RoadMap project

Dust aerosol properties on Mars from spacecraft: A current perspective

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Dust on Mars Workshop
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This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101004052

Outline

- Context
- History
- The planet Mars
- Radiative transfer & aerosol properties
- Retrieving aerosol properties from spacecraft
- Our current understanding

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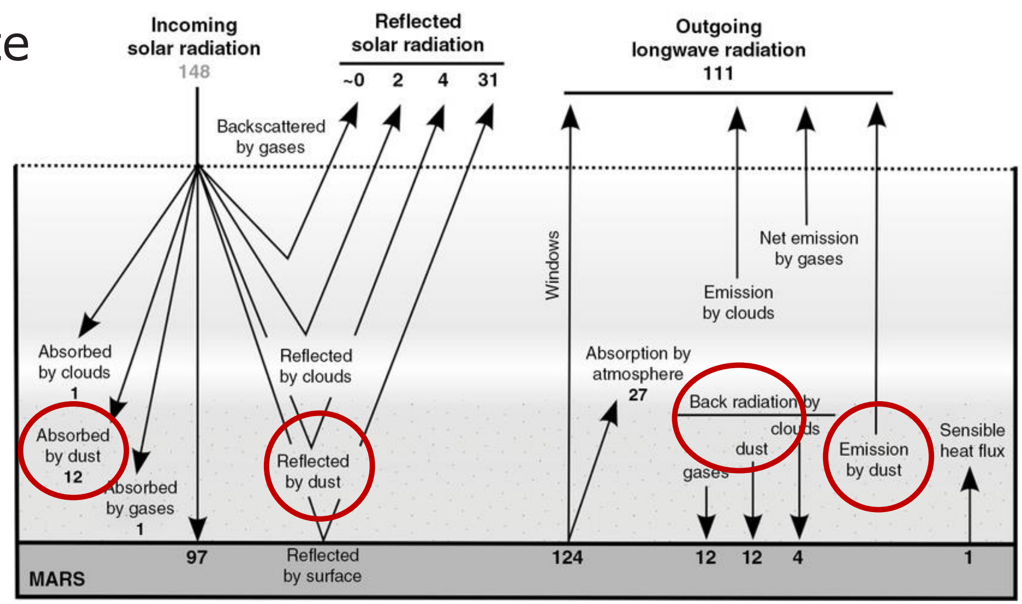
Why studying dust is important?

Airborne dust absorbs and scatters light

⇒ Local warming & cooling in the atmosphere

It modulates thermal and dynamical structure of the atmosphere

⇒ affects atmosphere and climate



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History (1/2)

Mariner 4 (1965)

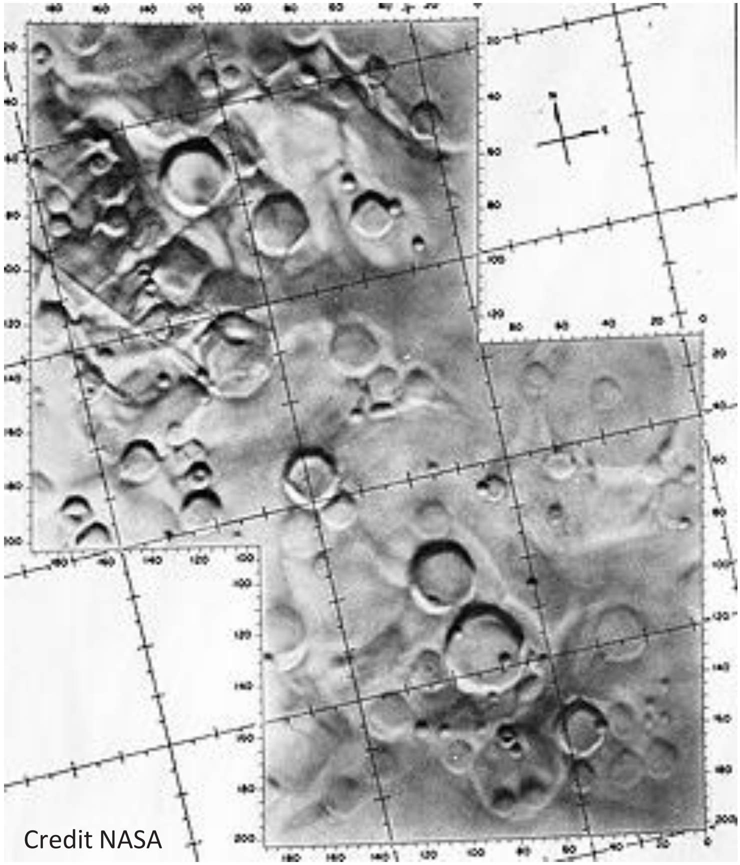
- First flyby: 22 pictures
- First detailed picture of the surface

⇒ dull & cratered planet (Moon-like appearance)

Mariner 6 & 7 (1969)

- Other flyby pictures: same dull terrains
- But thermal profiles suggest the presence of airborne aerosols

Mariner 4: flyby pictures



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History (2/2)

- Mariner 9 (1971-72)
  - First orbiter, arrived during a global dust storm (GDS) event
  - About 20,000 pictures, UV & IR spectroscopy
  - Observed the global dust storm (GDS) decay, dust strongly influences temperature

- Vikings 1 & 2 (from 1976 to early 80's)
  - 2 orbiters & 2 landers
  - observed GDS events, study impact on atmosphere & climate

- Start of continuous monitoring (from 1997)
  - started with Pathfinder & Mars Global Surveyor
  - since many more (Odyssey, MER, MRO, MEx, Phoenix, MSL, MOM, MAVEN, TGO, Insight, …)

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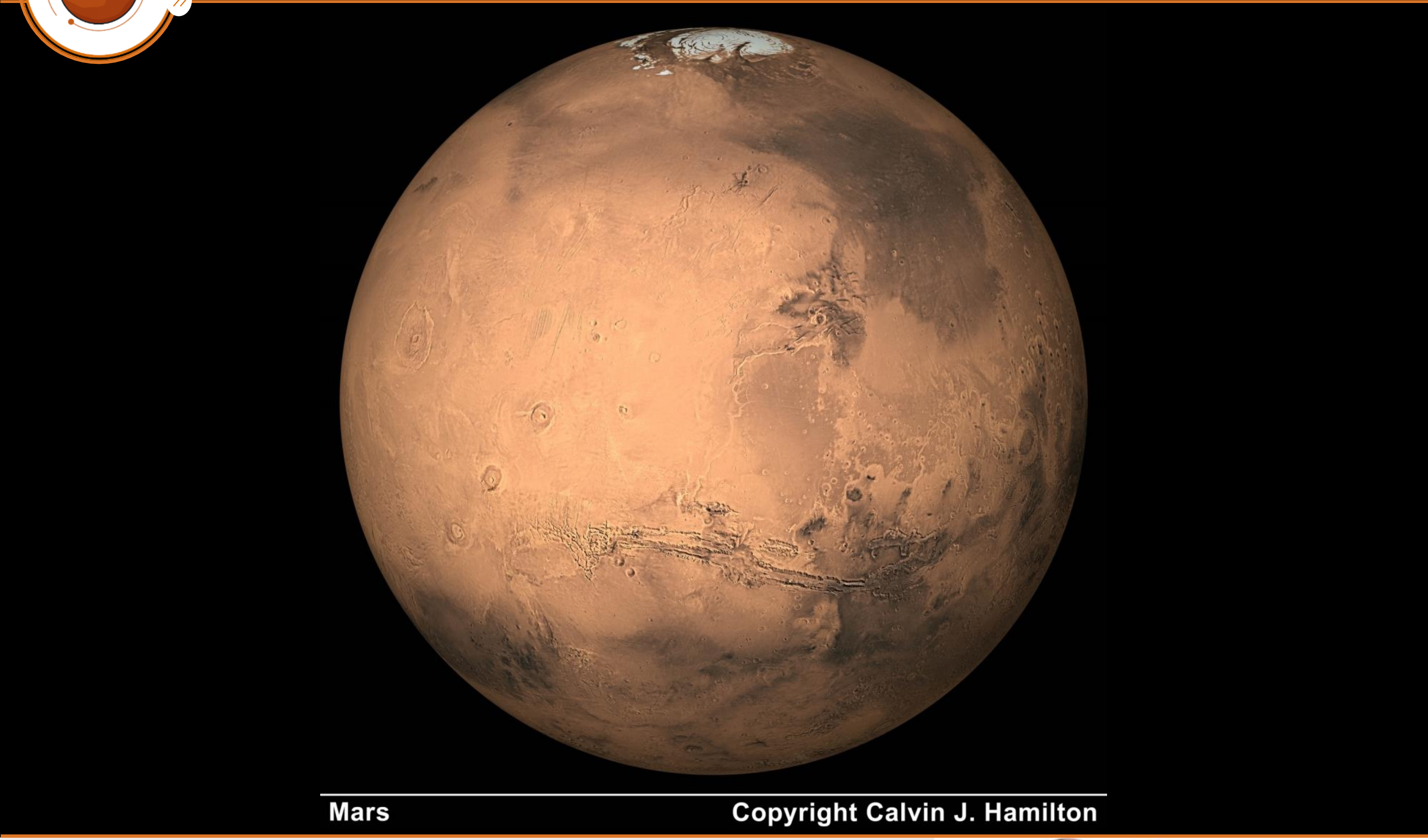
The planet Mars



