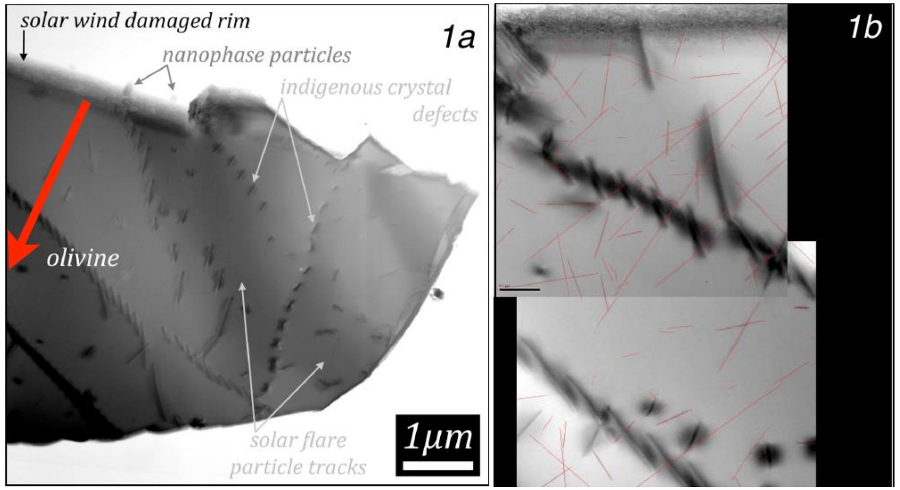


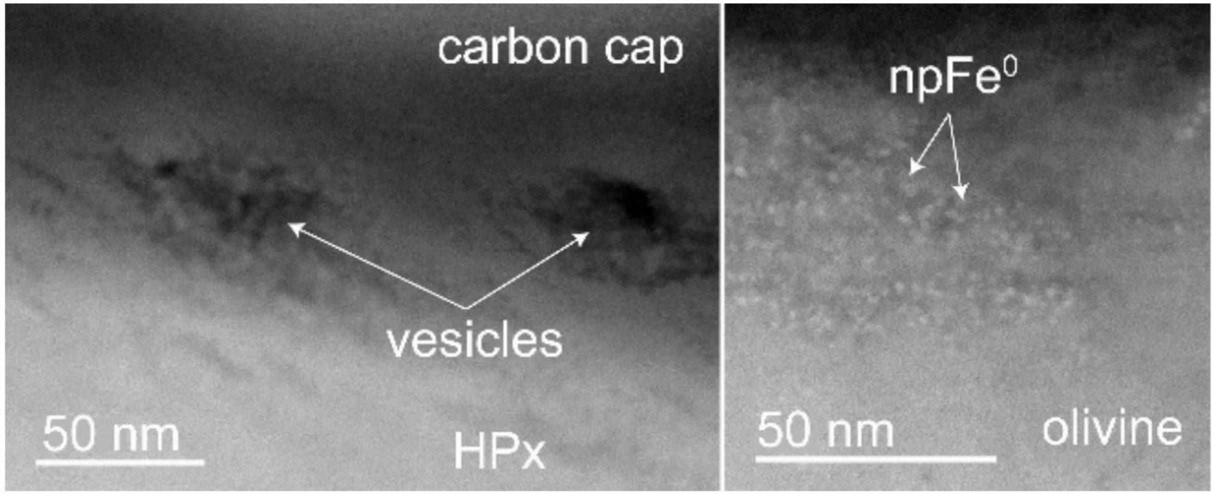
Credit: Pieters et al. (2016)

Why? - blistering

- Itokawa particles: not the typical "lunar-type" SW
- Fewer $npFe^0$ particles, more of radiation damage from the solar wind irradiation - particles show vesicles, solar wind tracks

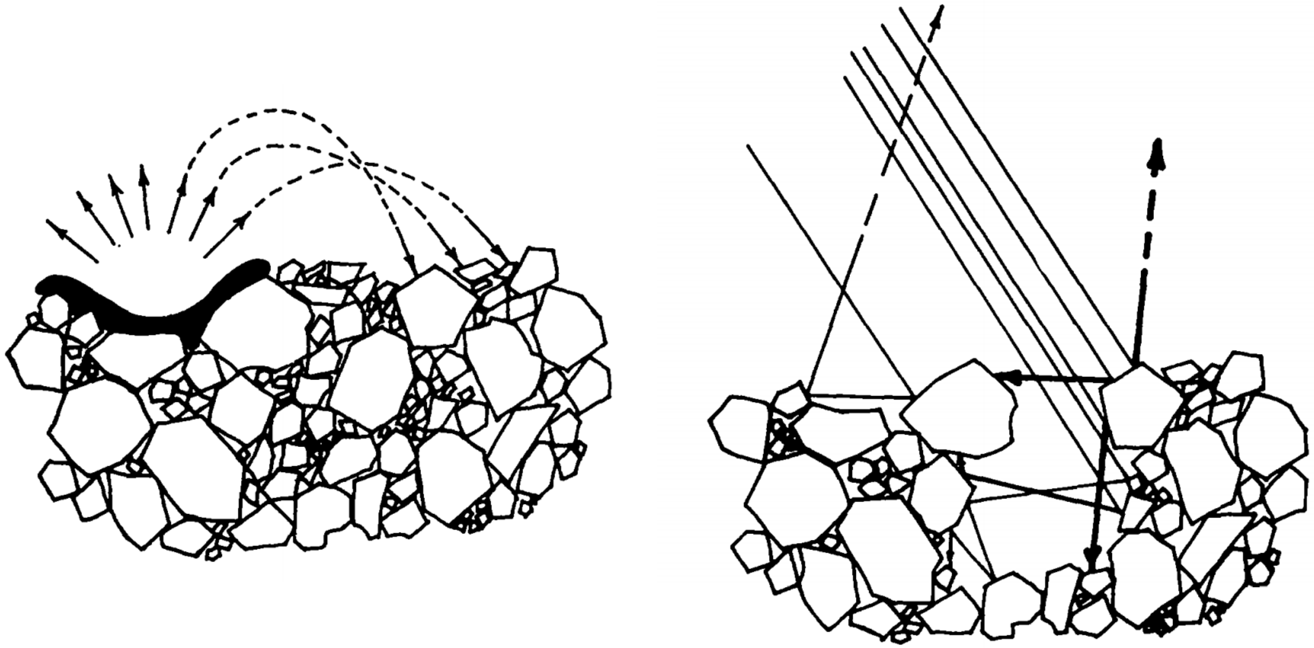
Fig.1a. Bright field image (BFI) of Itokawa 0211, FIB section 1. *1b.* BFI mosiac from 0211, sect. 1 (indicated by the red arrow in fig. 1a). The thickest rim and highest track density are at the top, while the thinnest rim and lowest track density are at the bottom (red arrow in above image). Tracks are highlighted in red for ease of viewing. Track densities are plotted as red squares in figure 2.





Space environment

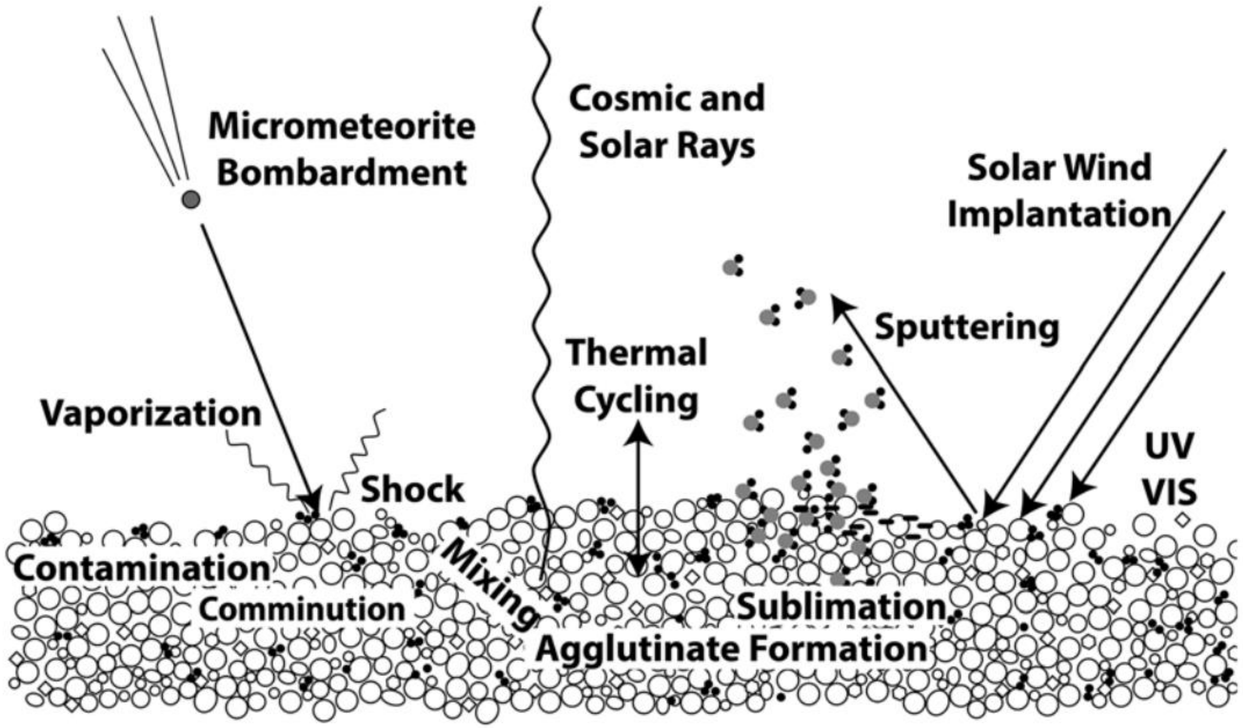
- First thoughts: vapour deposition and sputtering



Credit: Cassidy and Hapke (1975)

Space environment

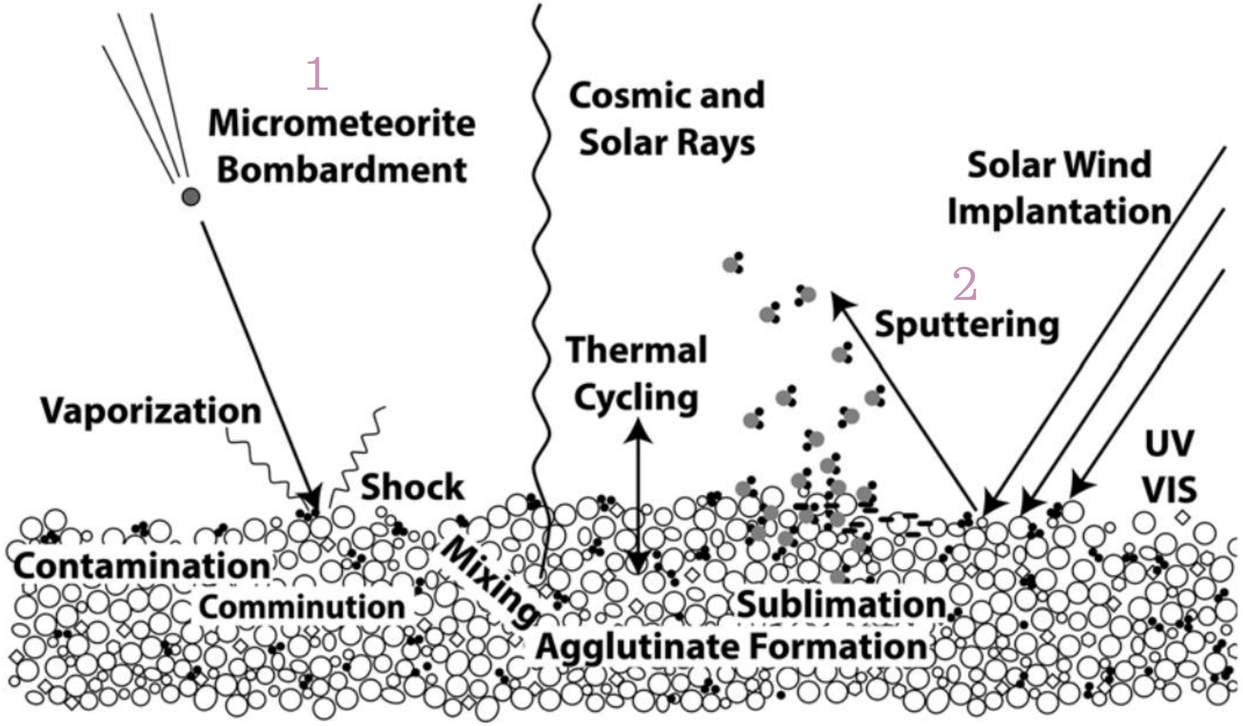
- But now we know:



Credit: Pieters et al. (2016)

Space environment

- But now we know:



Credit: Pieters et al. (2016) - modified

Space environment

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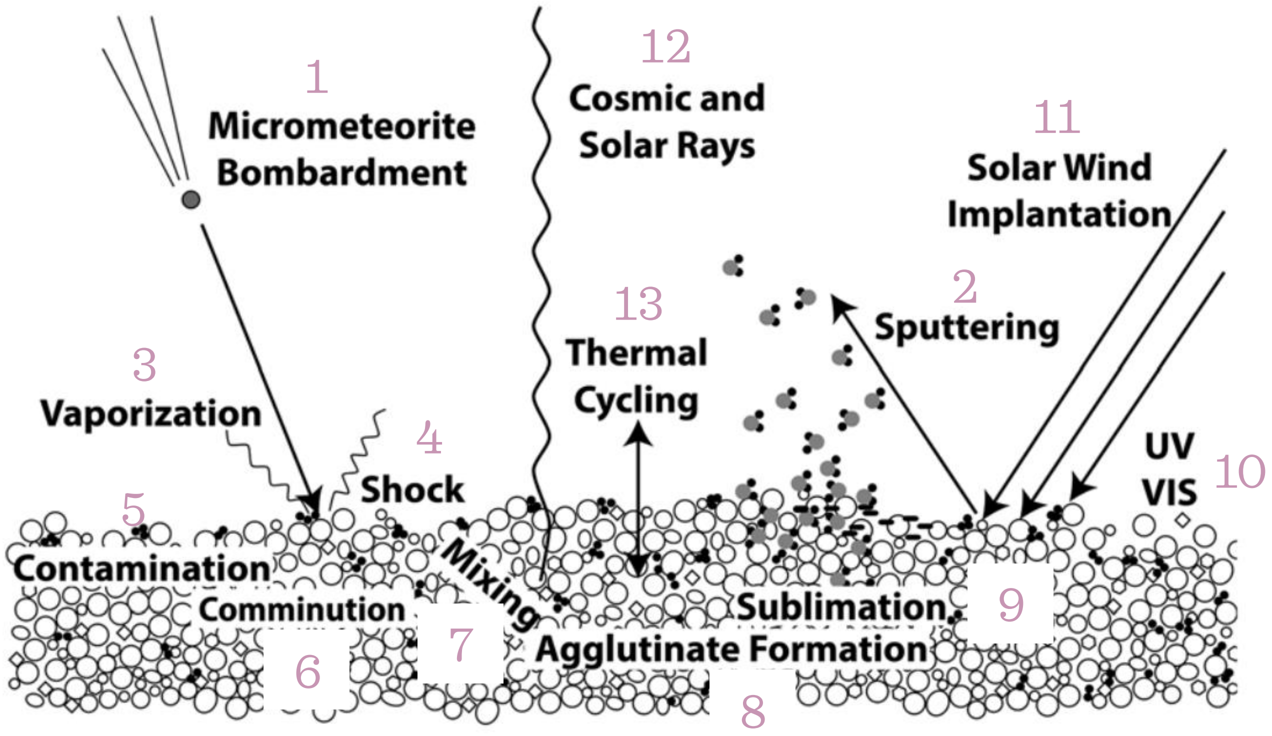

Space environment

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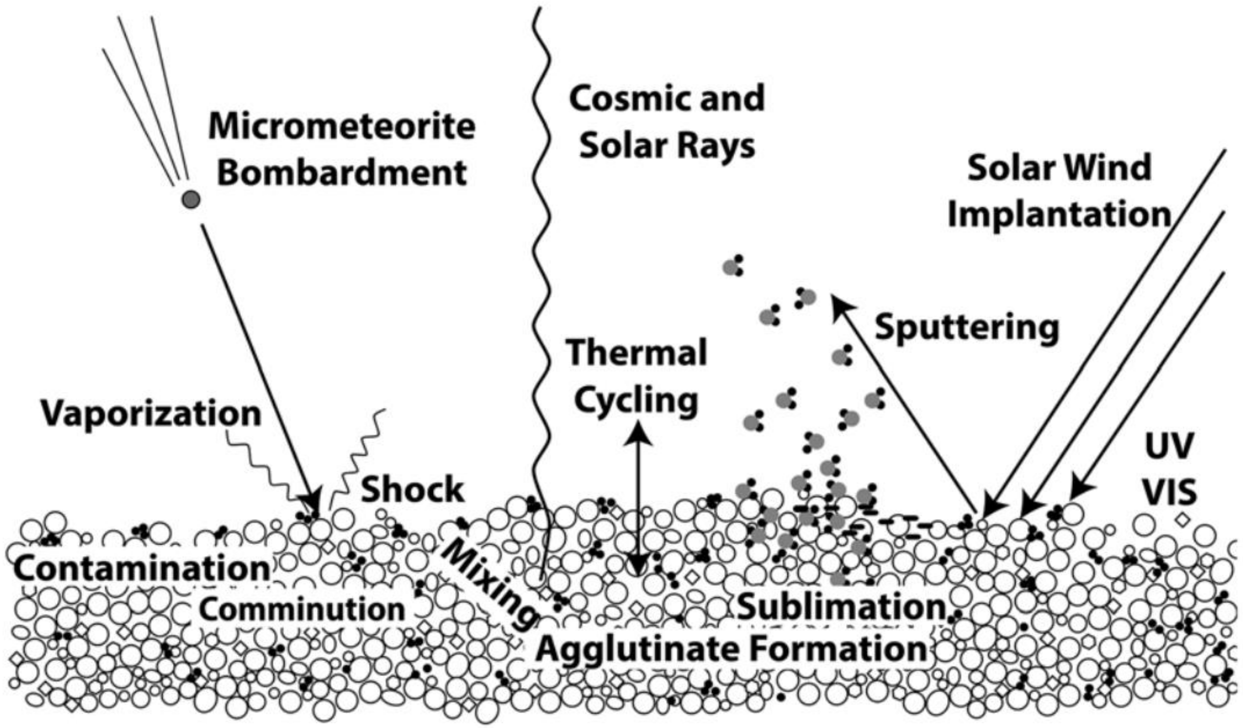
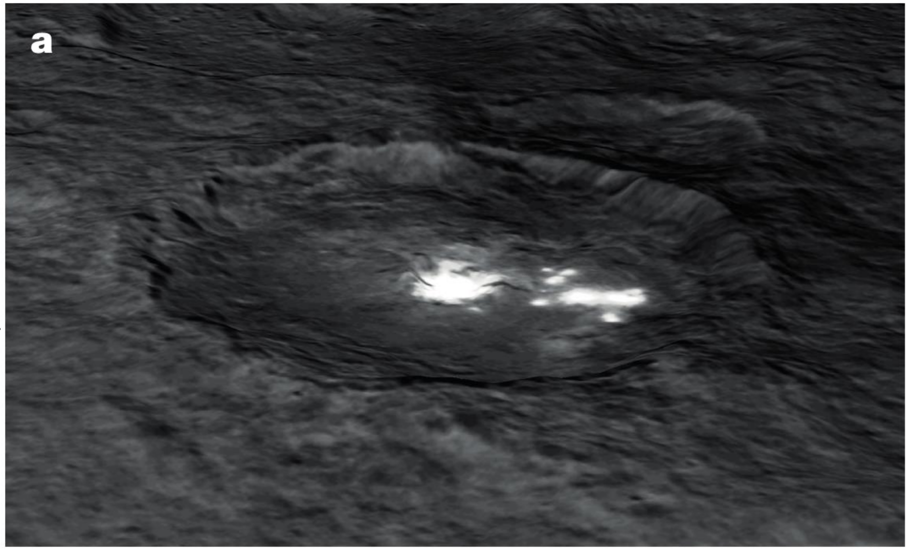


- Vary across the SS!!!

Credit: Pieters et al. (2016)

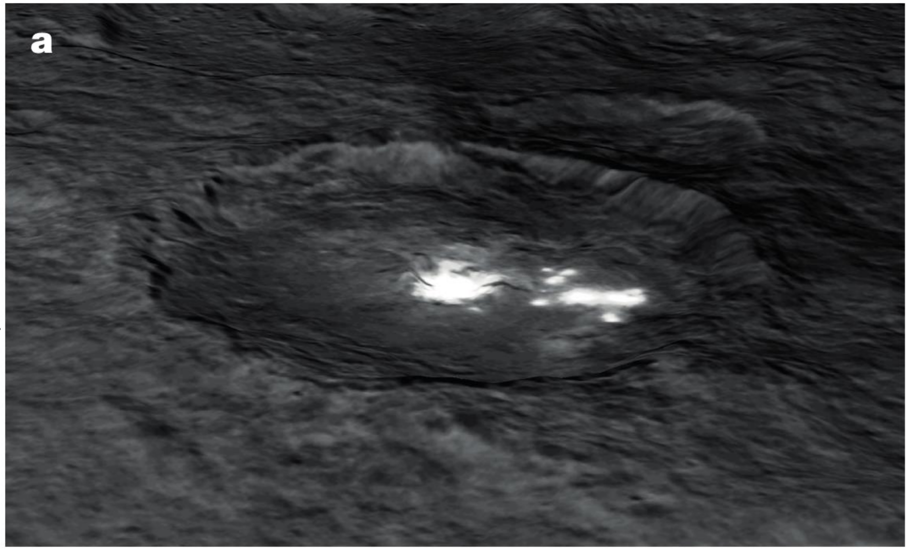
Rejuvenation processes

- Other processes act against SW:
  - Impacts
  - Asteroid shaking, close approaches
    - 16 planetary R
  - Activity (vapor loss in Occator crater on Ceres)
  - Thermal cracking (faster than microimpacts, 1 au)
  - Other



Credit: Nathues et al. (2015)

Rejuvenation processes



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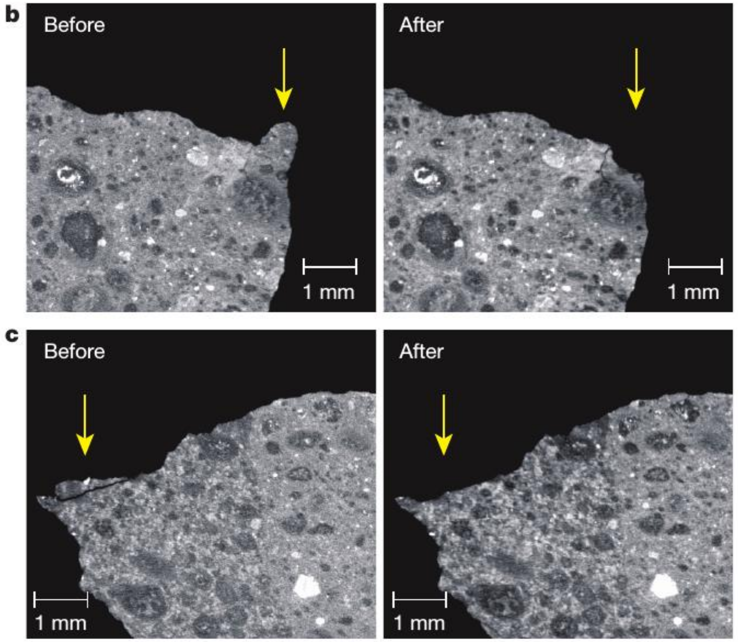
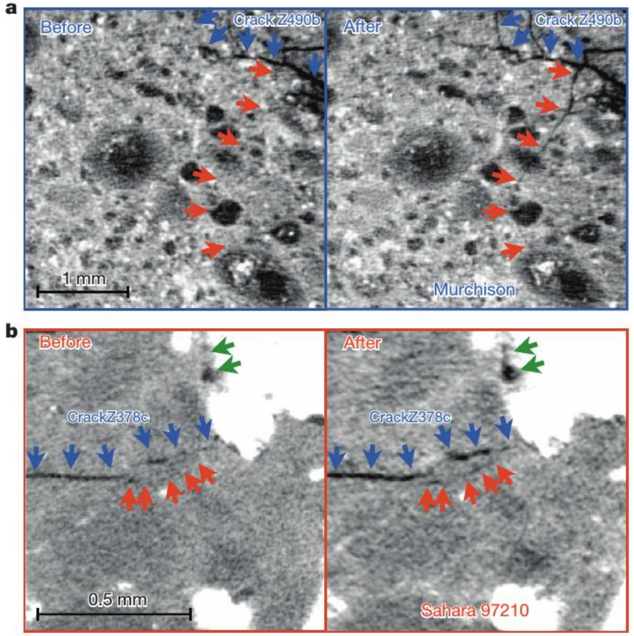




Credit: Nathues et al. (2015) and Delbo et al. (2001)

SW:
Individual cases

Meteorites vs asteroids

- It was not clear why are the spectra of meteorites so distinct from the asteroids
- The asteroid spectra aren't so prominent and are redder
- Soon after the start of SW research the reason was obvious (S – OC, Vesta – HED, C – CC)

