Space Weathering

DJ 4/28

(0) Freshly pulverized lunar rocks have higher albedo than regolith from same place

(1) On Moon, young surfaces (eg rays) have higher albedo than old.

→ darkening mechanism

(2) Older surfaces redden

→ reddening mechanism

(3) Mineral absorption bands weaken with age

→ band weakening mechanism

Related – meteorite spectra have few or no exact counterparts in their supposed source region = the asteroid belt. Why?

Ideas

(1). Vitrification by impact

(2). Solar wind & CR "damage" (– but what?)

(3). Nanophase iron deposits

(3) seems to be an important process but there is evidence also for (2). (1) is widely held to have been an experimental mistake.

Lunar Rays (Hawke et al 2004)

Three Types

Compositional Rays	Mixed	Immaturity Rays
light (Fe poor) highland matter on dark (Fe rich) basalts	← a little of both →	light because of youth c.f. weathering time

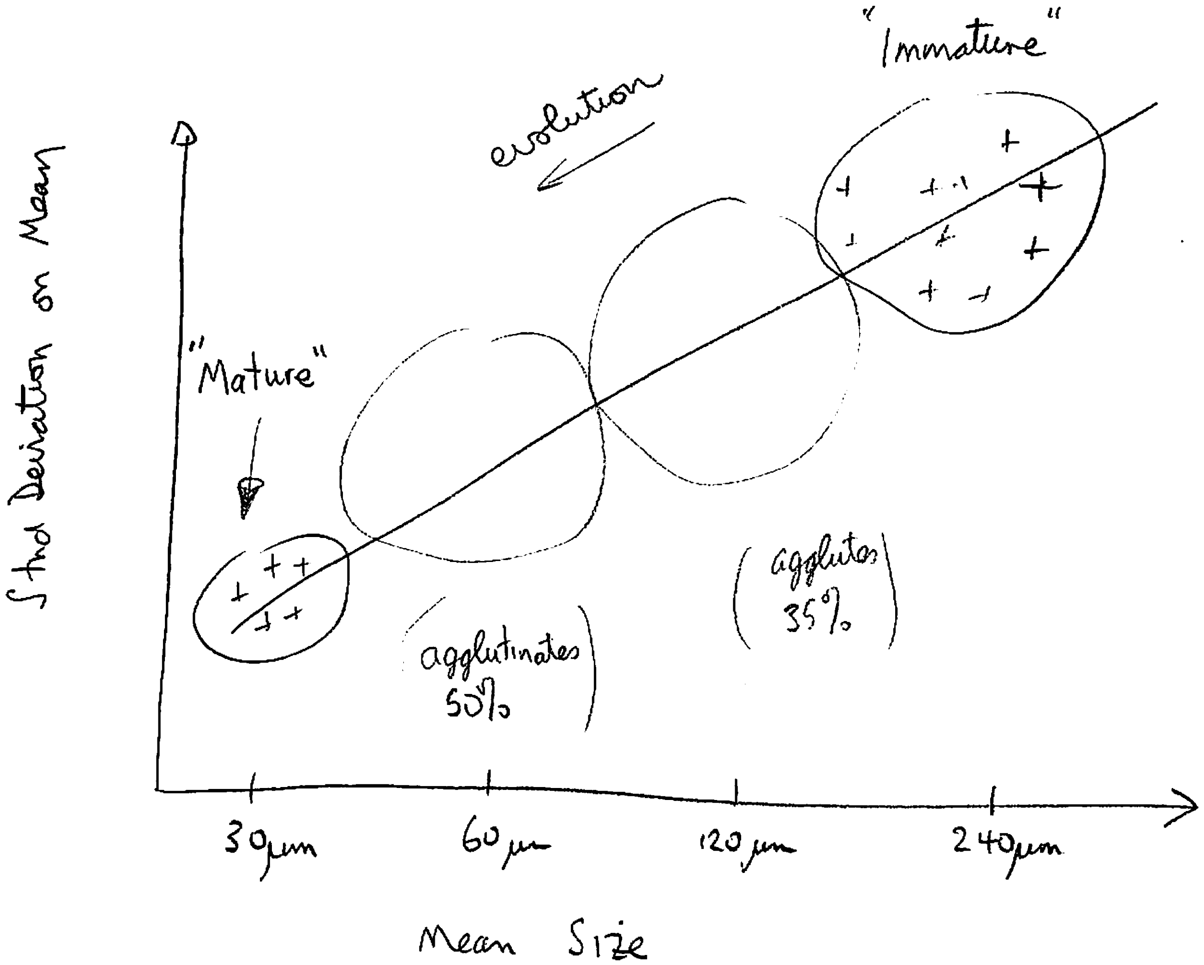
Compositional rays may survive > Gyr ; depends on mixing + dilution timescale