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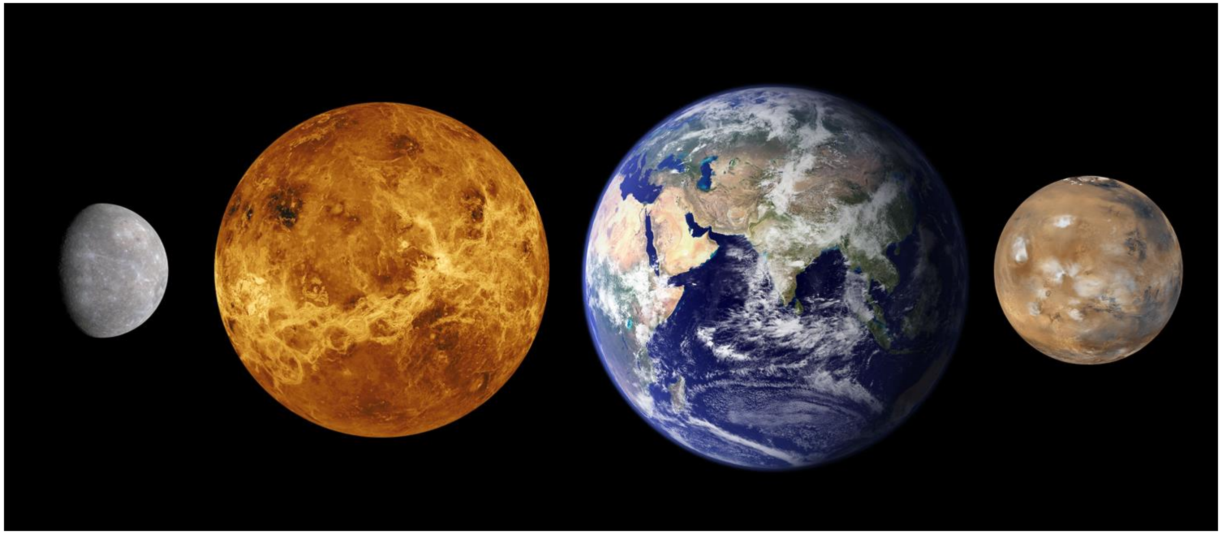
4th planet of the Solar system

- Telluric planet
- Diameter: 3394 km 0.53 x Earth
- Masse: 6.2×10^{23} kg 0.11 x Earth
- Gravity: $3.72\ m/s^2$ 0.38 x Earth



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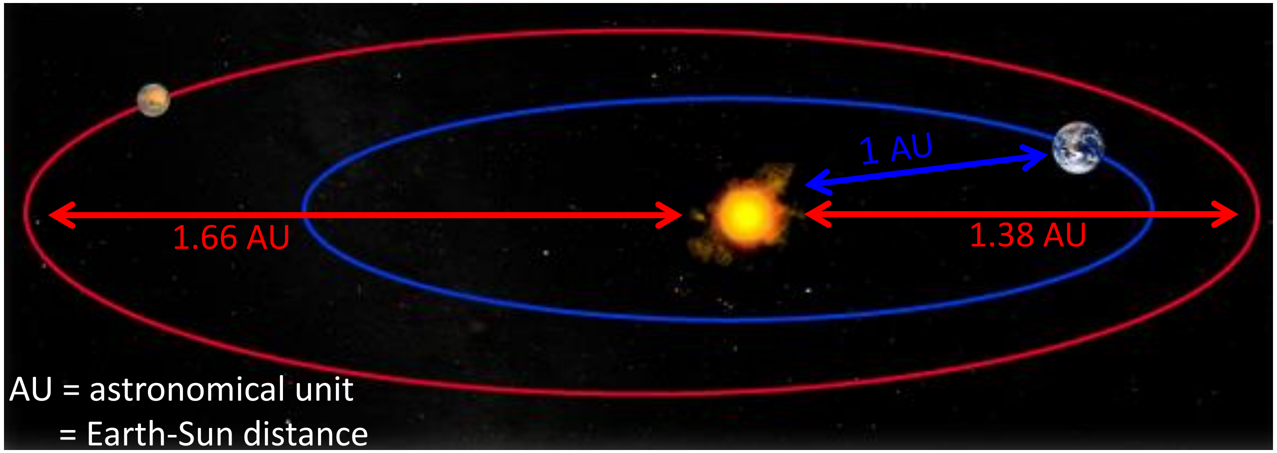
Orbit and rotation

Revolution around the Sun

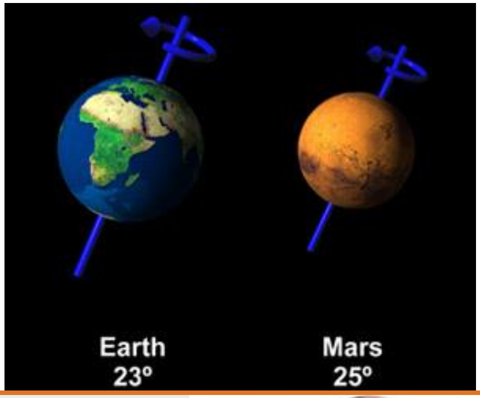
1 Martian year: ~ 687 days
(terrestrial)



Rotation on axis

1 Martian day or sol: ~ 24h40 min

Axial tilt



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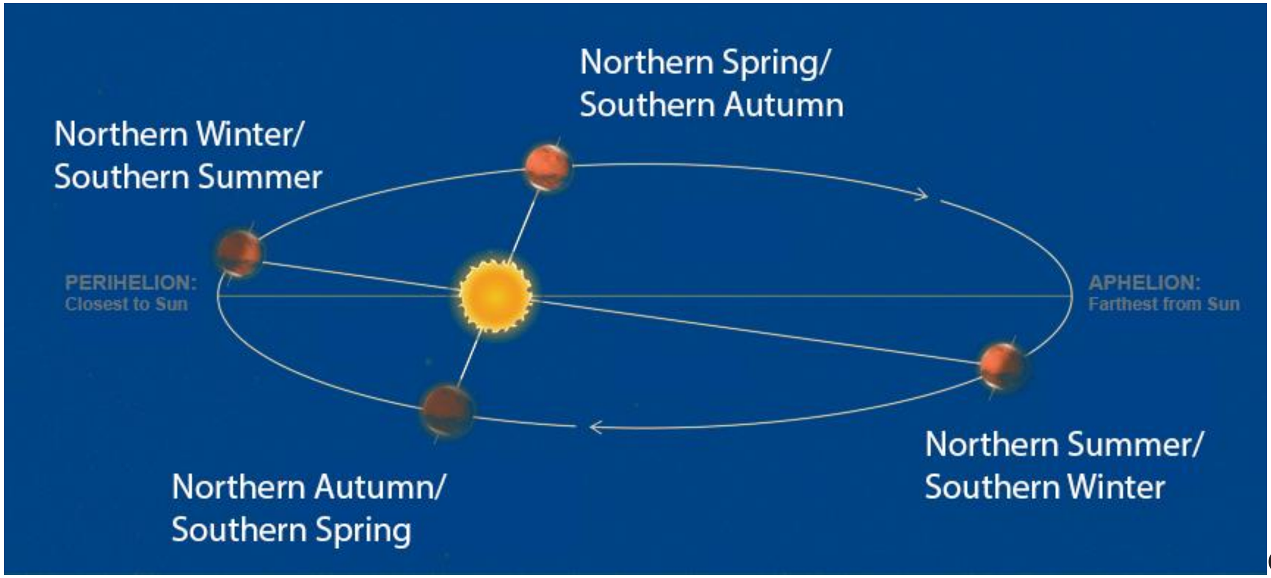
Asymmetry between North & South hemispheres

+ 45% more solar energy received at perihelion than at aphelion

- South: Extreme seasons — cold winter and warm summer
- North: temperate seasons — milder winter and cooler summer



Credit: NASA/JPL-Caltech

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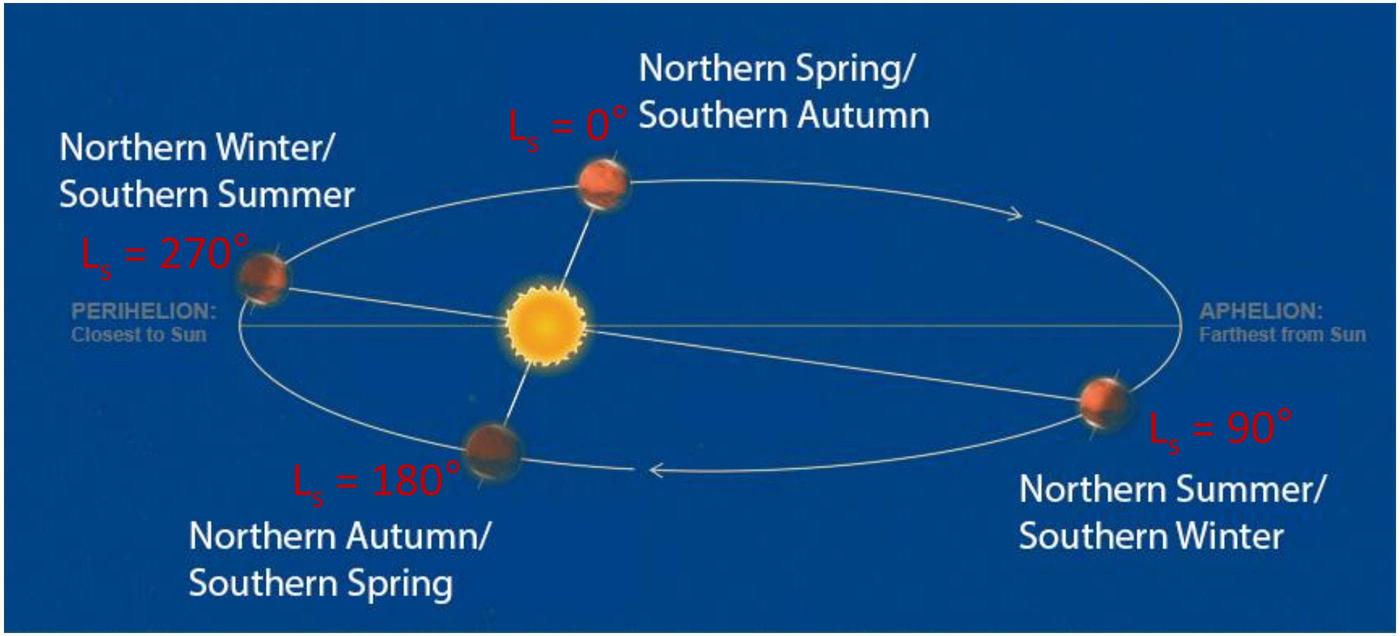
Seasons (2/2)

Progression in the Martian year

⇒ Solar longitude (L_s)