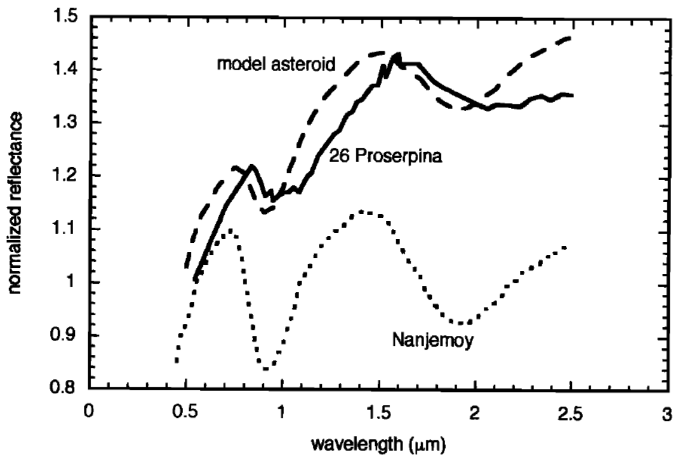
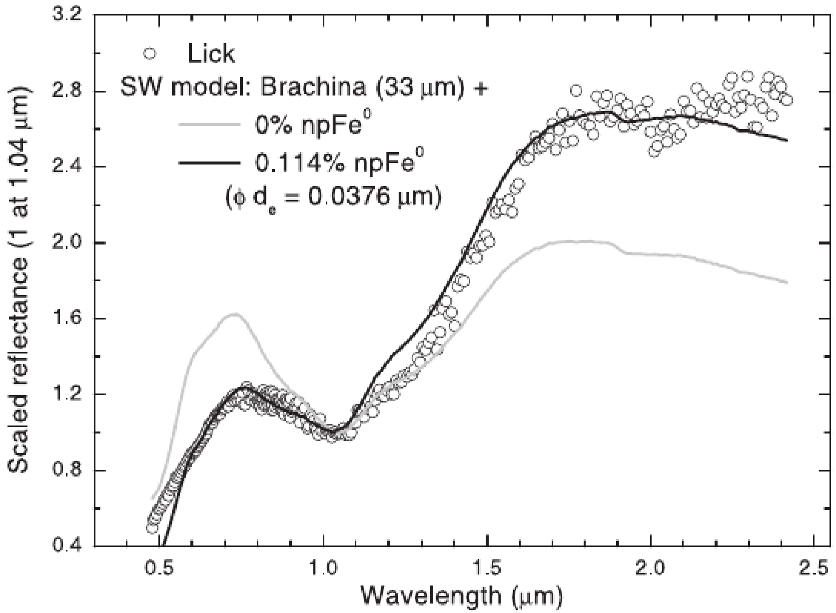


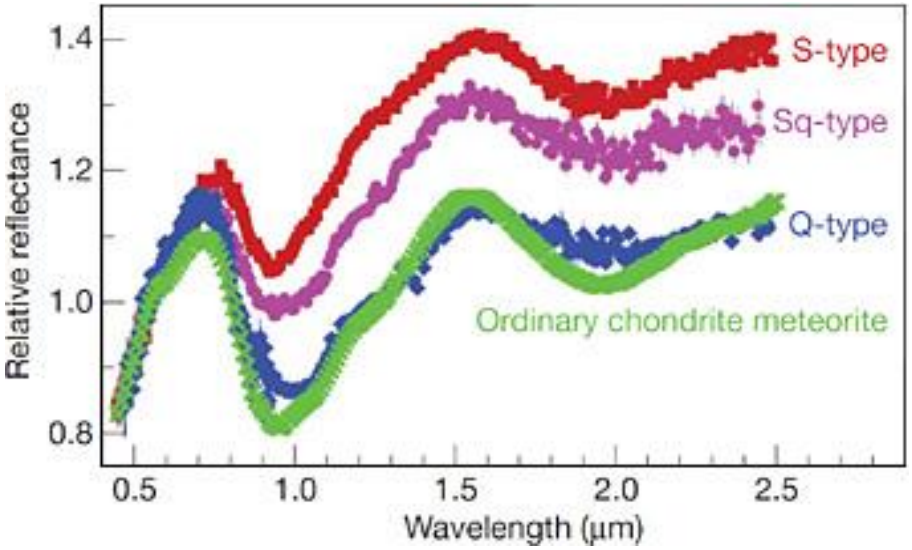
Figure 28. Modeling space weathering on an asteroid. The figure shows the bidirectional reflectance spectrum of Nanjemoy, an H6 ordinary chondrite, and the spectral physical albedo of 26 Proserpina, an S - asteroid. The dashed line is a theoretical regolith spectrum modeled by adding 0.025% SMFe to Nanjemoy. The spectra are arbitrarily nomalized. See text for details.



Credit: B. Hapke (2001) and Brunetto et al. (2007)

Q- to S-types transition

- Q-types look like fresher analogues of S-types and have spectra similar to ordinary chondrites
- Q-types:
  - Small asteroids, e.g. (1862) Apollo, 1.5 km
  - Mostly NEAs → different space environment
  - Regolit size distribution is different → SW differs
  - + regolith rejuvenation is more frequent due to approaches
- S-types have various sizes in MB- and NE-region
- Transition observed for sizes between 0.1 and 5 km
- SW evolution



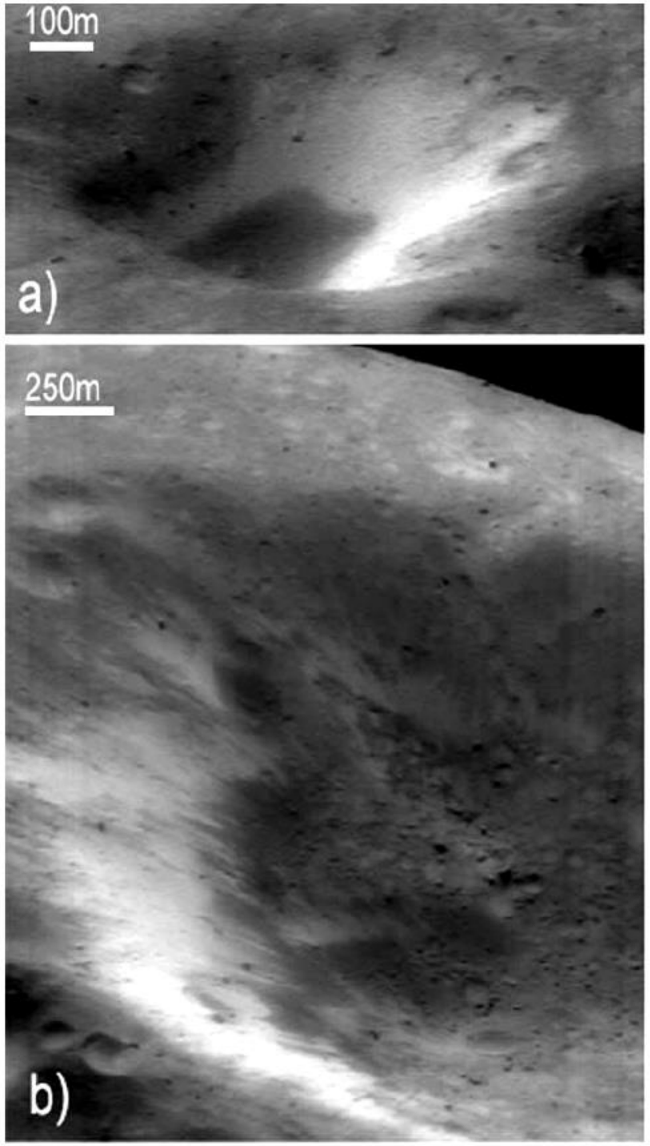
Credit: R. Binzel

SW on NEAs

- Conditions similar to those valid for the Moon
  - Difference in the gravitation and the time in the near-Earth region
- Best studied are those asteroids visited by a probe
- Generally, fresh are the craters and the areas of steep slopes, the rest of the surface is weathered

SW on NEAs - (433) Eros

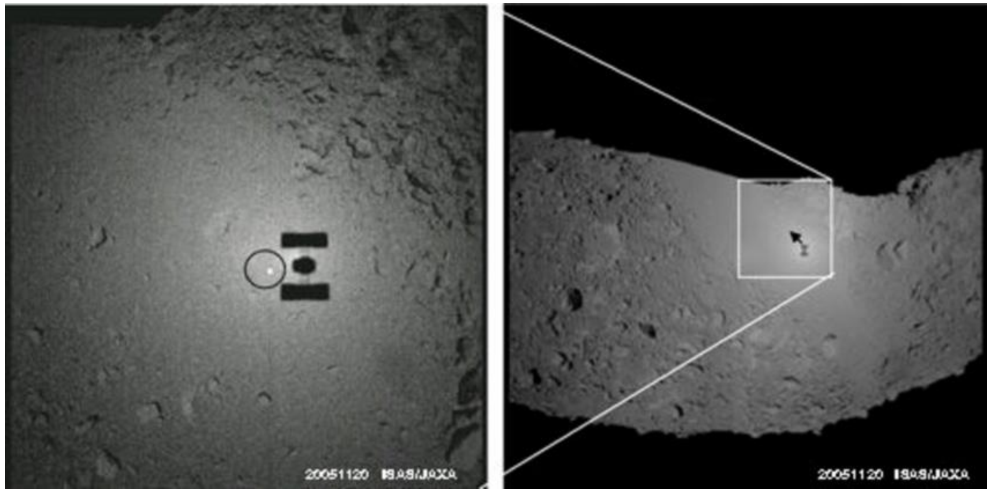
- Visited by the NEAR spacecraft
- S-type asteroid (ordinary chondrites)
- Areas where fine-grained material is accumulated ("ponds")
- Strong albedo contrast (40 %) but other parameters change only slightly



Credit: Mantz et al. (2004)

SW on NEAs - (25143) Itokawa

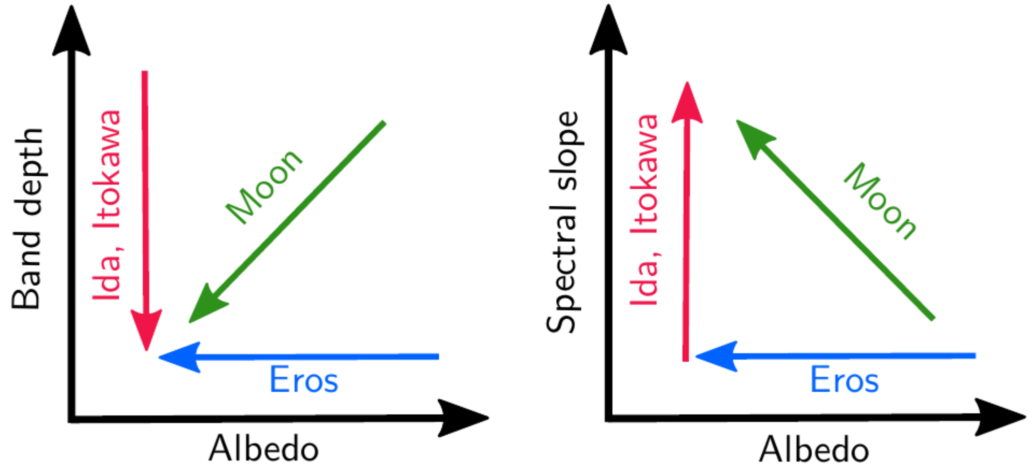
- Also S-type
- Visited by the Hayabusa probe
- Compared to Eros, only slight changes of all parameters
- Seems to be all mature
- Hayabsa mission brought back samples
  - Analyses on only a few grains at a time
  - Blistering + vapour deposits
  - Nanophase containing sulfur, not only iron
  - Little gardening, but frequent movement (smooth edges, but abundant solar tracks)



Credit: Vernazza et al. (2015)

SW on MBAs – (951) Gaspra and (243) Ida

- Flybys of the Galileo spacecraft
- Gaspra seems younger
- Ida's moon Dactyl is even fresher due to lack of regolith