Immaturity rays may have ½ life ~ 500 – 800 Myr.
Uncertain

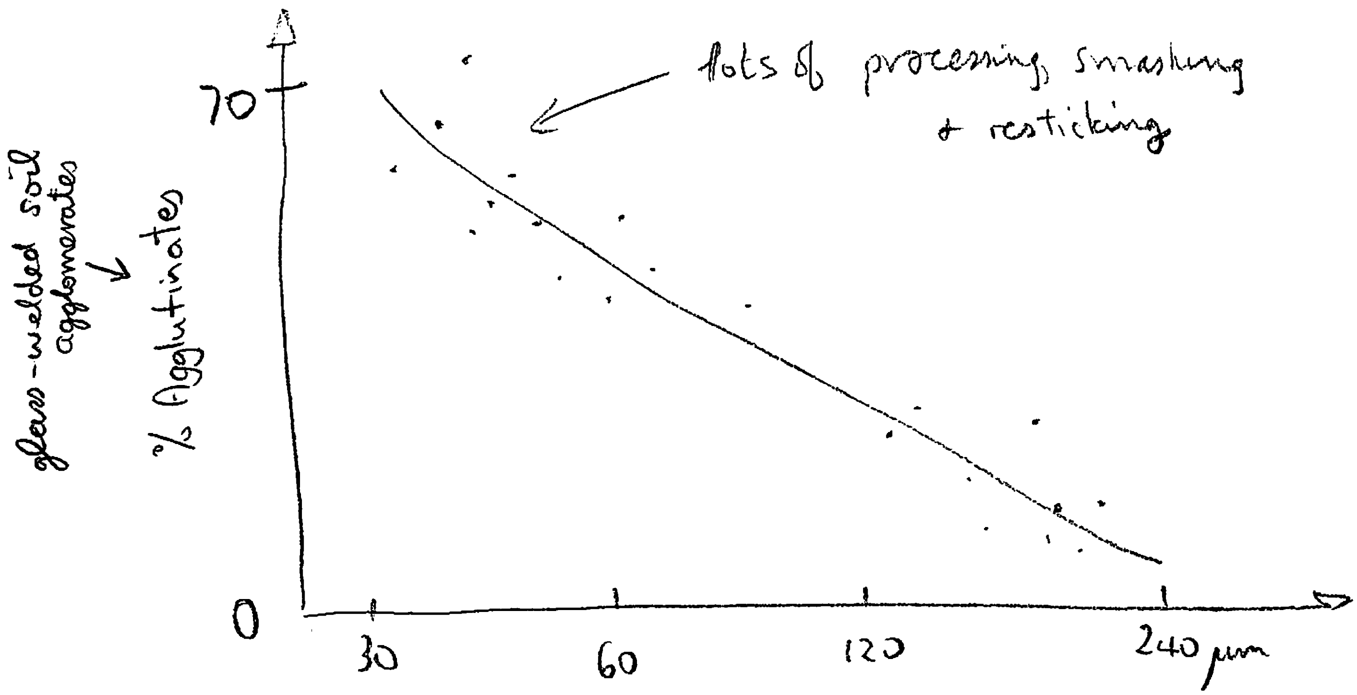
Mixed → Compositional, over time

⊕ Rays do not necessarily imply youth

Lunar Samples

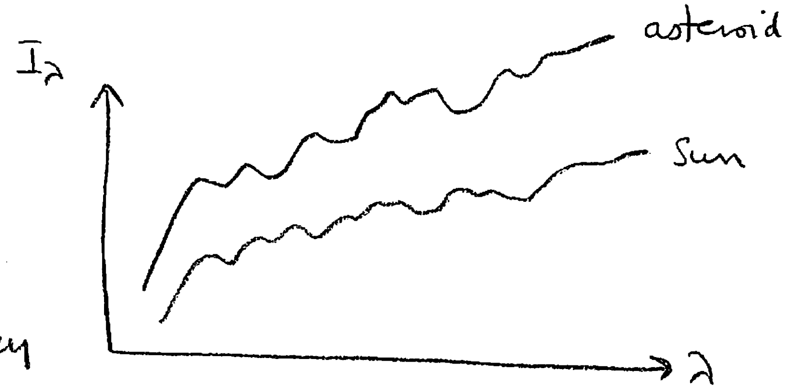


McKay et al (1974)