1 Martian year = 360° of L_s



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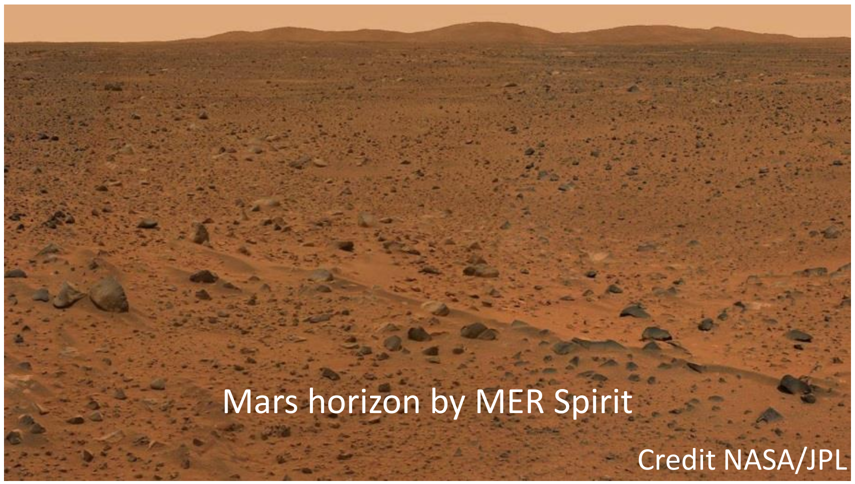
Martian dust

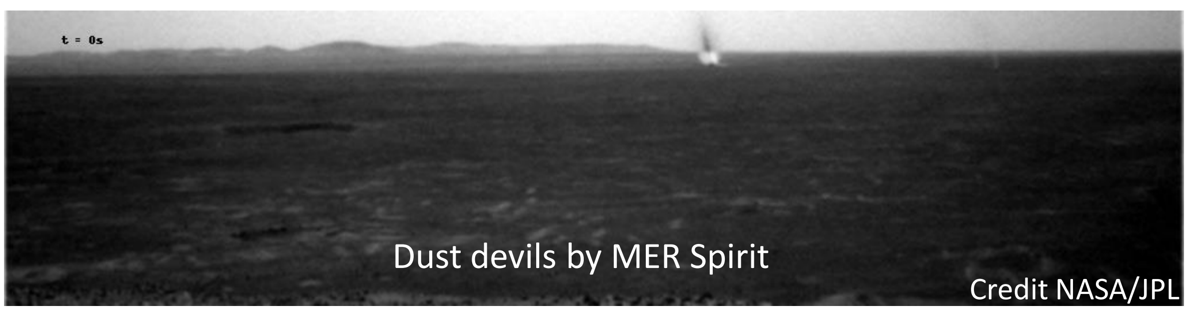
Dust is ubiquitous on Mars !


Mars horizon by MER Spirit
Credit NASA/JPL

Covers the surface of Mars:
Color => iron oxyde


Martian dusty haze by Viking orbiter
Credit NASA

Lift in the atmosphere by winds and storms!



Dust devils by MER Spirit
Credit NASA/JPL

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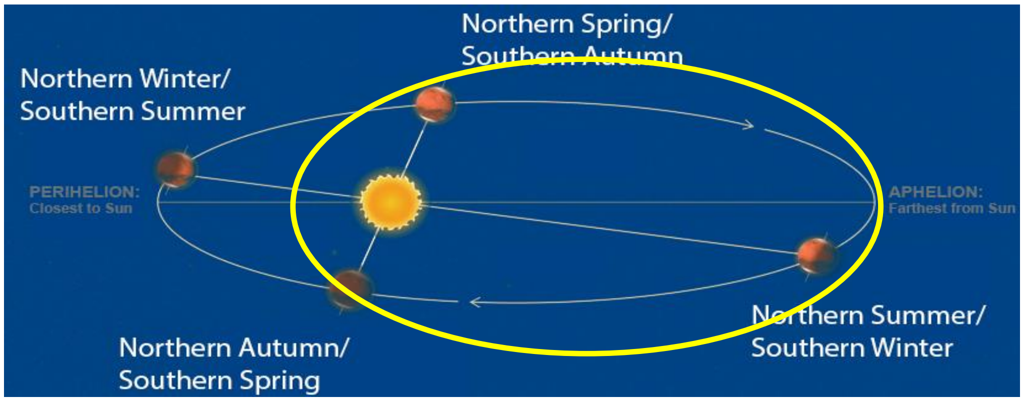
Non dusty season

Occurs during the "colder" season around Aphelion



Period characterized by:

- Low dust loading
- Repeatable from year to year (*)
- Local storms and dust devils (*varying patterns)

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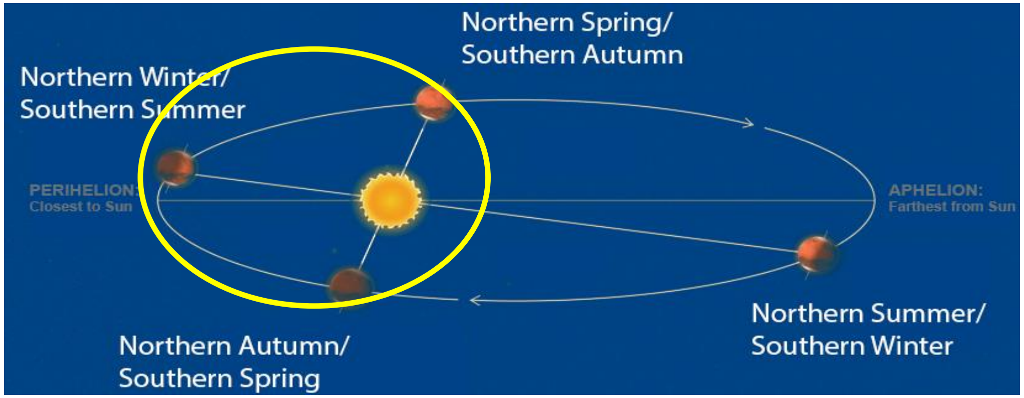
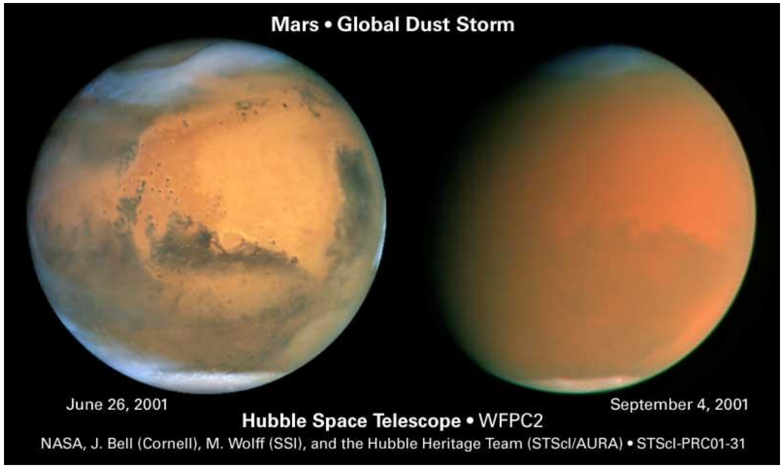
Dusty season & dust storms

Dusty season: occurs during the "warm" season around Perihelion



- Higher dust loading
- Important interannual variability
- Dust storm spatial extent
  - Local (frequent)
  - Regional (usually 1-3 per year)
  - Global (not every year, 1 out of 3 year in average)
- Storms often form at the edge of the polar caps



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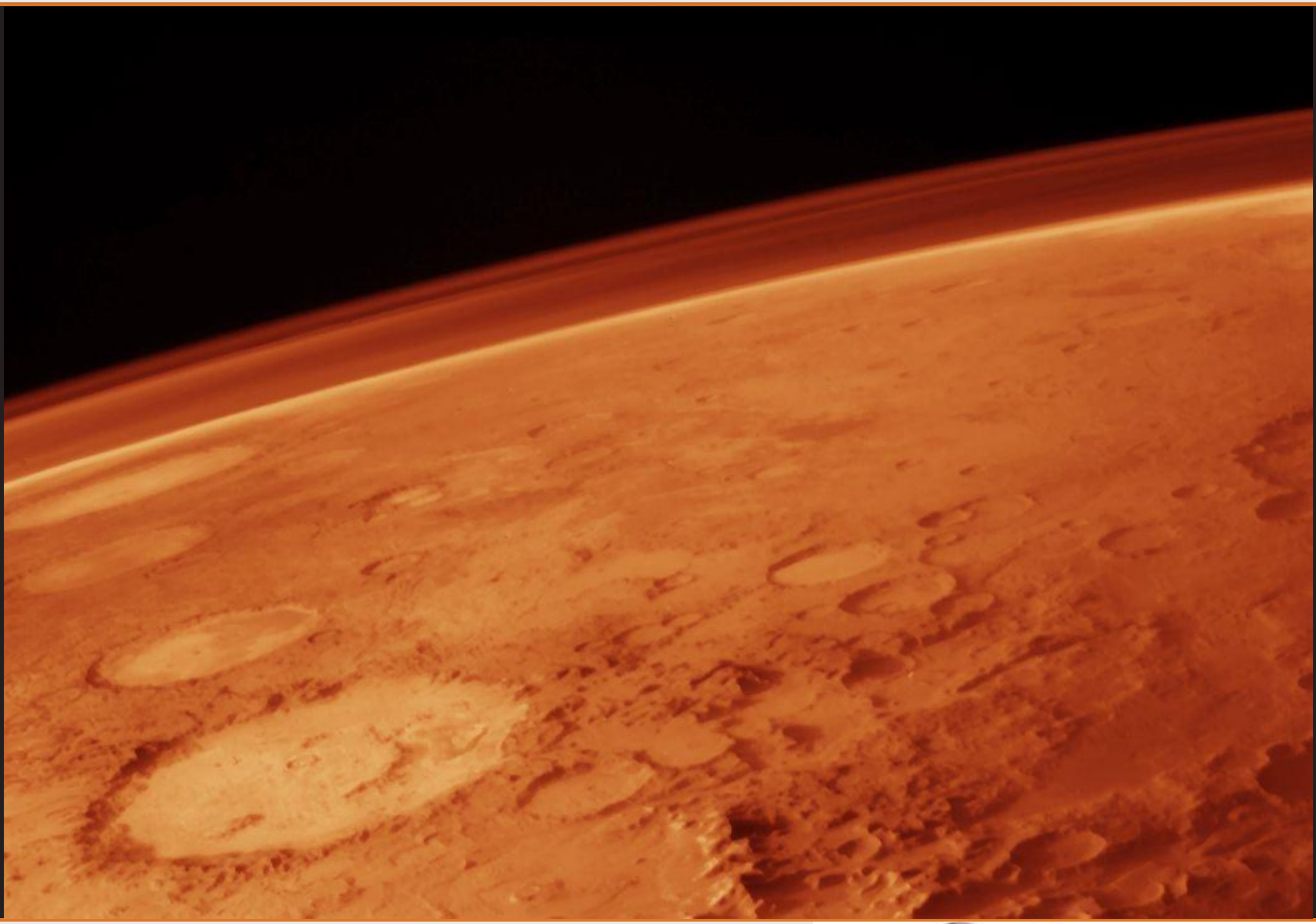
Radiative transfer