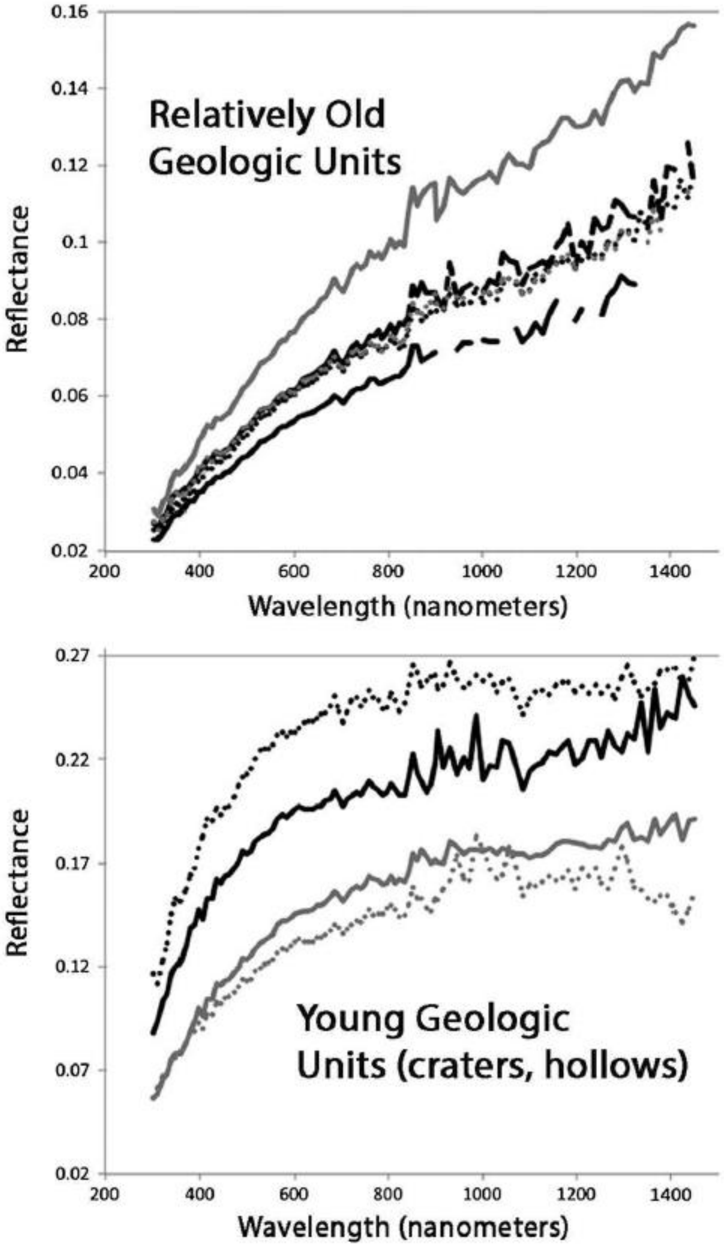
Based on: Gaffey et al. (2010)

SW on MBAs – (4) Vesta

- V-type, low-Ca pyroxene (HED meteorites)
- Dawn mission
- Young and old craters were identified
- From observations, no reddening of the spectra or band depth evolution
  - Not due to development of the nanophase iron, but rather mixing with material of impactors (carbonaceous chondrite-like material)
  - Due to lower flux of solar wind ions in the MB and due to lack of iron or sulfides that could produce darkening (magnetic field?)

SW on Mercury

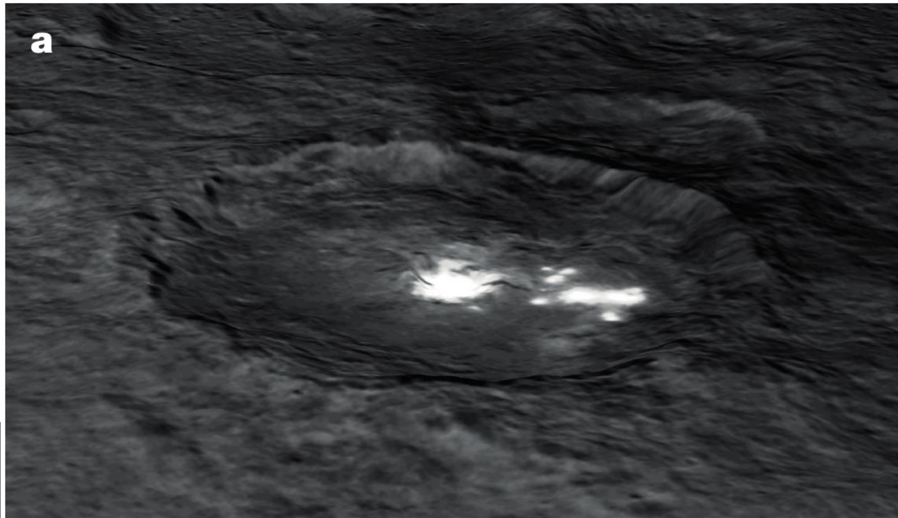
- Mercury is closer to the Sun than the Moon
  - Speed and flux of impactors is greater (also due to higher mass)
  - Solar wind irradiation is greater
- Smaller abundance of iron
- But still the fresher surface looks brighter and has less steep slope
- Maybe nanophase amorphous carbon is present



Credit: Pieters et al. (2016)

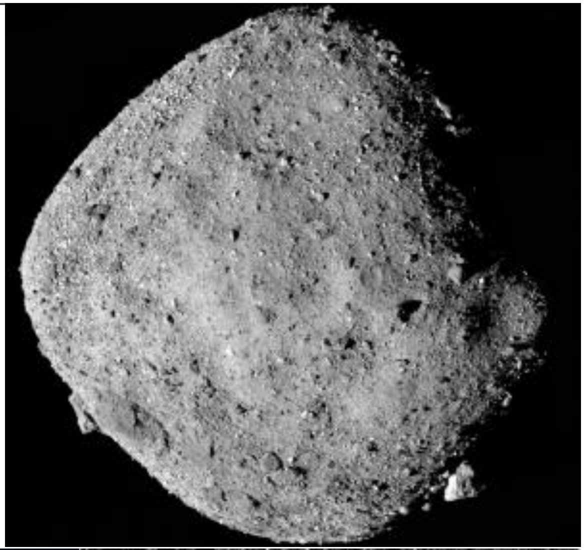
SW on MBAs – (1) Ceres

- Dawn spacecraft
- Overally dark with small albedo variation
- Craters excavate volatile materials and hydrated silicates from depth and these evolve with time
- Especially water is unstable and leaves only salts in its place



Credit: Nathues et al. (2015)

Ongoing missions – OSIRIS-REx

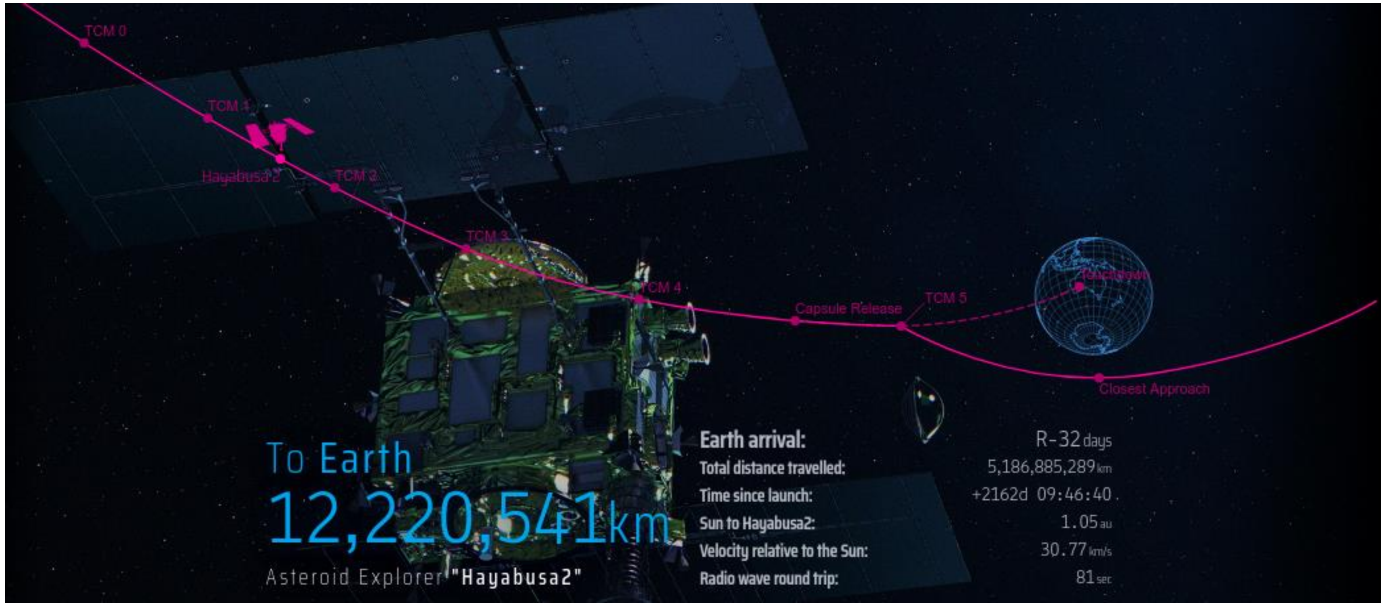


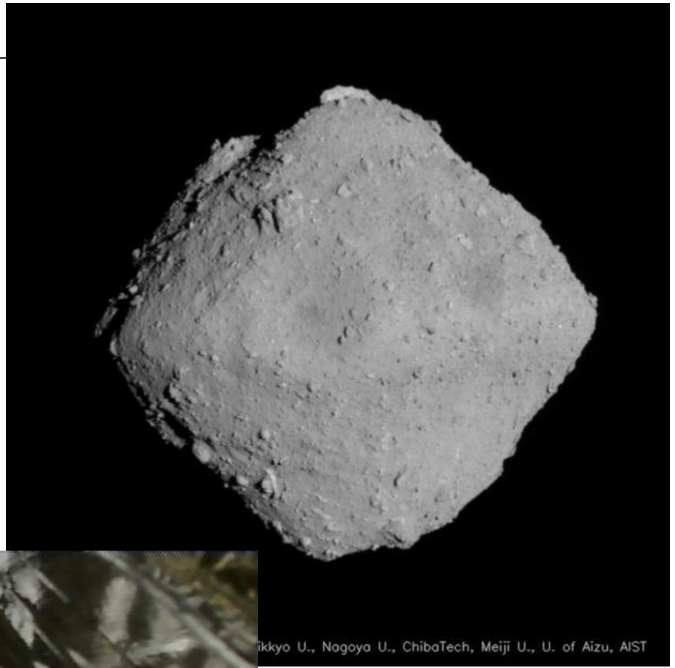
- Mission to the C-type asteroid (101955) Bennu
- OSIRIS-REx’s key science objectives include:
  - Return and analyze a sample of Bennu’s surface
  - Map the asteroid
  - Document the sample site
  - Measure the orbit deviation caused by non-gravitational forces (the Yarkovsky effect)
  - Compare observations at the asteroid to ground-based observations
- Sample return (1st: Oct 20, 2020)
  - Will return in 2023

Credit: asteroidmission.org

Ongoing missions – Hayabusa 2

- Mission to the C-type asteroid (162173) Ryugu
- Sample return (beg. and mid. 2019)
  - Will return in 2020





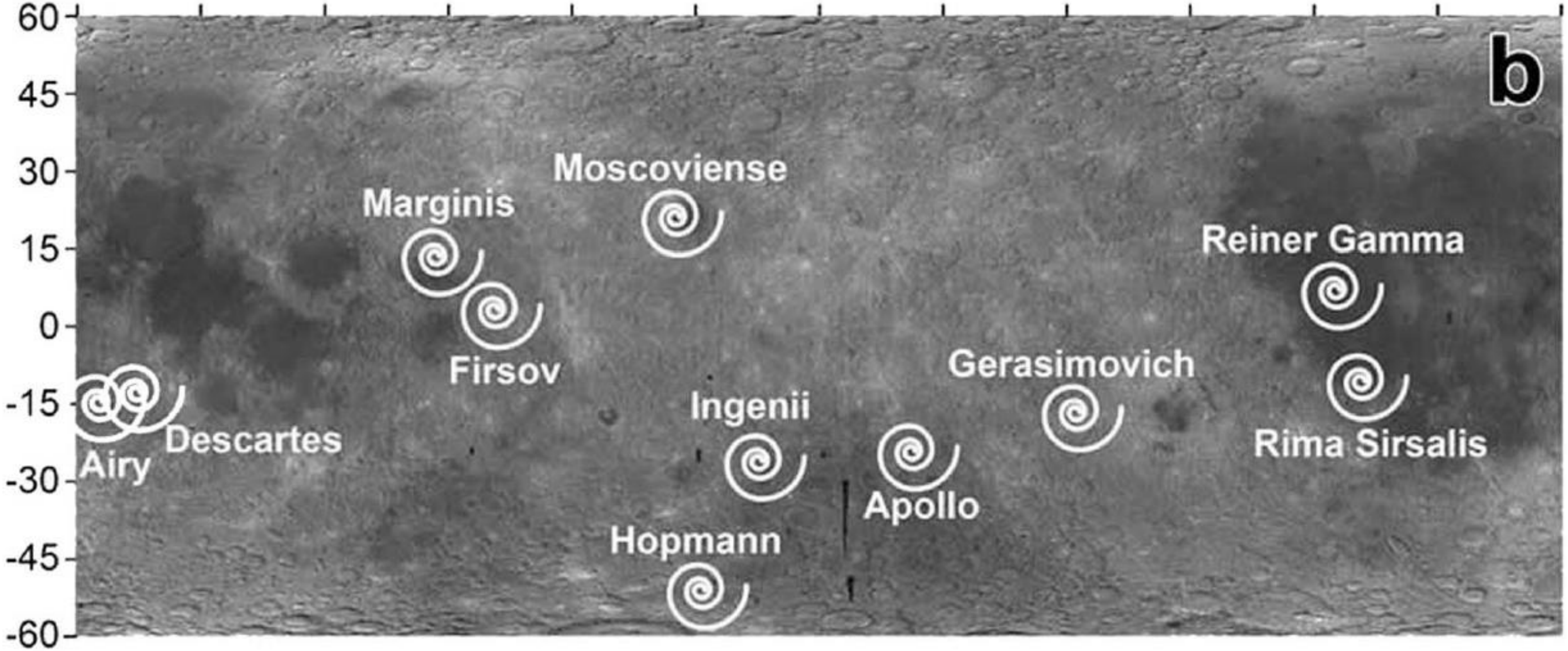
Credit: hayabusa2.jaxa.jp

Part 5:
Lunar swirls

What are the lunar swirls?