Asteroids

Spectrum in reflection is product of solar spectrum x reflection efficiency



Use "reflectivity" $S = \left. \dfrac{I_\lambda(\text{asteroid})}{I_\lambda(\text{sun})} \right|_n$

↑ normalised to 1 @ some wavelength

and also $S' = \dfrac{dS}{d\lambda}$ = "reflectivity gradient"

$S'' = \dfrac{d^2S}{d\lambda^2}$ = "reflectivity curvature"

$S' = 0$ = sun-colored or "neutral" spectrum

$S' < 0$ = blue

$S' > 0$ = red

Also use "colors" from astronomical magnitude data eg. B-V, V-R, R-I, J-K etc .... but these are sometimes confusing.

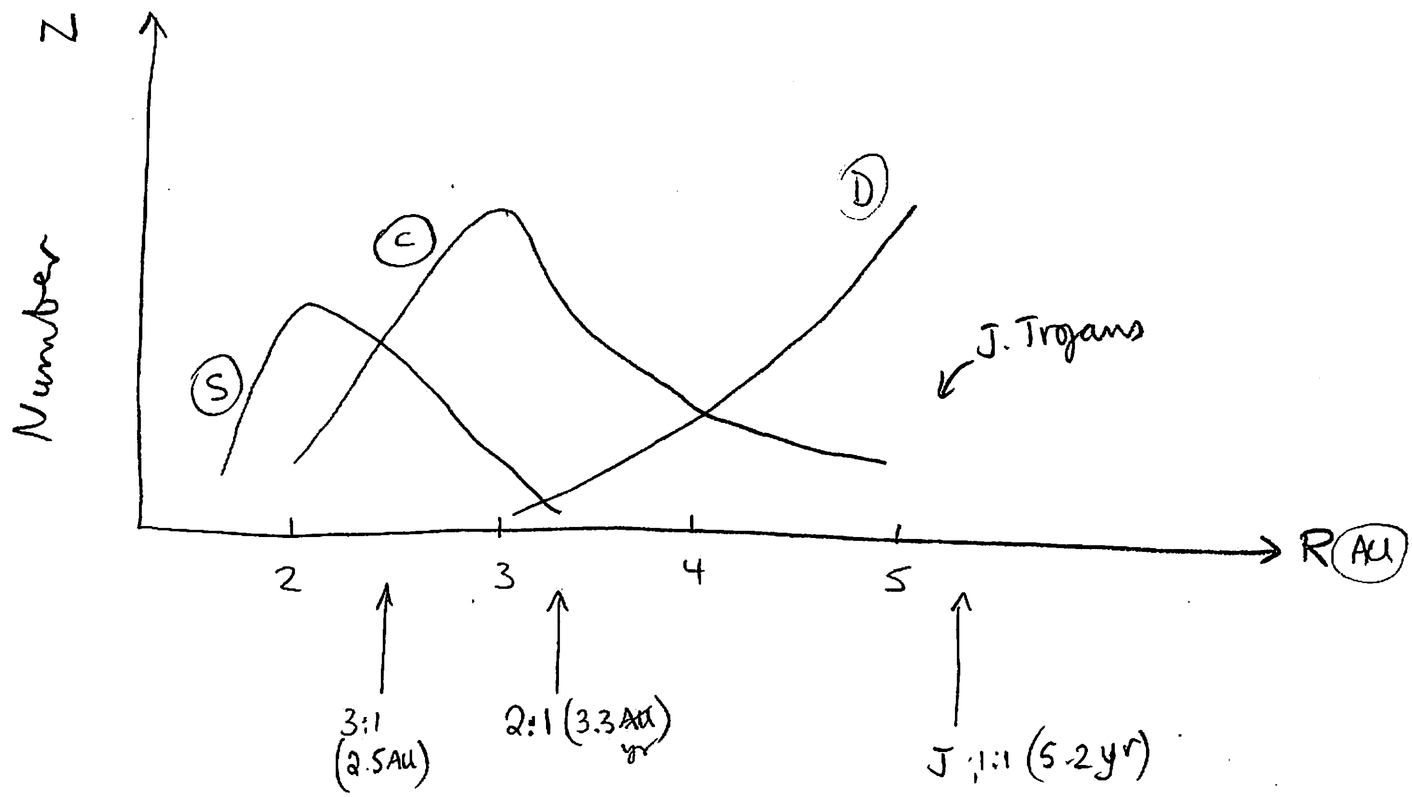
- Asteroid spectra can be grouped into "spectral classes", based on color (c.f. Tholen's taxonomy system).
  - Over time, more complicated taxonomies also involving albedo and IR colors have been used, but they don't yet add much to change the taxonomy