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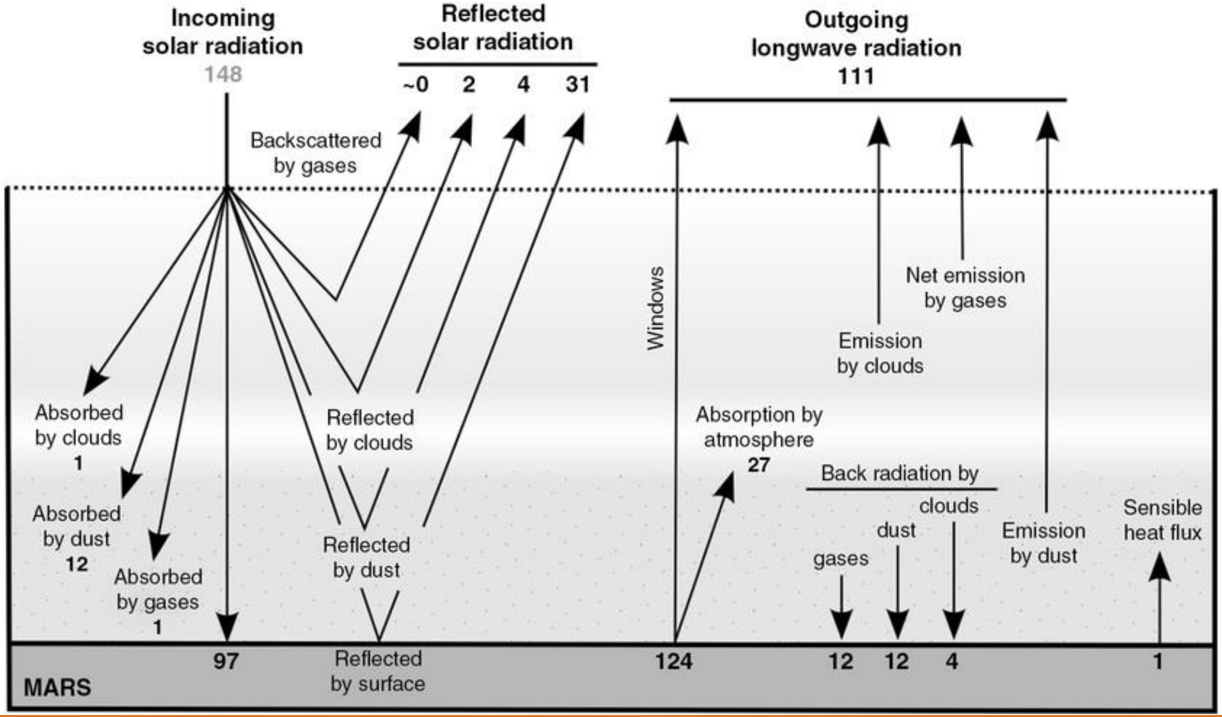
Radiative transfer

Study the interactions between the light and the atmosphere & surface

⇒ Different types of interaction: absorption, scattering, reflection (scattering from a surface)



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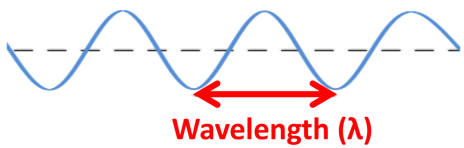
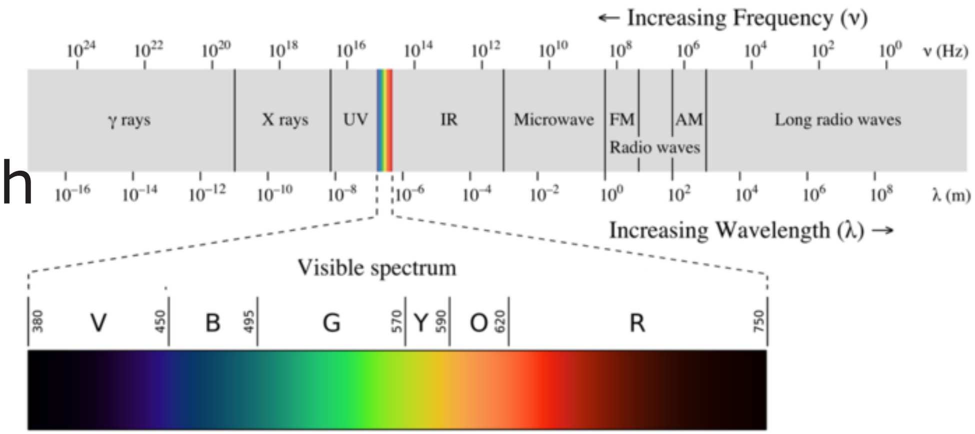
Light-dust interaction

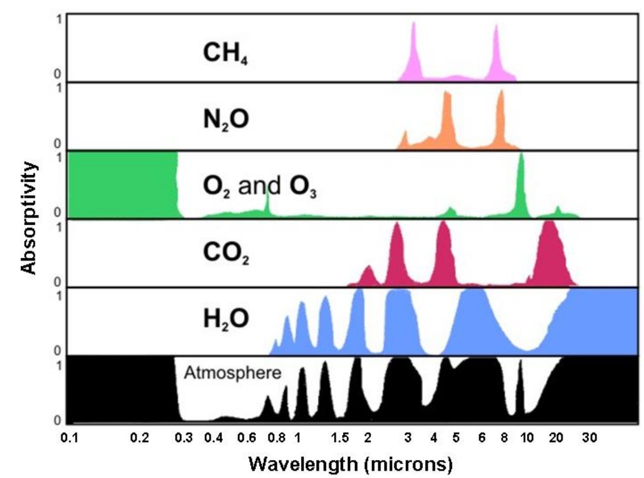
Light is an electro-magnetic wave defined by its wavelength





Each molecule/particle has a specific interaction with light that is wavelength dependent & related to its intrinsic properties:

- Composition
- Size
- Shape



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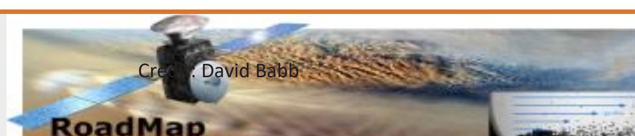
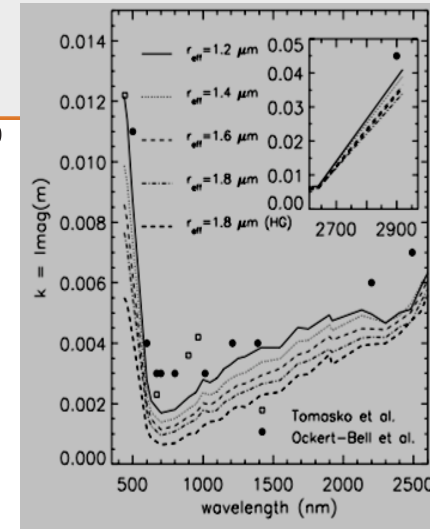


Dust properties (1/3)

From Wolff et al. 2009



Composition:

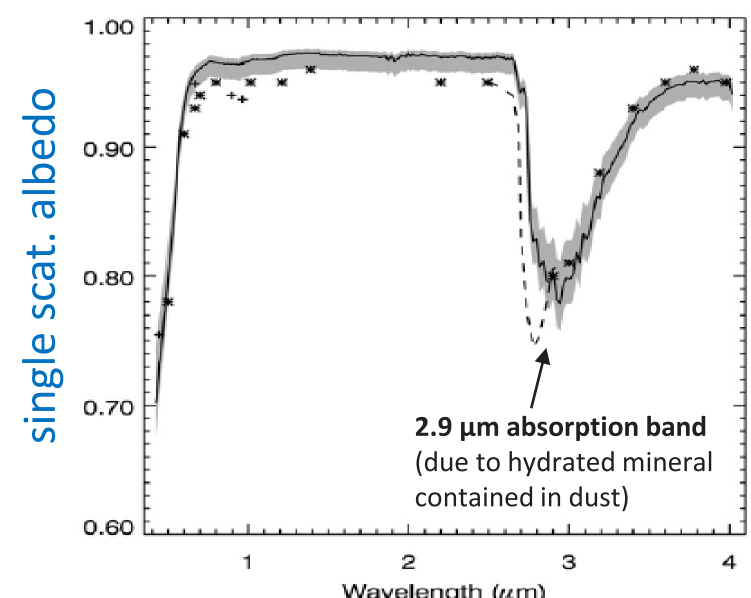
- Real refractive index: light bending (refraction)
- Complex refractive index: absorption

⇒ single scattering albedo (SSA): scattered vs absorbed fraction

$$SSA = \frac{C_{sca}}{C_{sca} + Cabs}$$

For dust:

- In the UV: SSA < 0.70 (>30% absorption)
- In the visible: SSA = 0.70-0.95 (5-30% abs)
- In the NIR: SSA = 0.96-0.97 (3-4% abs)
- ~9.3 μm (LIR) SSA ~ 0.2-0.3 (70-80% abs)
- ~20 μm (FIR) SSA ~ 0.1 (90% abs)



From Maattanen et al. 2009

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Dust properties (2/3)

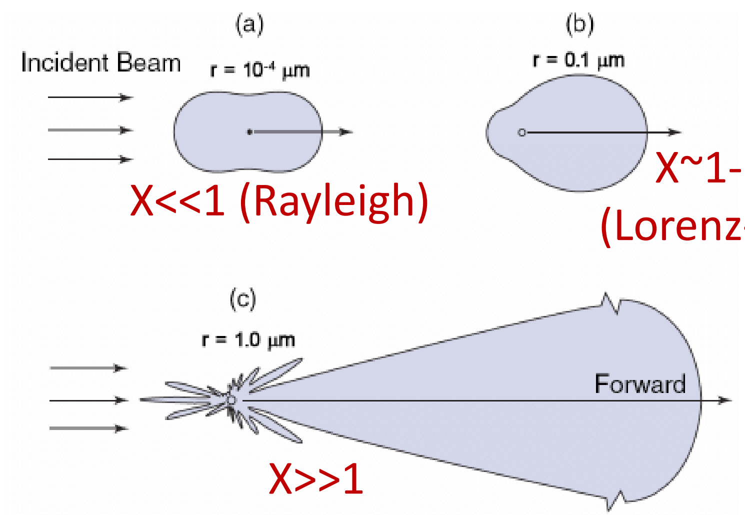
Particle size

- extinction cross-section: ability to interact with light
- Size parameter: $X = \frac{2\pi r}{\lambda}$ (r: particle radius; λ: light wavelength)

Martian dust particle size:

- r_{eff} = 1-2 µm typically
- smaller particles at higher altitudes
- larger particles up to 4 µm during storms near surface

Distributions: r_{eff} & v_{eff} (1st & 2nd moms) as defined in [Hansen and Travis, 1974]



X<<1 (Rayleigh)

X~1-10 (Lorenz-Mie)

X>>1 Geometrical optic

Dust (1.5µm) (IR)

Dust (1.5µm) (UV-visible)

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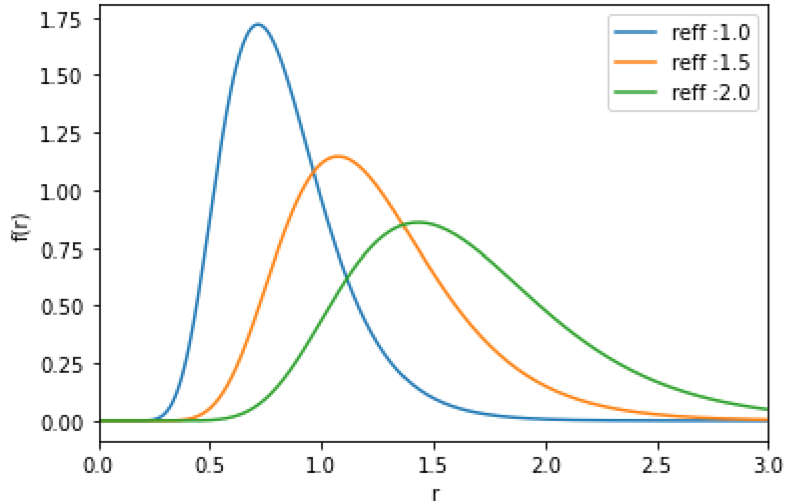
Particle size distribution

Variable r_{eff} (µm)   (v_{eff} = 0.1)



$$r_{eff} = \frac{\int_{r1}^{r2} r\pi r^2 n(r)dr}{\int_{r1}^{r2} \pi r^2 n(r)dr} = \frac{1}{G}\int_{r1}^{r2} r\pi r^2 n(r)dr$$

G is the geometric cross section area

$$v_{eff} = \frac{1}{G r_{eff}^2}\int_{r1}^{r2} (r - r_{eff})^2 \pi r^2 n(r)dr$$

Distributions: r_{eff} & v_{eff}
as defined in [Hansen and Travis, 1974]

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Dust properties (3/3)

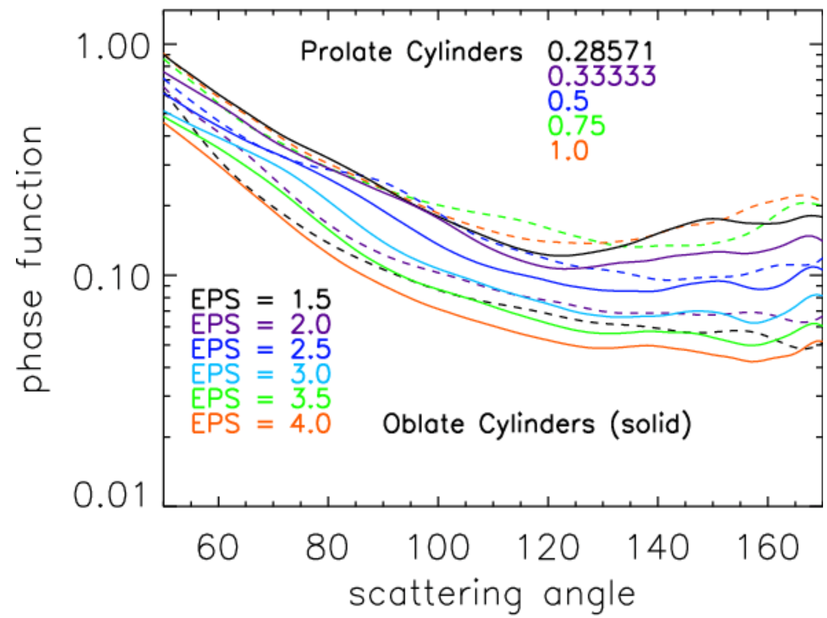
Particle shape

- Phase function: angular probability distribution for scattering

Influence of the shape on the phase function

Phase function comparison of cylindrical prisms with a sphere

using cylindrical prisms with different D/L ratio (diameter/length) [Wolff et al., 2009, 2010]



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Dust properties from spacecraft

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The beginnings (70's & 80's)

Sparse measurements of orbiters and combination with landers allowed to:

- Observe a global dust storm (GDS)
  ⇒ importance of dust & radiative properties

- Deduce the general seasonal & spatial trends of dust cycle

- Estimate the particle size: r_{eff}=1.6-1.8 μm & v_{eff}=0.2-0.6

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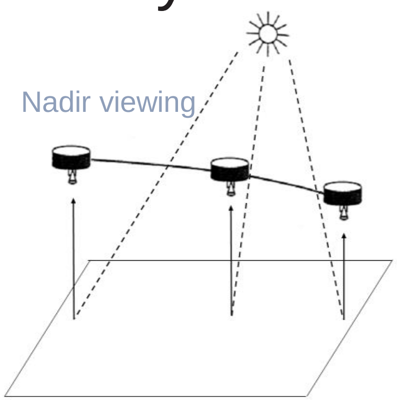
Beginning of global coverage

Using MGS Mars Observer Camera (MOC, visible imager) and Thermal Emission Spectrometer (TES, IR spectrometer)

- Possible to monitor globally the dust activity (from MOC)
  - ⇒ Dust storms are occurring constantly (not only during "storm season")
- Daily quantitative retrievals of dust opacity column by TES
  - – Along with temperature (T) (and water ice)
  - ⇒ Seasonal dust cycle & spatial distribution



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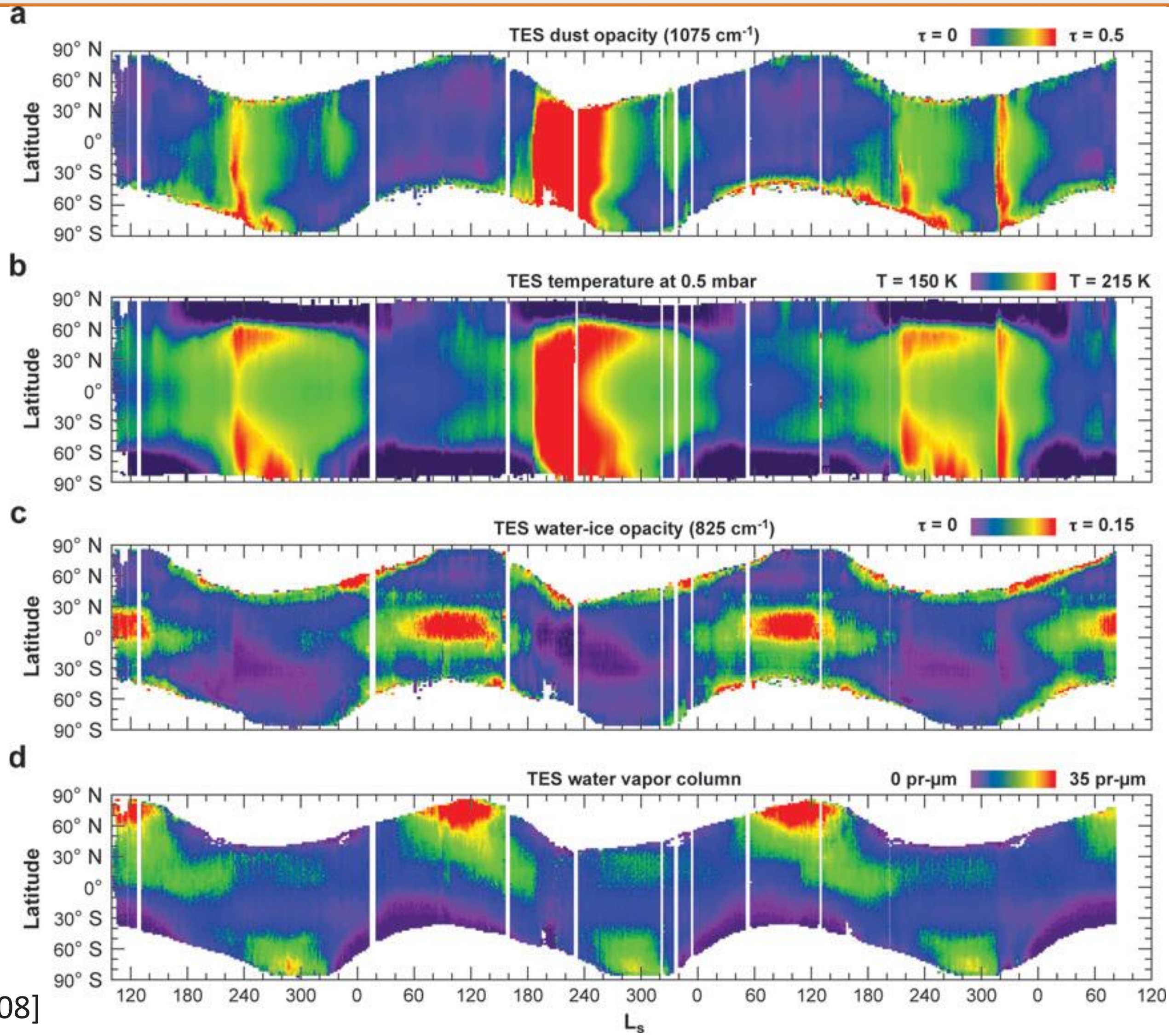
Dust cycle from TES (& other cycles)