- Lunar swirls are higher albedo features on the surface of the Moon
- Albedo patterns are curvilinar (sinusiodal) with no connection to the local topography
  - See Quickmap
- They are present all over the lunar surface
  - In maria: more complex shapes, higher contrast
  - In highlands: more simple
- Always connected to amplified magnetic field (but not vice-versa!)
  - Usual field: ~ 1 – 5 nT
  - for Reiner Gamma: 22 nT at 30 km altitude
  - for Gerasimowich swirl 28 nT at 30 km altitude

Where can we find them?



Credit: Kramer et al. (2011)

Why are they so outstanding in SW studies?

- Amplified magnetic field in lunar swirls → Magnetic field stand-off theory

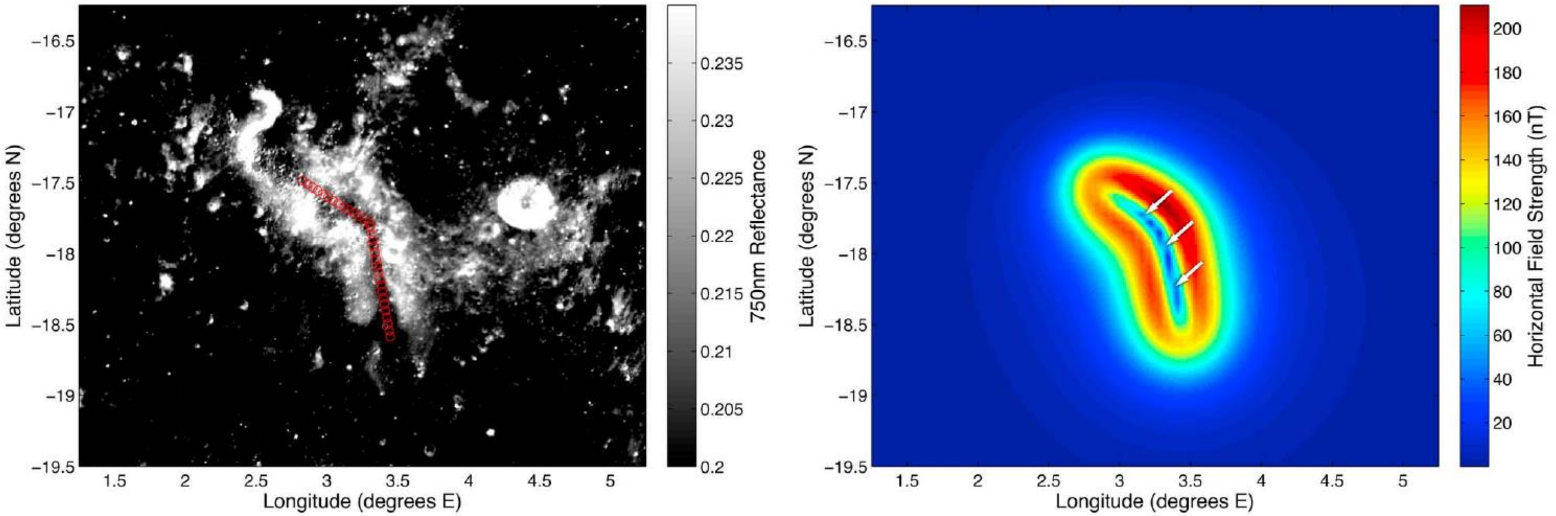
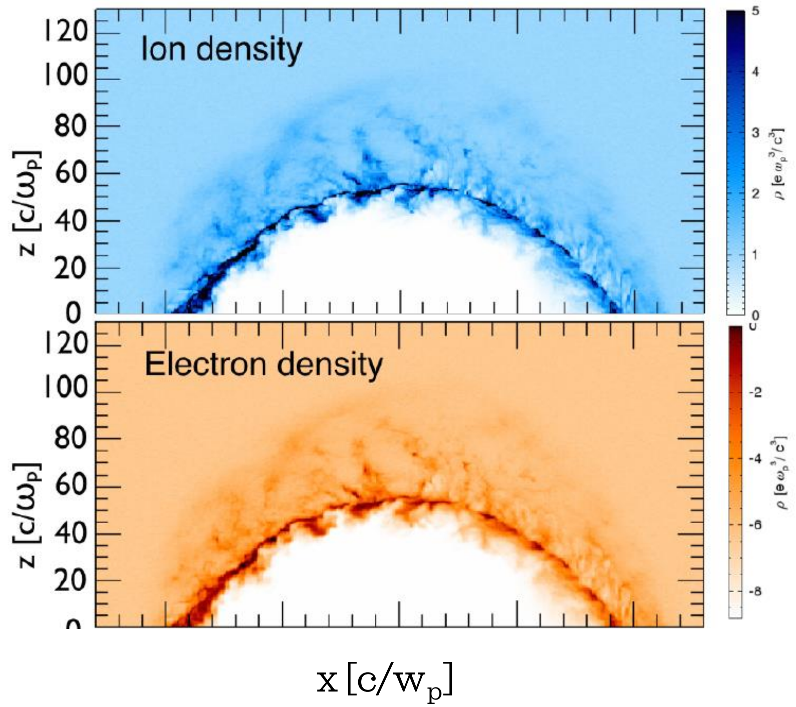


Figure 11. (left) Airy study area showing Clementine albedo map with red circles indicating the locations of the source model's 32 dipoles. (right) Resulting horizontal magnetic field strength predicted at the surface. White arrows indicate where field lines become vertical in the intraswirl dark lane. Figure 12 compares the model field predicted at the spacecraft altitude with the LP MAG observations.



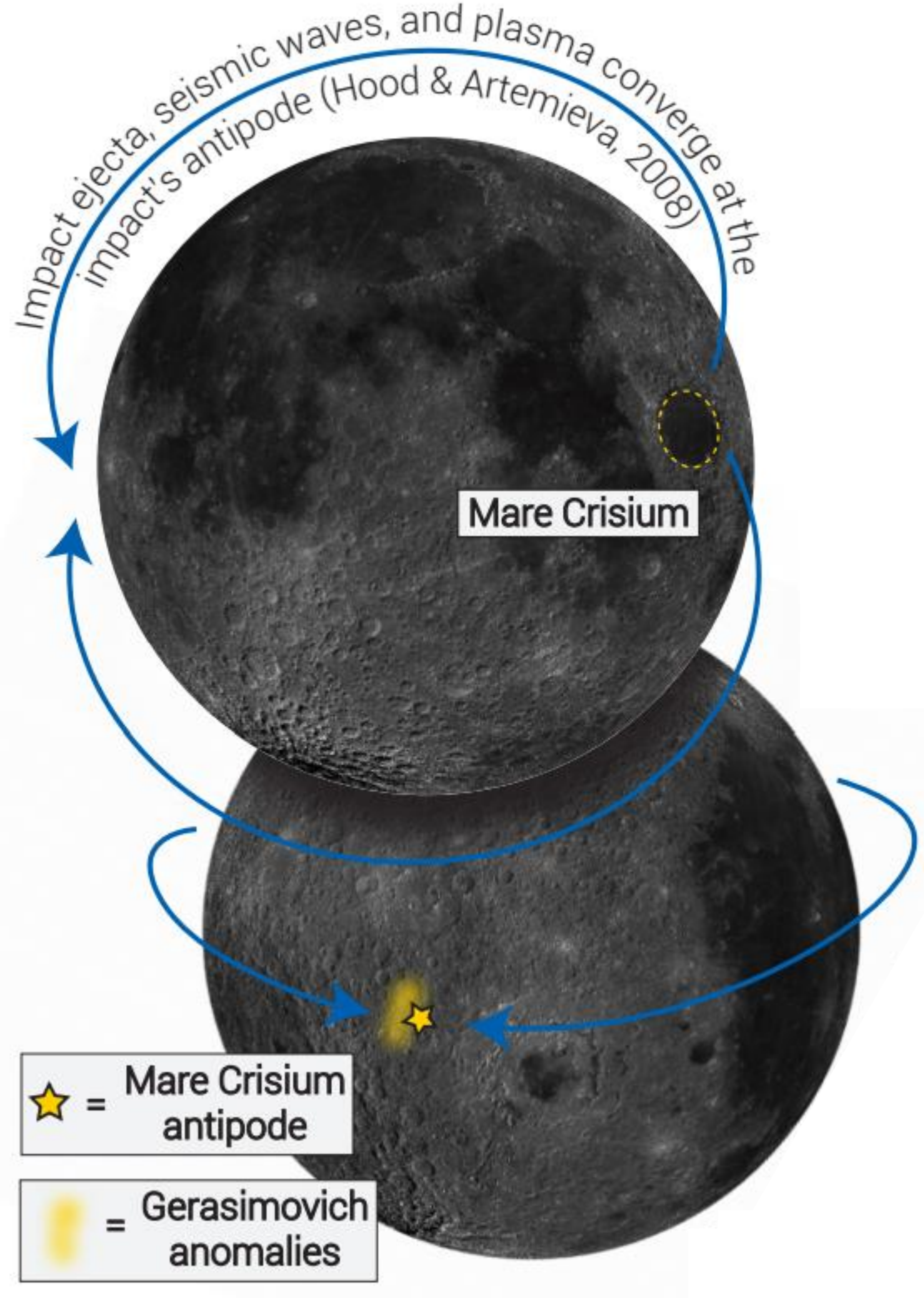
Theories of their origin

- Theory of cometary impact (Schutz and Srnka, 1980)
  - Recent cometary impacts ($< 10^8$ yr ago)
  - Turbulent flows scoured the surface
    - Material heating above the Curie temperature → magnetization
    - Altered the topmost layer
  - But!
    - Would result in different surface roughness in the swirl areas – ruled out by Diviner and Mini-RF (cm-scale)
    - Radar – only several cm thick

Theories of their origin

- Antipodal theory (Hood et al., 2001)
  - Many large swirls are in areas antipodal to the big impact basins + offset to west
  - Magnetization of the swirl area