S - type 'reddish' $S' \sim 10\%/1000 Å$, $p_v \sim 0.15-0.25$

C - type 'neutral' $S' \sim 0-5\%/1000 Å$, $p_v \sim 0.04-0.07$

D - type 'very red' $S' \sim 10-20\%/1000 Å$, $p_v \sim 0.04$

⊙ Asteroids in various classes have different orbital distributions. (Gradie & Tedesco 1982)

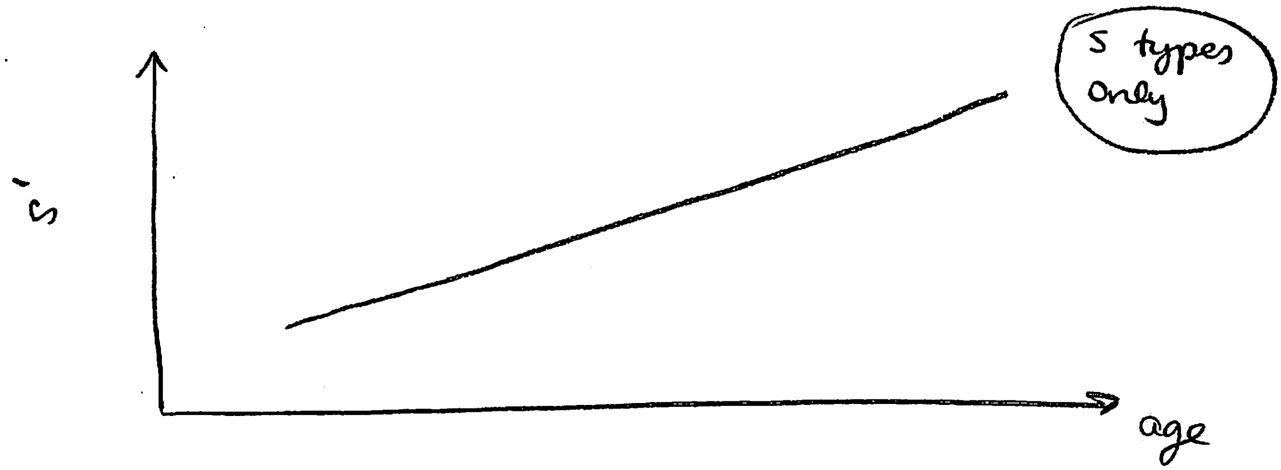


⊙ The inner belt (R~2AU) is the most strongly dynamically coupled to the Earth + should be the source of most meteorites.

BUT the most common meteorites (chondrites) do not spectrally look like S types. Why not?

Weathering?

Recently, asteroid age estimates have been made from families – disrupted asteroids.