Non dusty season: annual repeatability

Dusty season: variable

Dust & T correlation

Dust & ice clouds anticorrelation



[Smith, 2004,2008]

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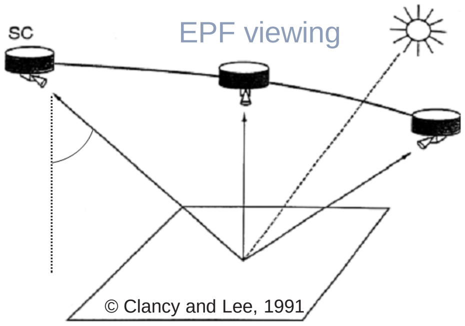
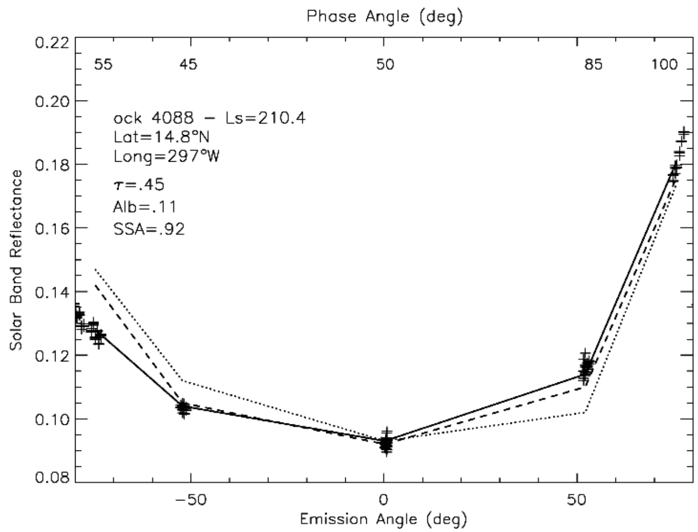
Dust properties from TES (1/4)

EPF (Emission Phase Function) measurements were performed by TES



Aiming the same location with different angles

⇒ Study dust properties (PF, size, shape)



- Solar band channel (0.3-3 µm)
⇒ distinction of aerosol types (dust/ice cloud)
- Mean size: r_{eff}=1.6 µm & v_{eff}= 0.2-0.4
- Dust storm size: larger particles 2-3 µm
- Shape: cylinder particle (moderate axial ratio)

From [Clancy & Wolff, 2003]

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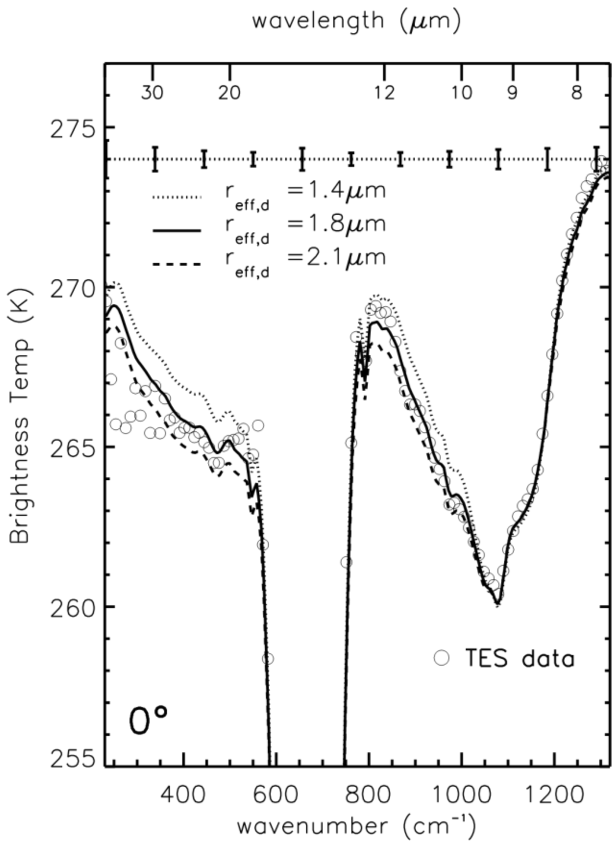
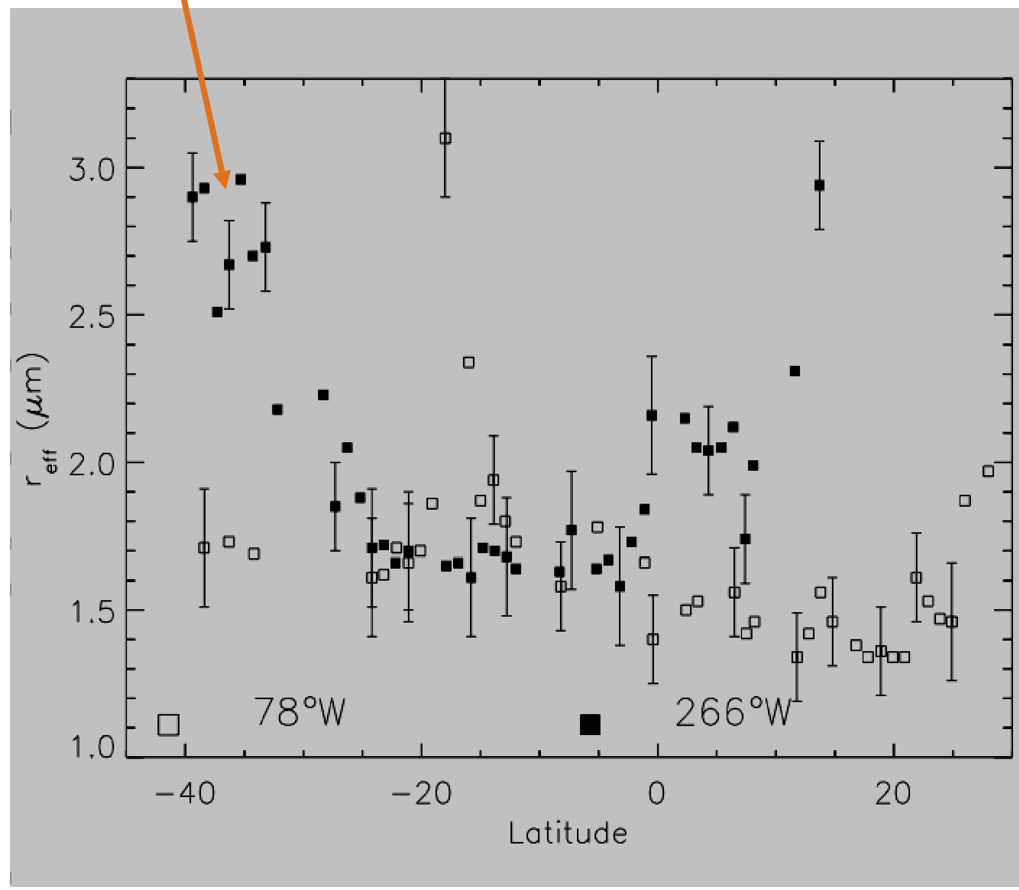
Dust properties from TES (2/4)

Larger particles observed during 2001 dust storm





From [Wolff & Clancy, 2003]