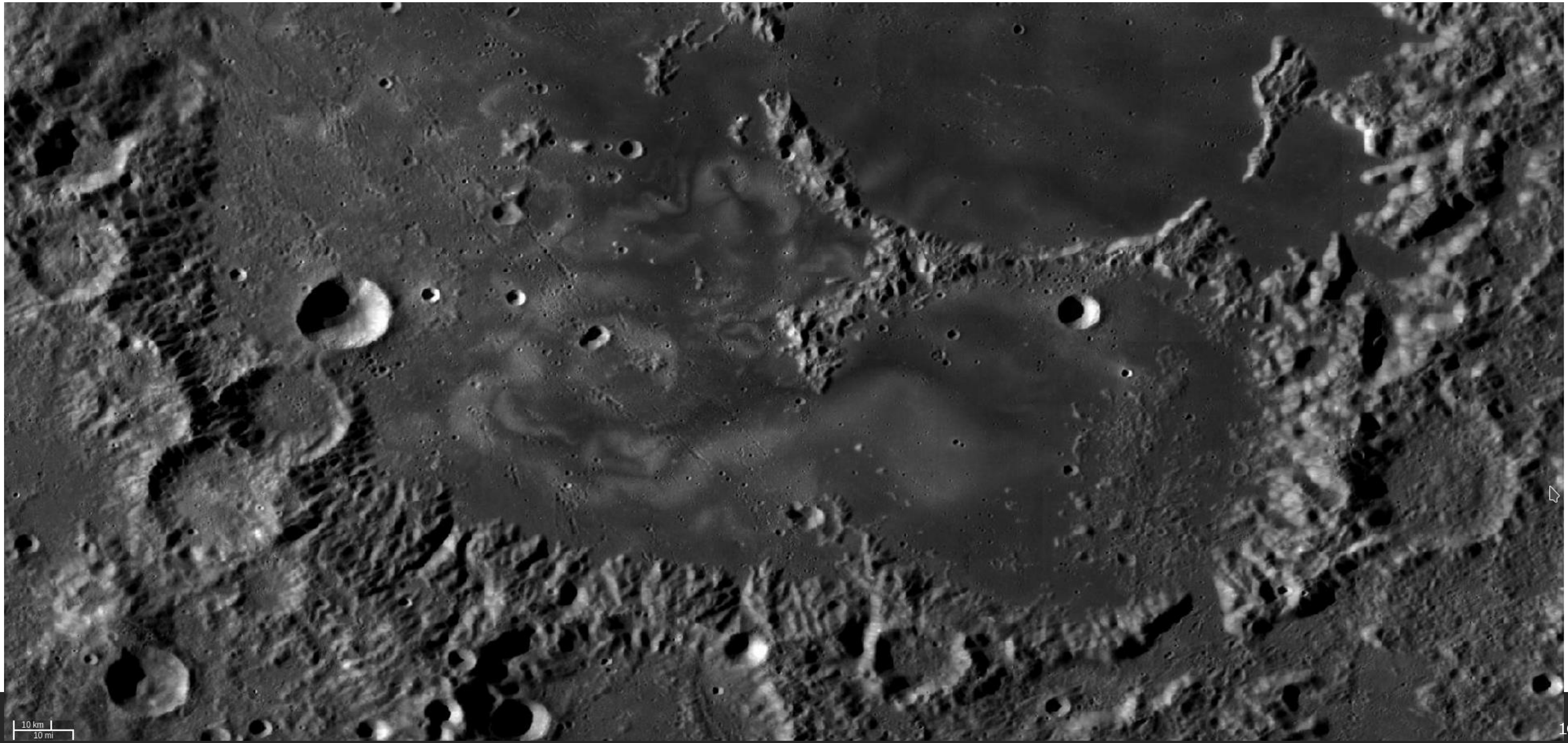
  - But: some swirls are not antipodal



Credit: M. Kelley, poster (LPSC 2019)