(Willman et al 2010)

Model fit i) not consistent w/. one darkening/reddening agent

ii) timescales $\tau_1 \sim 1.0 \pm 0.2$ Gyr (sol. wind)

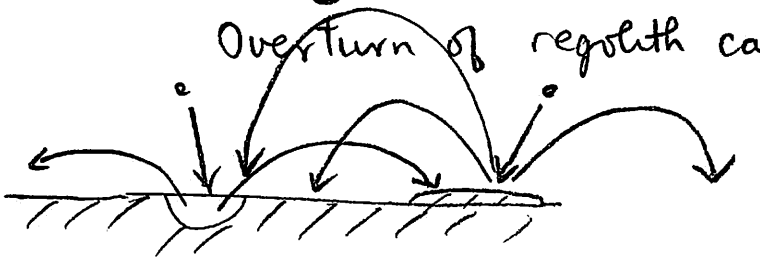
$\tau_2 \sim 2.0 \pm 0.3$ Gyr (impact gardening?)

$$\tau_1 \text{ @ 1 AU} \sim \frac{1.0}{2^2} \sim 250 \pm 50 \text{ Myr}$$

τ_2 not so easy to scale to 1 AU

Gardening

Overturn of regolith caused by repeated impacts.



Includes both

Excavation + Burial

- Gardening timescale $t_g \sim 4$ Gyr @ $d \sim 4$ m on the Moon

- $t_g \propto d$, roughly (Shoemaker et al 1970)

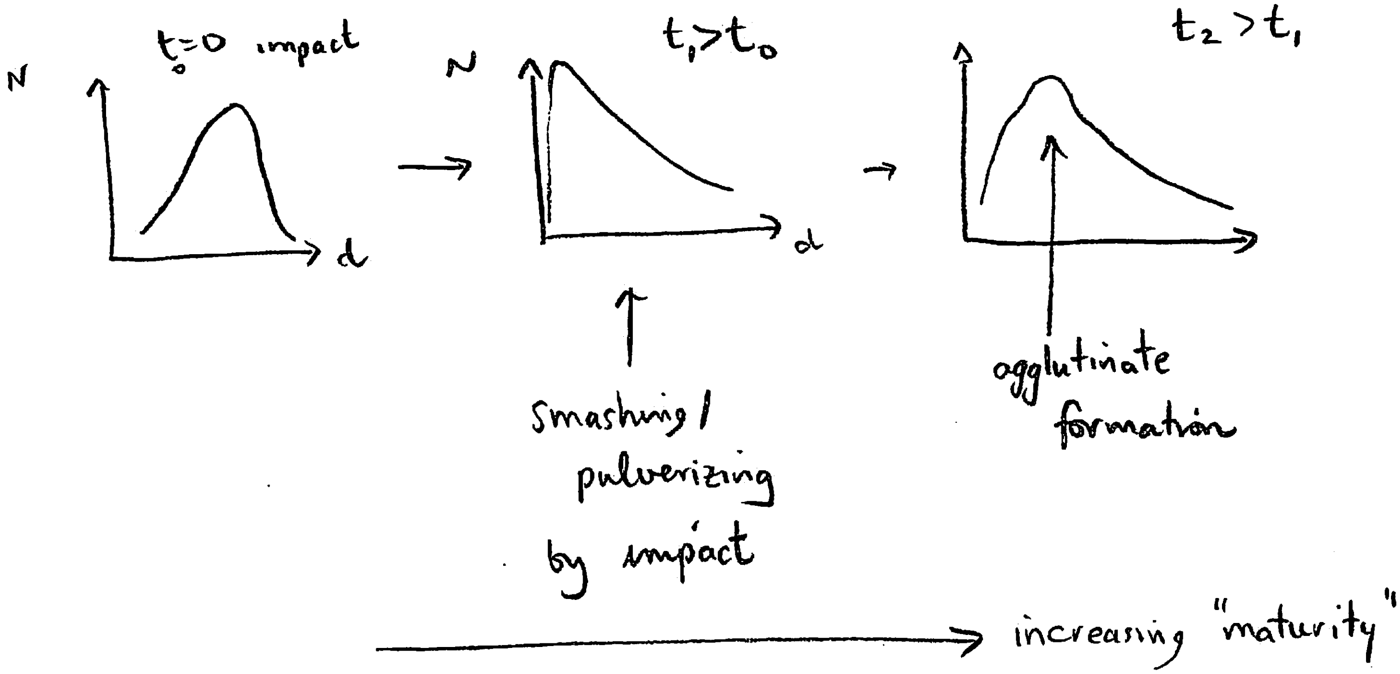
  [eg: @ $d \sim 1$ m, $t_g \sim 1$ Gyr; $d \sim 10$ cm, $t_g \sim 100$ Myr]

- Grains in the upper mm of the regolith have $t_g \sim 1$ Myr.