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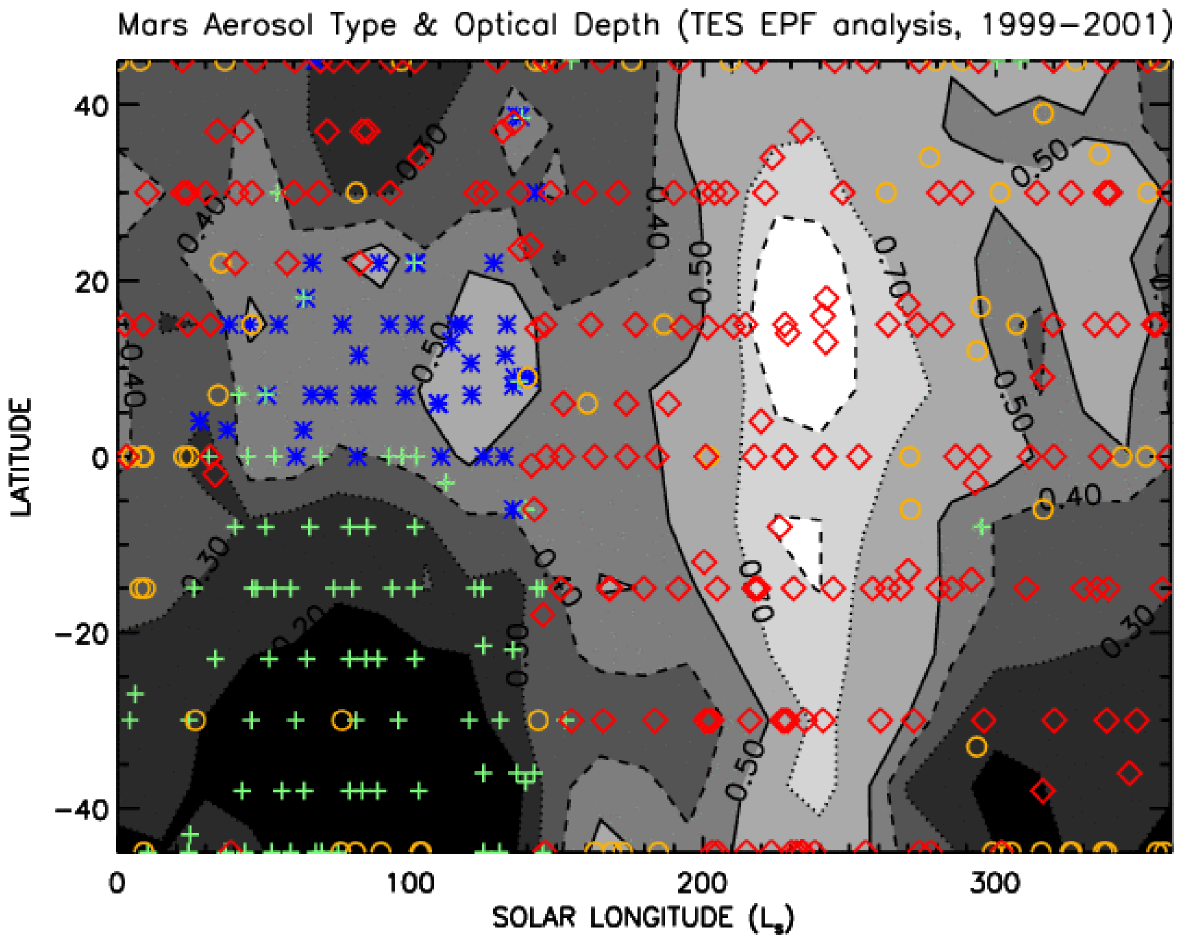
Dust properties from TES (3/4)

Distinction between dust and ice clouds



Ice cloud (1-2 µm)

Ice cloud (3-4 µm)

Dust (~1.6 µm)

Bright dust (1.0-1.2 µm)

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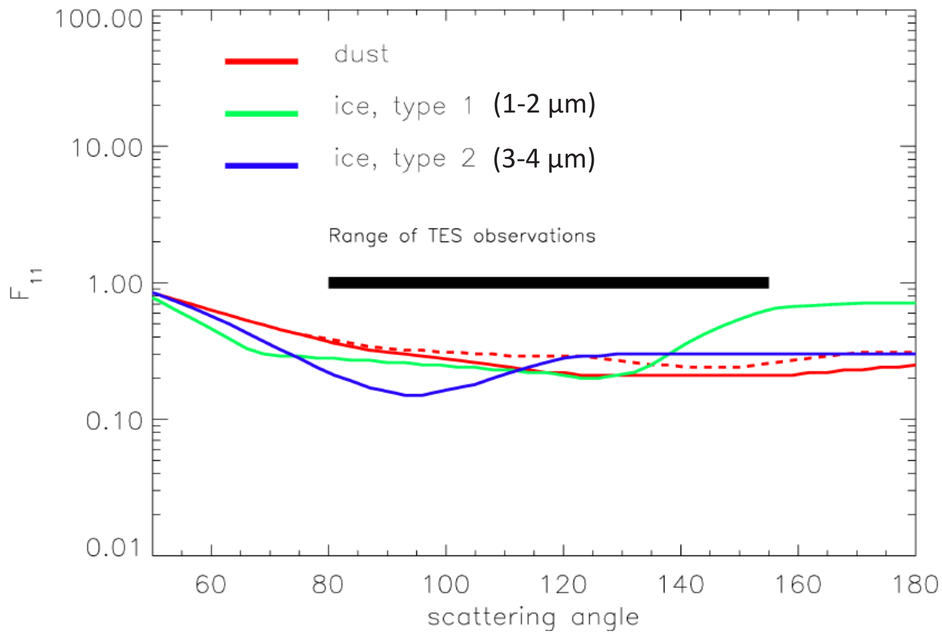
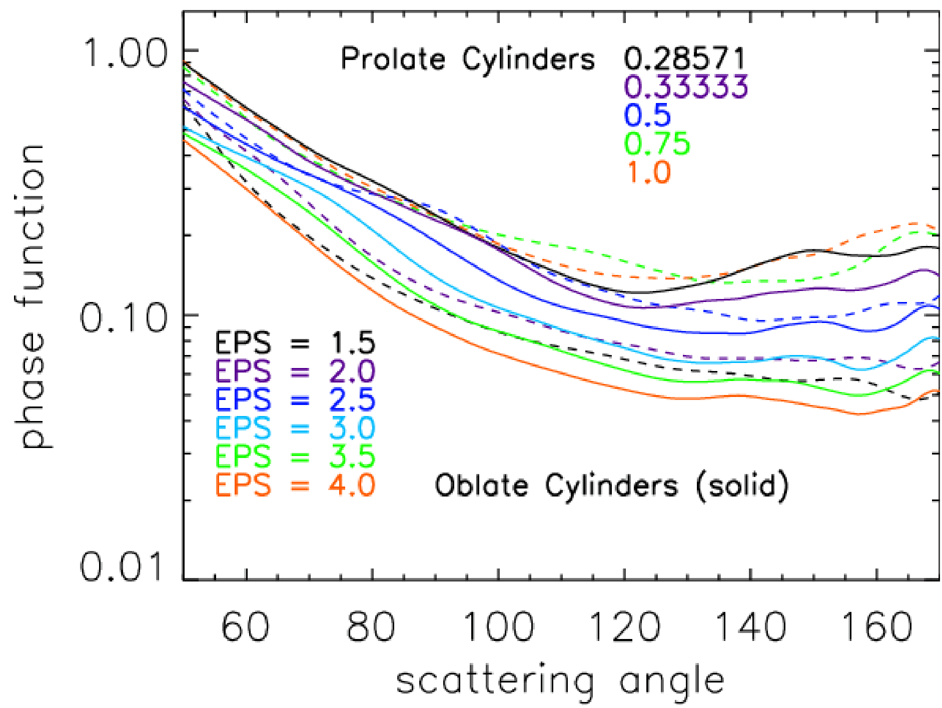
Dust properties from TES (4/4)

Aerosol phase function



Dust phase function with different shapes



Phase function using different particle shapes!

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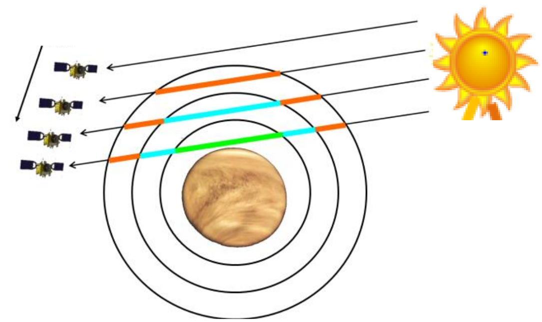
Altitude distributions

Mars-Express (Mex) (since 2003)

SPICAM UV-NIR spectrometer



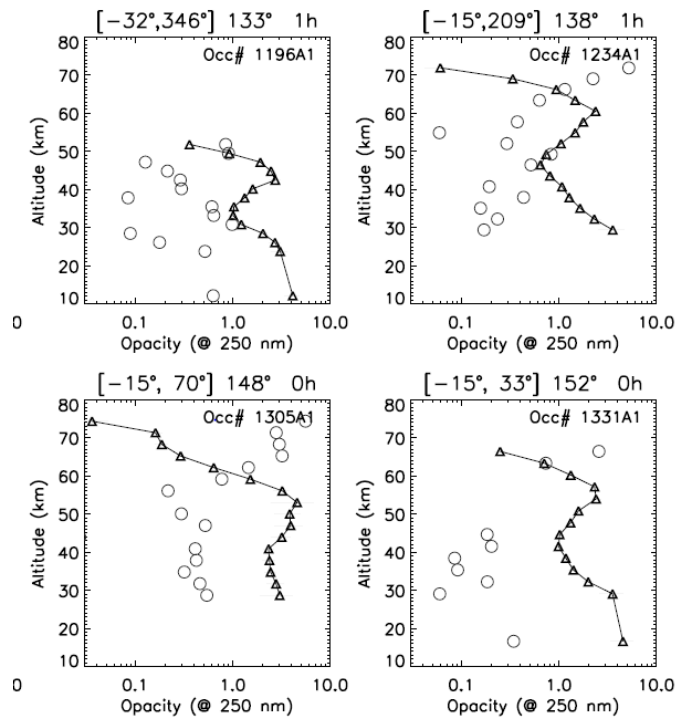
Occultation

- Observing sunset/sunrize through the atmosphere
- Direct attenuation of the solar/stellar radiation

⇒ No RT calculation! (=>no complications)

⇒ Altitude distributions

(opacity, size)



From [Montmessin et al. 2006]

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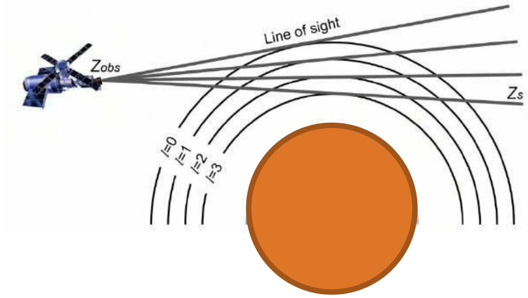
Altitude distributions

Mars Reconnaissance Orbiter (MRO) (since 2006)