Some examples – Reiner Gamma

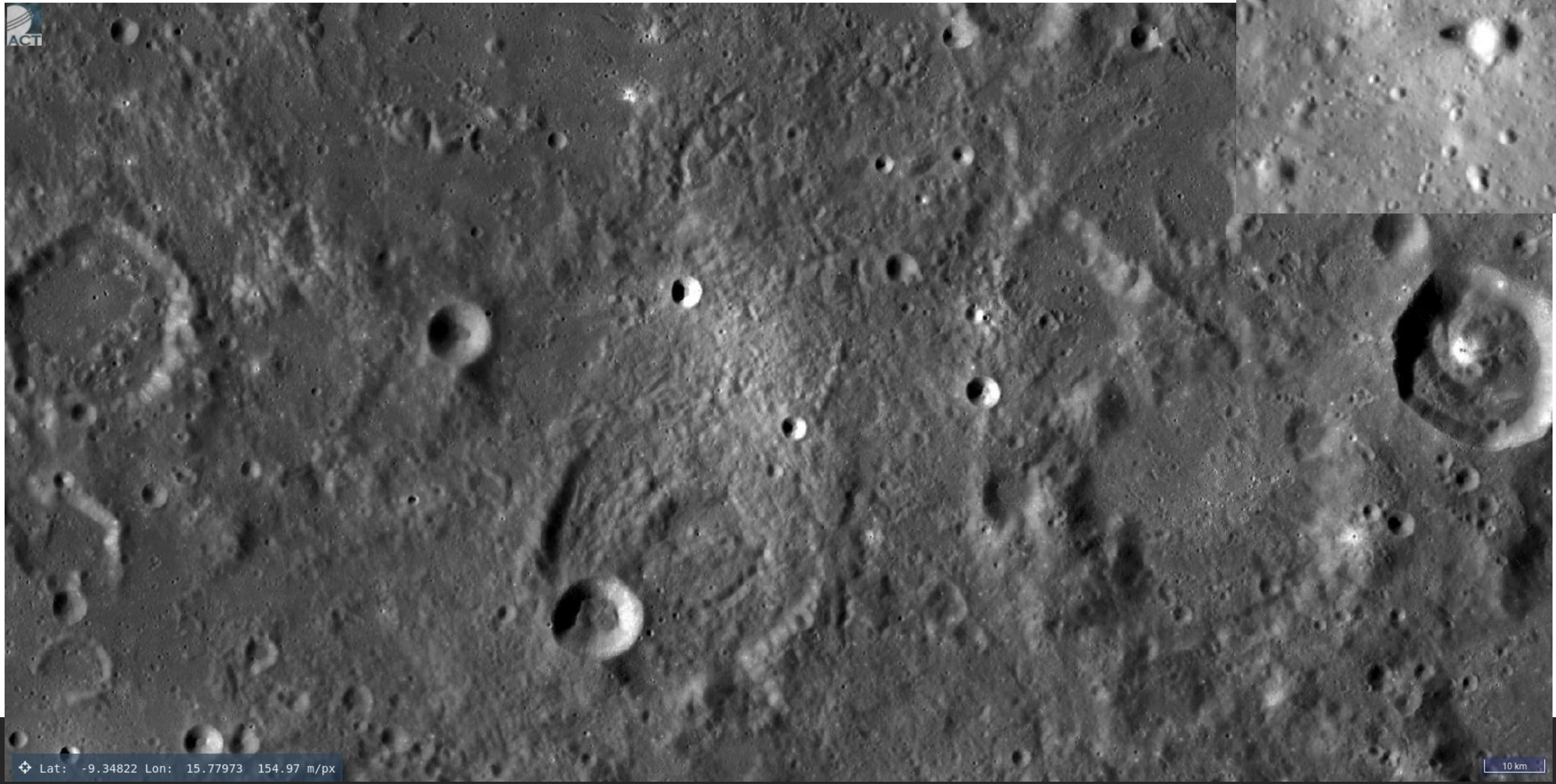
Some examples – Mare Ingenii

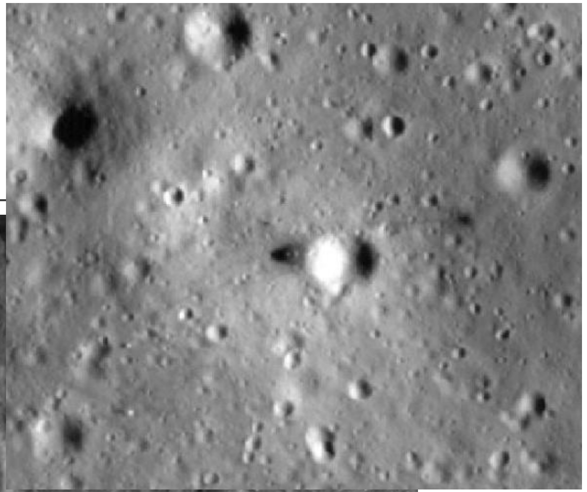


Some examples – Mare Marginis

Some examples – Airy

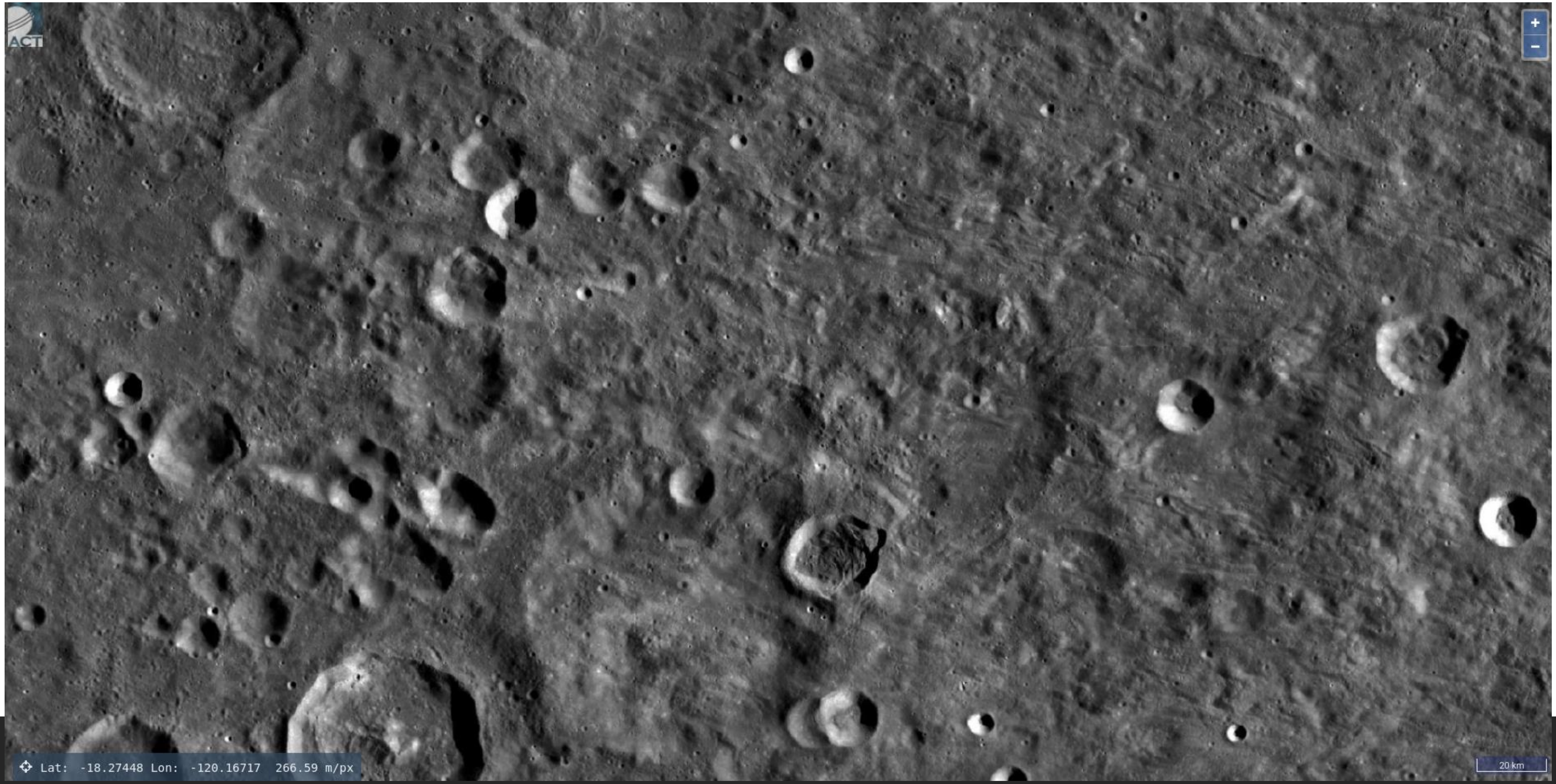
Some examples – Descartes





Apollo 16

Some examples – Gerasimovich



Some examples – Gerasimovich

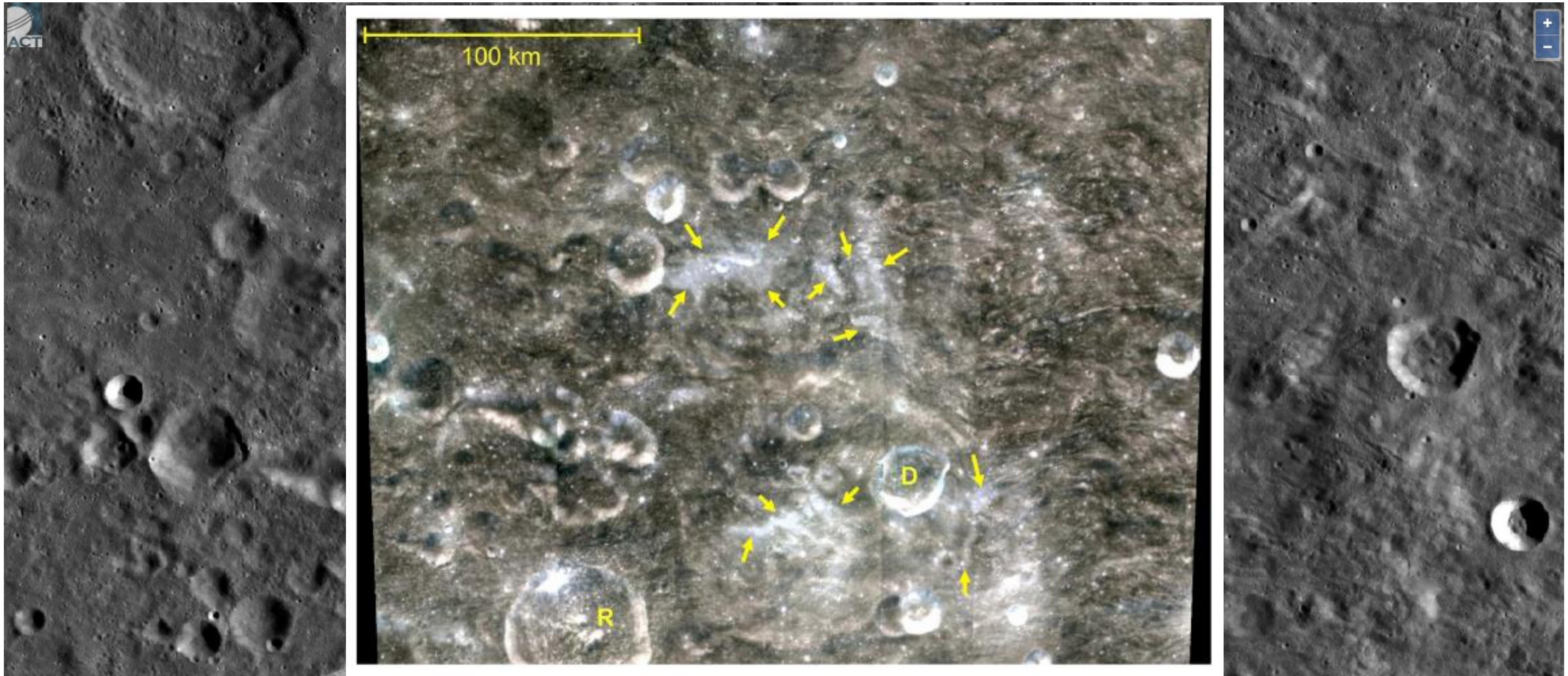


Figure 11. The Gerasimovich albedo anomaly in the vicinity of the Crisium basin antipode. Image covers 17.12°S–24.87°S, 231.12°E–241.87°E in sinusoidal projection. RGB color assignments are as in Figure 1. Label R denotes the crater Gerasimovich R (55 km diameter); D is crater Gerasimovich D. Arrows indicate swirl-like high-reflectance markings.

Credit: Blewett et al. (2011)

Some consequences of their studies

- Micrometeoroid impacts do not reproduce all-combined effects we see in the unshielded areas on the Moon
- Lunar swirls on the far-side of the Moon are more shielded than those on the near side

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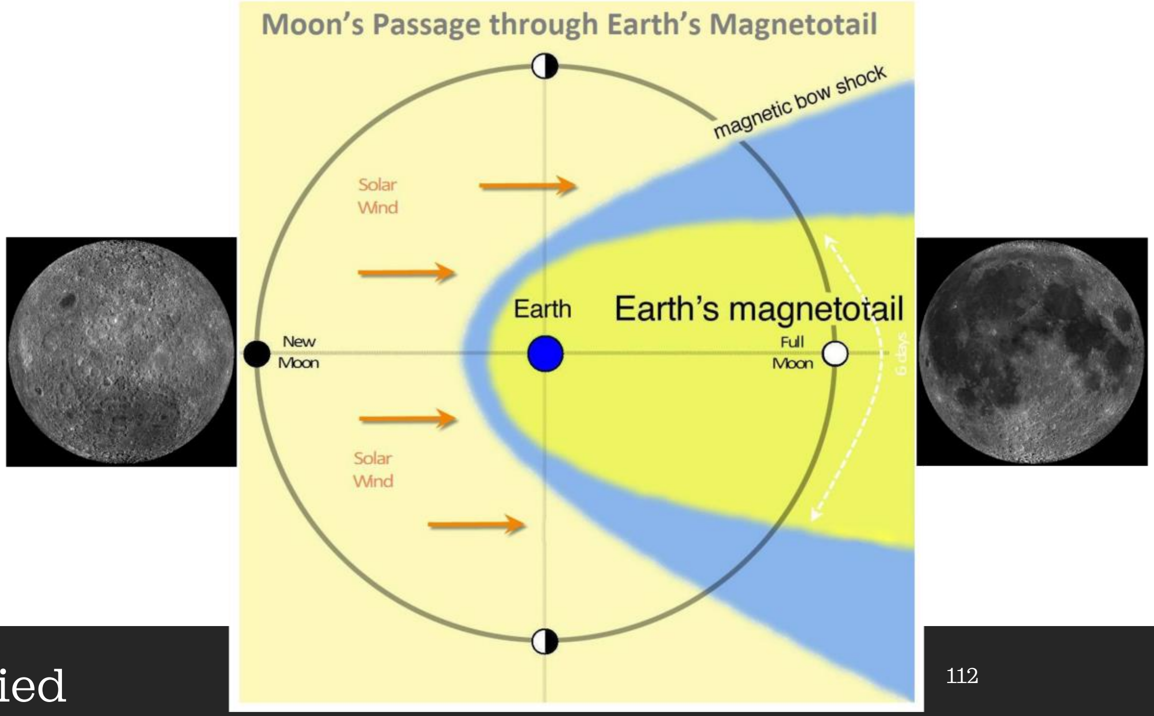
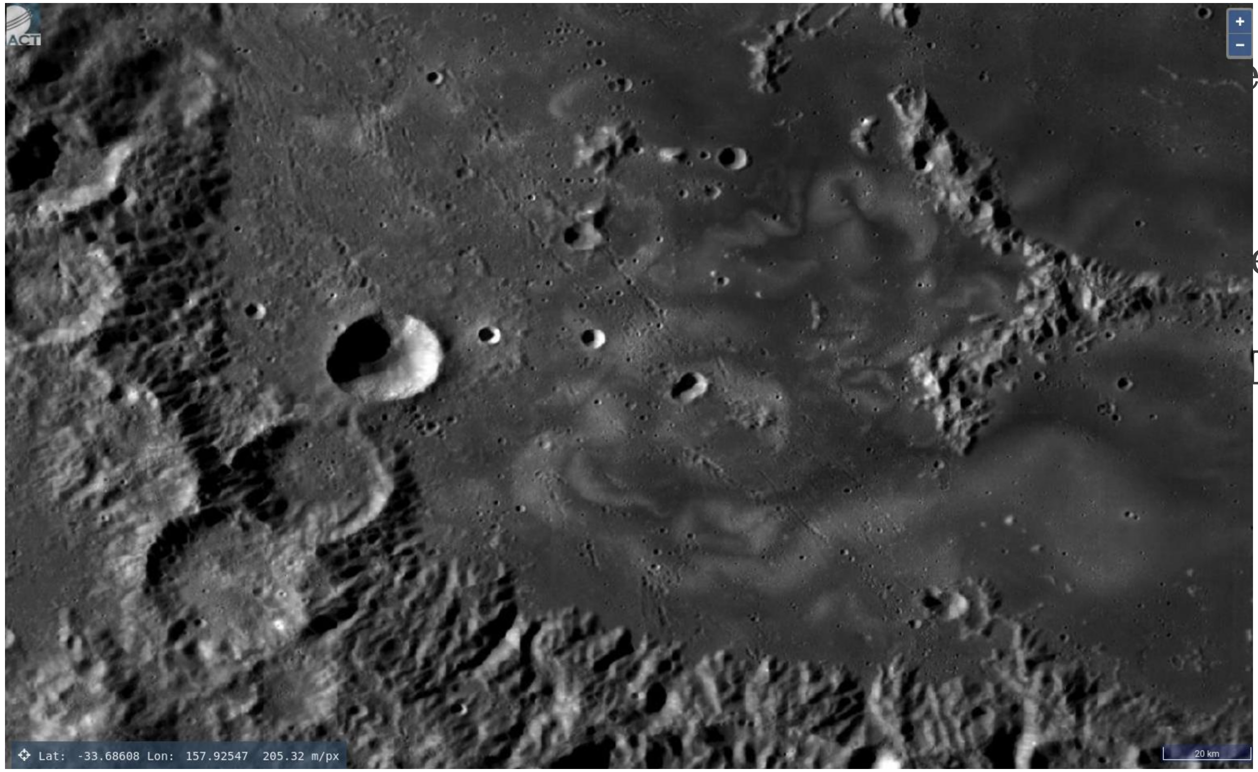


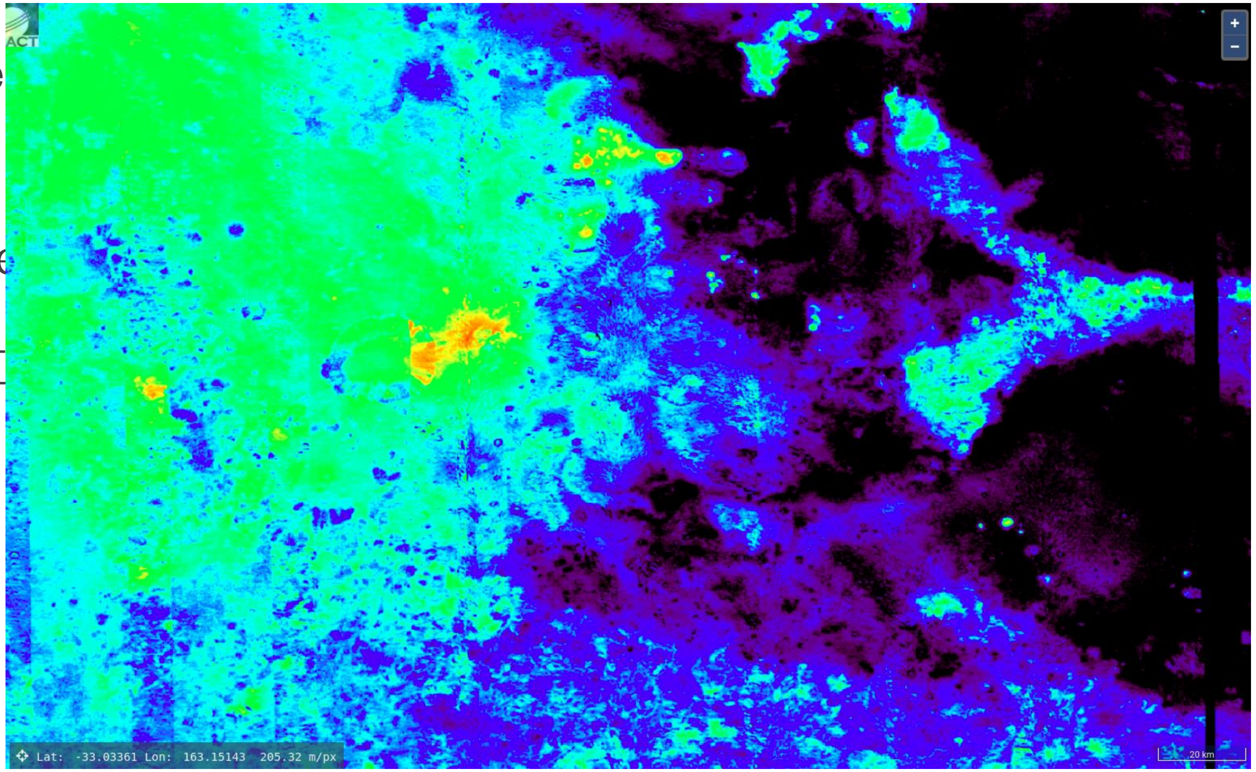
Credit: time-price-research-astrofin.blogspot.com - modified

Some consequences of their studies

- Micrometeoroid impacts do not reproduce all-combined effects we see in the unshielded areas on the Moon
- Lunar swirls on the far-side of the Moon are more shielded than those on the near side
- Spectral changes are dependent on the mineralogy
- OH abundance on the Moon (decreased in LS areas)
- Whole theory of dust levitation

Some consequences of their studies





Credit: LROC Quickmap

Part 6:
Simulations of space weathering

Laboratory simulations of SW

- Space missions such as Hayabusa give opportunity to study SW
- Other than that, we do the remote observations
- Not enough to gain the complete understanding → simulation of space weathering in labortatory
- Experiments cannot perfectly simulate the space environment
  - Temperatures
  - Pressures
  - Surface textures
  - Mineral compositions
  - BUT: increasing efforts to simulate the space environment as precisely as possible

Laboratory simulations of SW

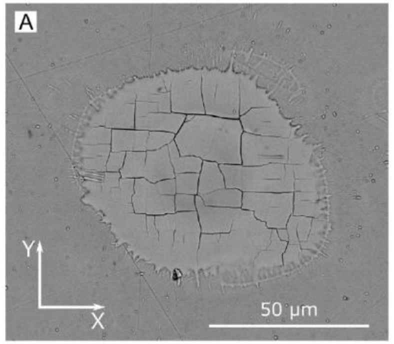
- Individual components of the space envirnomnet:
  1) Solar wind component
     - Through irradiations by ions of light elements
     - To get e.g.: 10^8 $H^+/cm^2/s$
  2) Micrometeoroid impacts
     - Particle accelerators
     - Laser irradiations
     - Simulating up to 100 μm particles flying x0 km/s, flux: 10^{-4} $m^{-2}s^{-1}$ (10 μm, at 1 au)
- Consequent measurement of spectra (+ other evaluations)