- Space weathering can compete with gardening if it can change albedo or color faster than gardening.

Regolith

Regolith size distribution is a function of age.



Data give

$$n(a)\,da = \Gamma\, a^{-q}\, da$$

with $n(a)da$ = # grains radius $a \to a + da$, Γ, q constants.

Roughly, $q \sim 4$.

Median Grain size weighted by Mass

Require

$$\int_{a_{min}}^{a_M} \tfrac{4}{3}\pi\rho a^3\, n(a)\,da \equiv \frac{1}{2}\int_{a_{min}}^{a_{max}} \tfrac{4}{3}\pi\rho\, a^3\, n(a)\,da$$

$$\int_{a_{min}}^{a_M} \frac{da}{a} = \frac{1}{2}\int_{a_{min}}^{a_{max}} \frac{da}{a}$$

$$\ln\left(\frac{a_M}{a_{min}}\right) = \frac{1}{2}\ln\left(\frac{a_{max}}{a_{min}}\right)$$

$$a_M = a_{min}\sqrt{\frac{a_{max}}{a_{min}}}$$

$$= \sqrt{a_{max}\,a_{min}}$$

eg: $a_{max} \sim 1\,mm = 1000\,\mu m$, $a_{min} \sim 5\,\mu m$ (smaller particles stick to others)

then $\boxed{a_M \sim \sqrt{5000} \sim 70\,\mu m \simeq 0.07\,mm}$

Median Grain Size Weighted by Area (more relevant for optics)

$$\int_{a_{min}}^{a_M} \pi a^2\, n(a)\, da \equiv \frac{1}{2}\int_{a_{min}}^{a_{max}} \pi a^2\, n(a)\, da$$

↑ assume geometric for now

$$\int_{a_{min}}^{a_M} \frac{da}{a^2} = \frac{1}{2}\int_{a_{min}}^{a_{max}} \frac{da}{a^2}$$

$$\frac{1}{a_M} - \frac{1}{a_{min}} = \frac{1}{2}\left[\frac{1}{a_{max}} - \frac{1}{a_{min}}\right]$$

$$\frac{2}{a_M} = \frac{1}{a_{max}} + \frac{1}{a_{min}} = \left(\frac{a_{max}+a_{min}}{a_{max}\,a_{min}}\right)$$

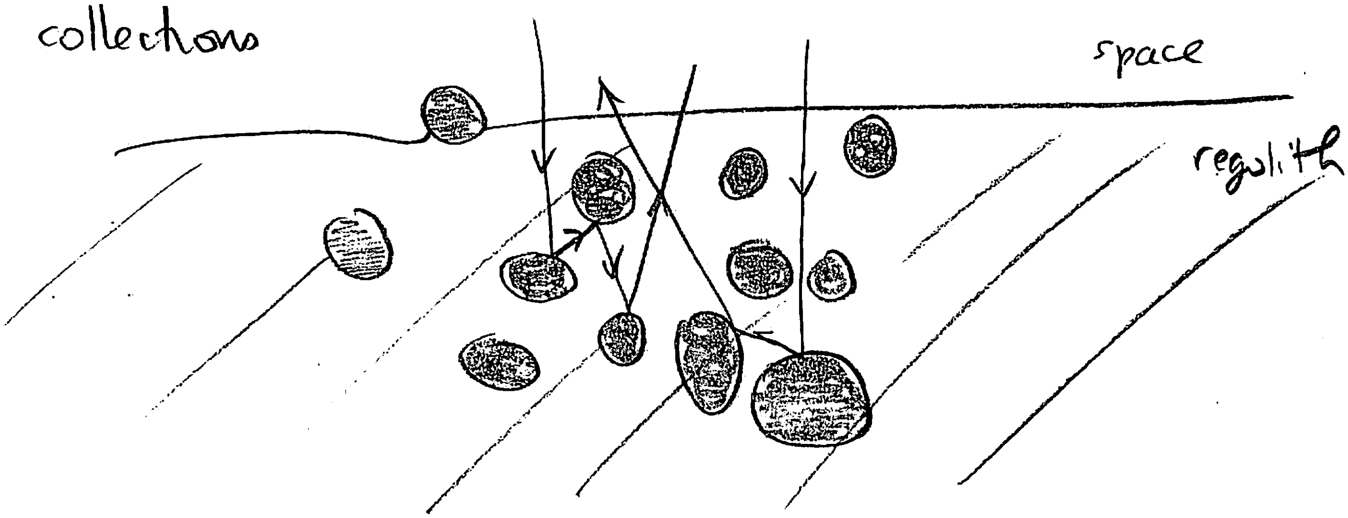
or $$a_M = \frac{2\, a_{max}\, a_{min}}{a_{max} + a_{min}}$$

$$\sim 2\, a_{min} \quad (\text{for } a_{max} \gg a_{min},\ a_{max} + a_{min} = a_{max})$$

eg. $$\boxed{a_M \sim 10\,\mu m}$$

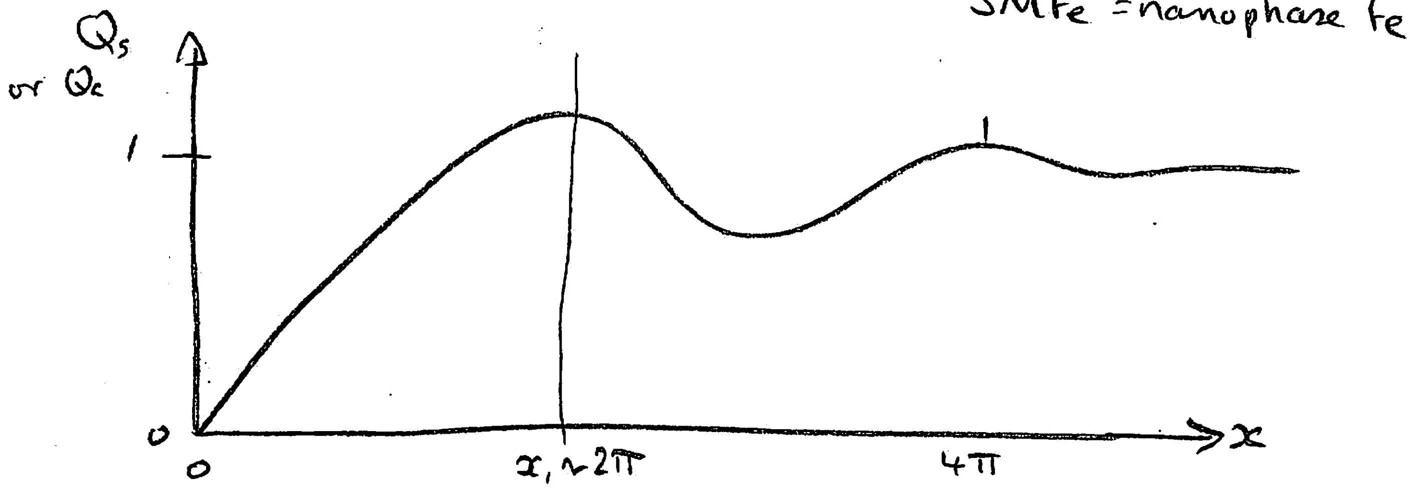
This is still optically large ($\frac{a_M}{\lambda} \gg 1$ for λ = optical = 0.6 μm).

For this reason, regolith optical properties have usually been tied to multiple scattering in optically large particle collections



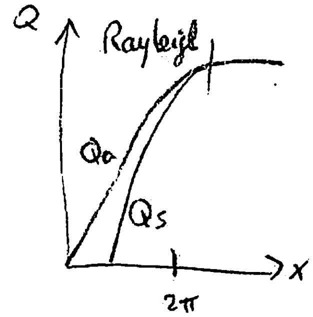
Hapke + others have argued, instead, that key aspects are nevertheless controlled by $a/\lambda \ll 1$ particles in the form of SMFe (Sub-micron Metallic Iron), also known as "nanophase iron."

SMFe = nanophase Fe



$x \ll x_1 \Rightarrow$ Rayleigh limit. All particles feel the same electric field as the EM wave goes by.