Conditions needed

1) Vacuum
   - Asteroids: 10^{-15} mbar
   - Experiments usually 10^{-2} to 10^{-10} mbar
2) Sample stabilization or not?
   - Re-oxidation of the sample (npFe)
   - All the experiment in vacuum (together with the spectral measurement) or appropriate storage
3) Doses similar to the astrophysical time-scales
4) Temperature is usually the room temperature

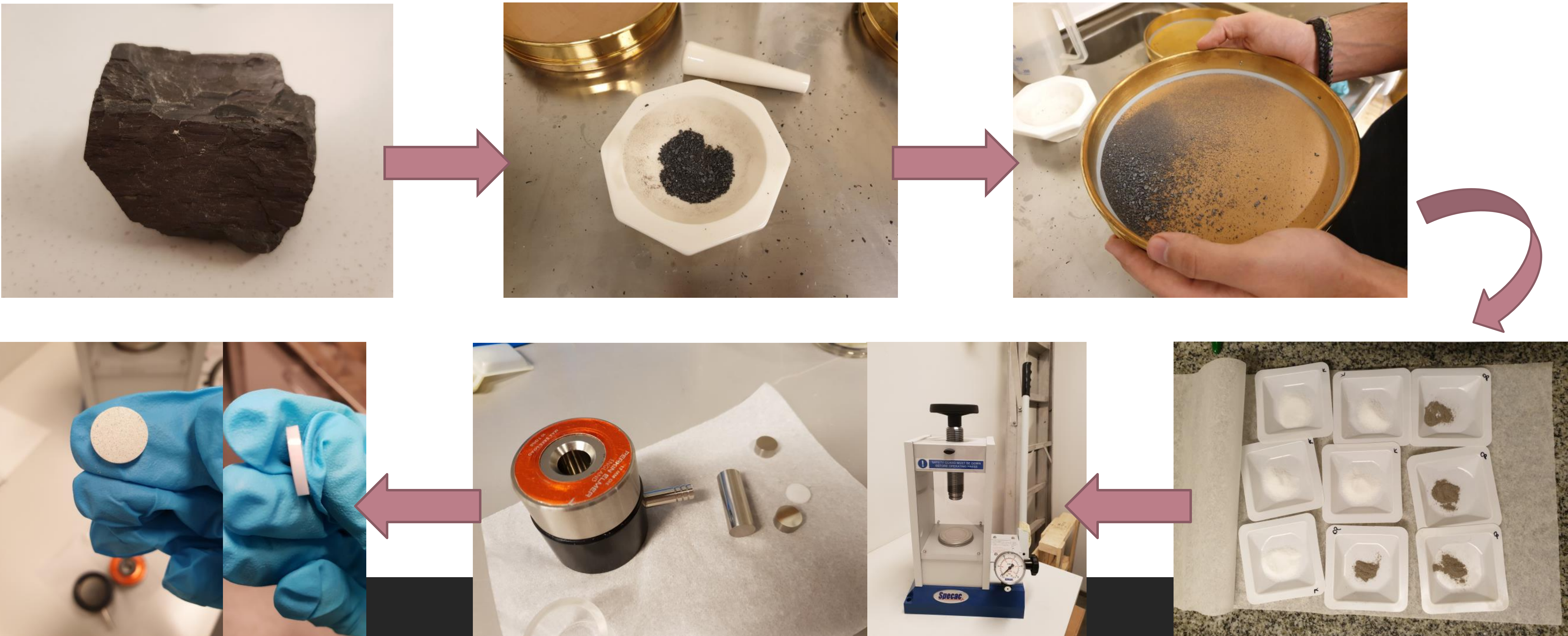
Materials

- Usually are used
  - Analogue minerals (olivines, pyroxenes)
  - Meteorites (Allande – CC, OC, HED)
  - Rarely: samples from the missions (lunar material, Itokawa regolith grains – study of their appearance, spectra, mineralogy, rather than irradiations)
- Depends on what you want to simulate
- Also the form of the material differs:
  - Crystals (cut and polished)
  - Powders (sieved or not)
  - Pellets



Credit: Yang et al. (2017), Lantz et al. (2017), myself

Step aside: How to make a pellet?



Ion irradiations

- H, He, Ar ions (various energies: 1 to 400 keV – distinct from the reality), other ions neglected due to their smaller contribution to the total flux
- Usually simulating the "slow" solar wind
- Flux differs throughout the solar system → the simulated time-scales are different
- Used: 10^{17} ions/cm^2

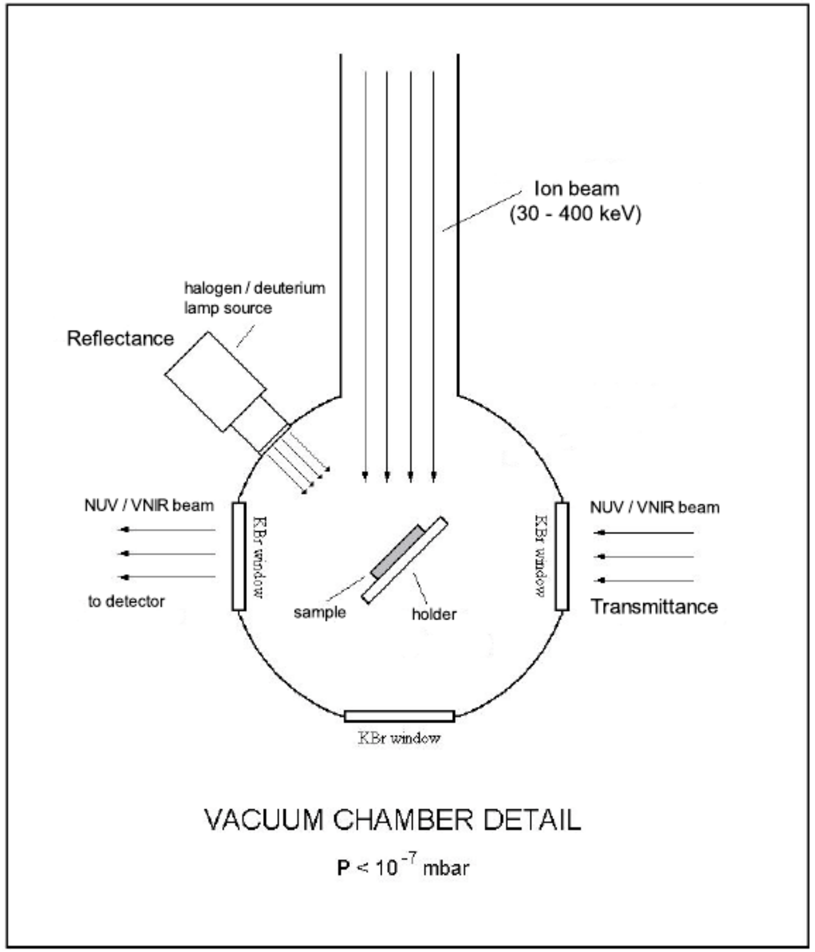
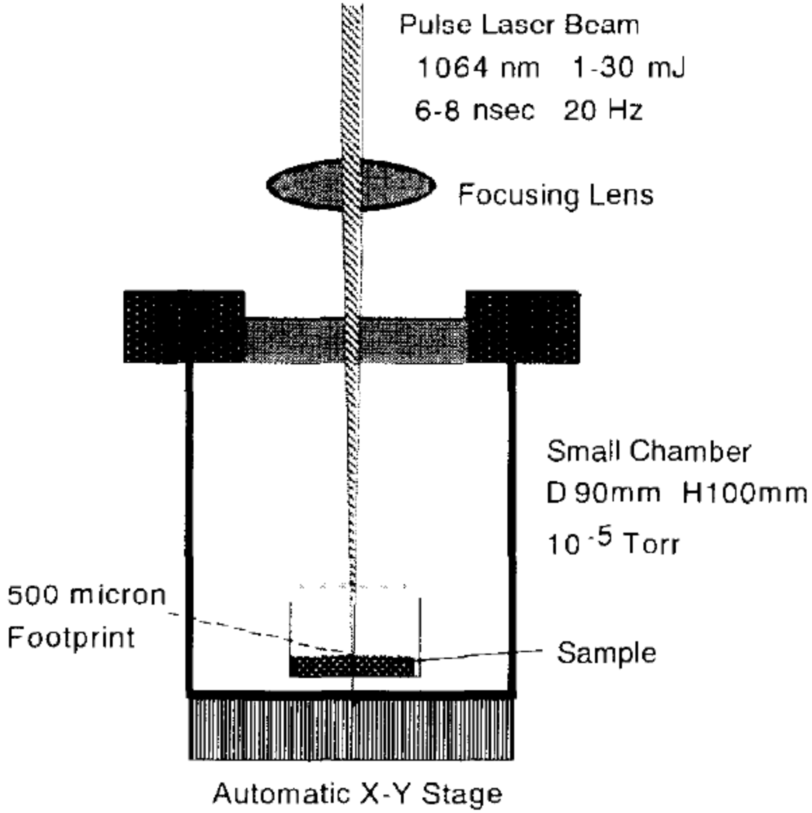


Fig. 1. Scheme of the vacuum chamber: solid samples are held on a finger. The chamber is interfaced to an ion implanter. Bi-directional reflectance spectra are acquired with a halogen/deuterium lamp source and the NUV-Vis-VNIR spectrometer.

Credit: Kanuchova et al. (2010)

Laser irradiations

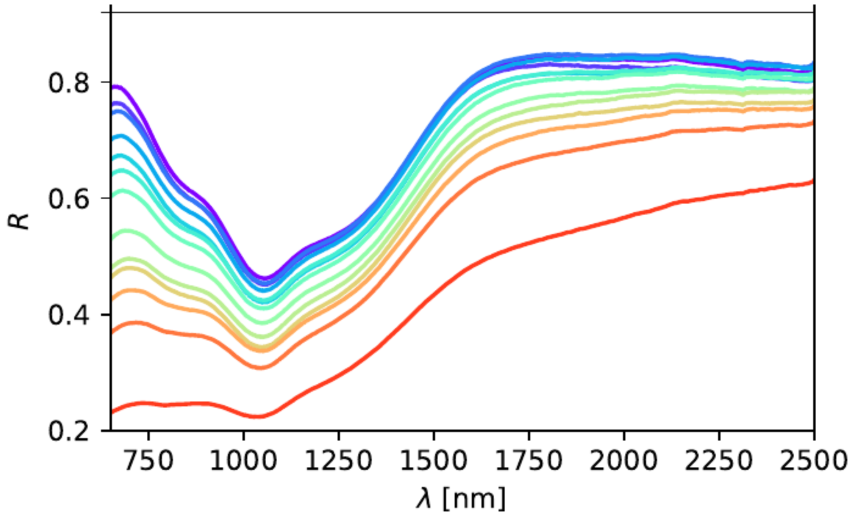
- Mostly used: Nd:YAG laser
  - 1064 nm
  - Nanosecond regime, energies 1-30 mJ, 20 Hz repetition rate
  - Comparable time-scale of vaporization process to the real situation
  - But rather heating of the surface
- New approach (Fazio et al., 2018):
  - Individual femtosecond laser pulses
  - Higher initial pressure (more similar to the real one)
  - Confined melting
  - Laser does not interact with the vapour plume



Credit: Sasaki et al. (2002)

Some results based on laboratory experiments

- Confirmed the observed trends of darkenning, reddening and band subduction in VIS-NIR of silicate materials



- Asteroid – meteorite connection

- Constraints on typical time-scales of weathering
  - 10^5 years solar wind
  - 10^8 years micrometeoroid impacts

- Degree of space weathering depends on mineralogy (already by Yamada et al., 1999)
  - Olivine shows greater changes than pyroxene
  - Changes are not linear with time

Some results based on laboratory experiments

- SW does not affect positions of spectral bands and relative area of VIS-NIR absorptions
- Weathering stages of the asteroids of Vesta family are in accordance with irradiations of eucite meteorites
- From ion-irradiations of olivine: surface exposure age of asteroid (832) Karin $\approx$ 5 Myr
  - in agreement with collisional history

Summary of lesson 2

- Space weathering significantly influences spectra in the SS
- It is **caused by two major effects** (solar wind and micrometeoroid impacts)
- Many bodies in the SS have been studied and the ongoing **missions** will provide more information
- One way to study SW is through the spectroscopy of the **lunar swirls**
- **Laboratory experiments** are capable of giving us clue on the basics of the space weathering mechanism