In Rayleigh limit



$$Q_a = \frac{8\pi a}{\lambda} \, \mathrm{Im}\left(\frac{m^2-1}{m^2+1}\right)$$ (imaginary part)

$$Q_s = \frac{128}{3}\pi^4\left(\frac{a}{\lambda}\right)^4 \left|\frac{m^2-1}{m^2+2}\right|^2$$ (modulus)

$Q_s \propto x^4$ + $x < 2\pi$ → Q_s v. small cf

$Q_a \propto x$

Small absorbing particles have cross section $\propto \frac{\pi a^2 a}{\lambda} \propto \frac{V}{\lambda}$

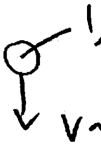
So blue (small) wavelengths are attenuated more than red (long) in the particles

$Q_a \propto \frac{1}{\lambda}$ gives red slope in mature soils due to nanophase iron particles each in the Rayleigh limit.

Note; if Im( ) = 0, as is nearly true for air, then $Q_s \propto x^4$ still dominates, and the scattered light is blue (like the sky).

Nanophase Fe a) Impacts

Production simulated by laser heating (Sho Sasaki et al)



$$\left.\begin{matrix} 1\,\mu m \\ V \sim 10\,km\,s^{-1} \end{matrix}\right\} \; t \sim \frac{10^{-6}}{10^{4}} \sim 10^{-10}\,s = \underline{0.1\,nsec}$$

Need very rapid laser flash. (7 nS was used)

Result – darkening, reddening due to nanophase iron is observed, with $\underline{E \sim 2.4 \times 10^{5}\ J\,m^{-2}}$

Micrometeorite impact rate is $f \sim 10^{-4}\ m^{-2}\,s^{-1}$ for $a = 1\,\mu m$

$$\left.\begin{matrix} m \sim \rho a^{3} \sim 10^{-15}\,kg \\ \text{if} \quad V \sim 20\ km/s \sim 2\times10^{4} \end{matrix}\right\} \; E \sim \frac{10^{-15}}{2}(2\times10^{4})^{2}$$

$$E \sim 2\times10^{-7}\ J$$

$\therefore$ Energy flux $\dot{E}_m \sim f E \sim 2\times10^{-7} \times 10^{-4} \sim 2\times10^{-11}\ J\,s^{-1}\,m^{-2}$

$$\sim 6\times10^{-4}\ J\,yr^{-1}\,m^{-2}$$

So $\tau \sim \dfrac{E}{\dot{E}_m} \sim \dfrac{2.4\times10^{5}}{6\times10^{-4}} \sim \underline{4\times10^{8}\ yr}$

Comparable to ray darkening times, so maybe this is plausible (<u>BUT</u> efficiency of impact weathering is unknown).

Nanophase Fe b) Solar Wind

Solar wind density $N_1 \sim 10^6 \ m^{-3}$

speed $V_{sw} \sim 500 \ km \ s^{-1}$

composition protons & electrons

$$\text{Energy flux} \quad \dot{E}_{sw} \sim \underbrace{\overset{m^{-3}}{N_1} \ \overset{m\,s^{-1}}{V_{sw}}}_{m^{-2}s^{-1}} \overset{J}{\left(\frac{1}{2} m_H V_{sw}^2 \right)} \propto V_{sw}^3$$

$$\sim 1.67 \times 10^{-27} \times 10^6 \times (5 \times 10^5)^3$$

$$\sim 2 \times 10^{-4} \ J\,s^{-1}\,m^{-2}$$

or $\dot{E}_{sw} \sim \underline{6000} \ J\,yr^{-1}\,m^{-2}$

<u>MUCH</u> larger than $\dot{E}_m$ (by factor of 10^7!)

Therefore, solar wind could be $10^7 \times$ less efficient but still have the same optical effect as impact weathering.

Swirls

- ⊕ Structured albedo markings on Moon w/. no topographic expression
- ⊕ Prototype = Reiner Gamma
- ⊕ Are spatially correlated w/. local $\underline{B}$ fields
- ⊙ Might be preferentially located at basin antipodes.

Ideas

1. Sites of comet impact. Impact magnetizes rock + coma creates the swirl.
2. Caused by charged particle interaction w/. surface
3. Caused by electrostatic dust transport, modulated by local $\underline{B}$ field & with compositionally distinct smaller grains being higher albedo + more mobile.

Swirls prove the action of solar wind in space weather = a role for space physics. Very valuable

but

no swirls found on Mercury (why not? $\underline{B}$ shielding?)

How do solar wind particles create nanophase iron? Sputtering?