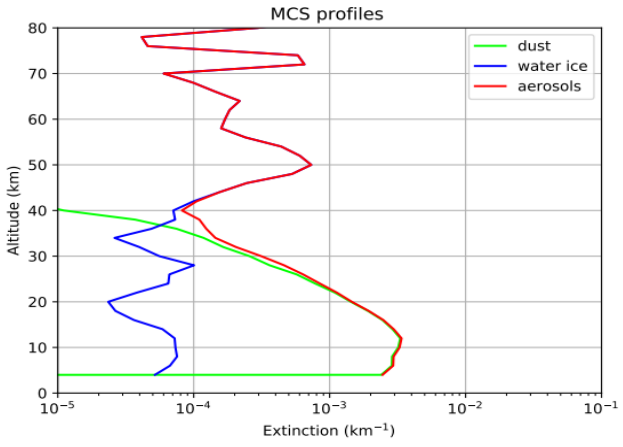
MCS: IR radiometry



Limb

- Observing the limb of the planet
- Emission by dust & atmosphere (FIR)

⇒ Require RT calculation! (=> complications)



⇒ Altitude distributions

Related to work of [Kleinböhl et al., 2009]

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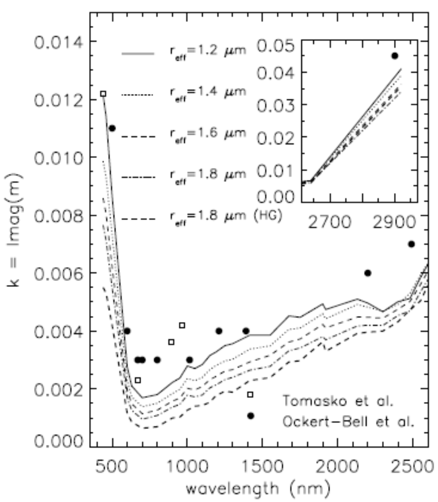
Refining dust properties

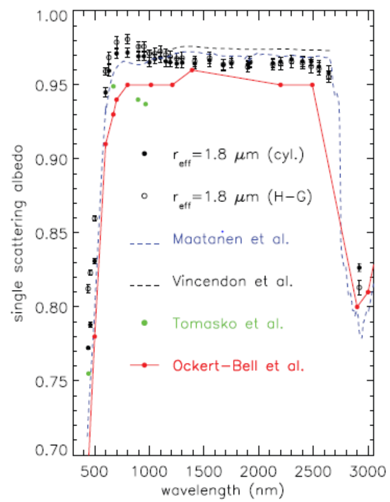
Using MRO/CRISM visible-NIR spectroscopy

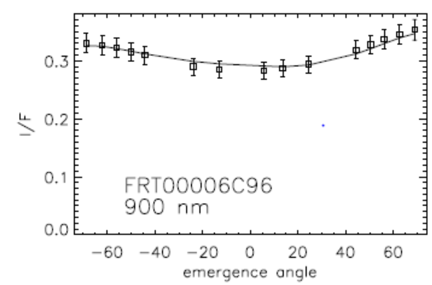
- EPF measurements
- worked during dust storm
- combined with ground truth opacities from MERs

⇒ complex refractive index & SSA

⇒ size (1.8 µm average for the observation used) & shape (cylinder with moderate axial ratio)







Work from [Wolff et al. 2009]

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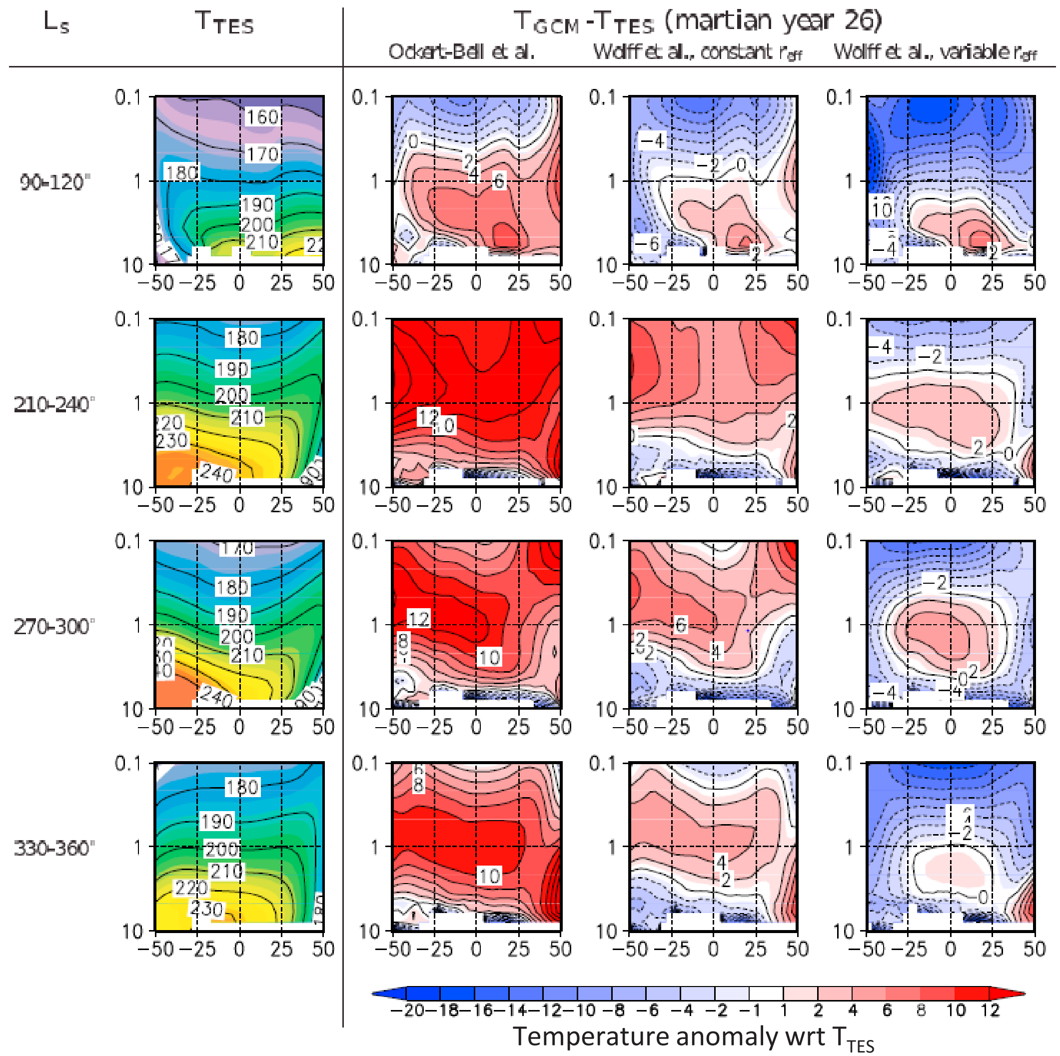
Improved dust properties in modeling

Global circulation models (GCM) are used to simulate and understand the chemical and physical processes occurring in the Martian atmosphere

(see Lori's presentation)

Use of the improved dust properties

⇒ helped to solve the temperature anomaly observed between T_{TES} & T predicted by models



Work of Madeleine et al., 2011

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Current status

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RoadMap project

Perform laboratory measurements on Martian dust analogues to improve retrieval and modeling:

- Lab measurements include:
  - Radiative & scattering properties (SSA, phase function, polarization)
  - Dust lifting characterisation, deposition, dynamics
  - Micro-physical properties

- Dust related goals of "atmopheric measurements Work Package"
  - Test the impact of new properties on nadir retrieval
  - Deduce particle size & aerosol’s composition from occultations

- Using TGO/NOMAD (from 2018)
  - UV-visible and NIR spectrometer

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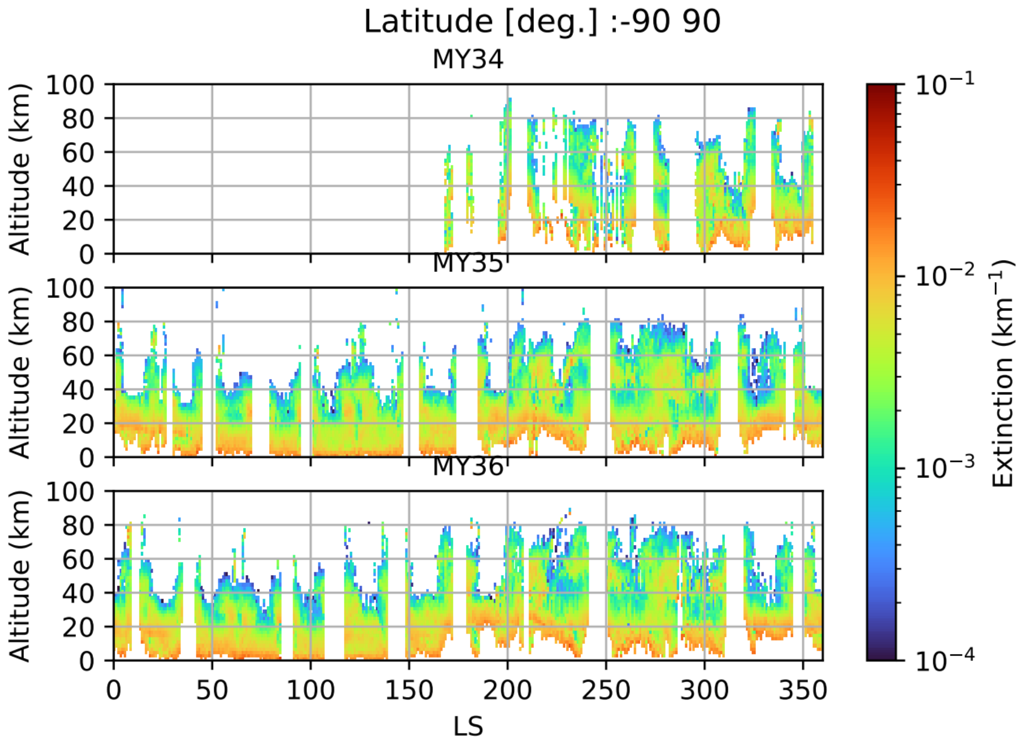
Aerosol altitude distribution from NOMAD

The 10,000+ TGO/NOMAD-UVIS occultations are used to produce a complete climatology of the aerosol altitude distribution.

No dust/ice cloud distinction!

⇒ Distinction possible combining with NOMAD-SO

Ongoing work…



Work of Flimon et al., in prep

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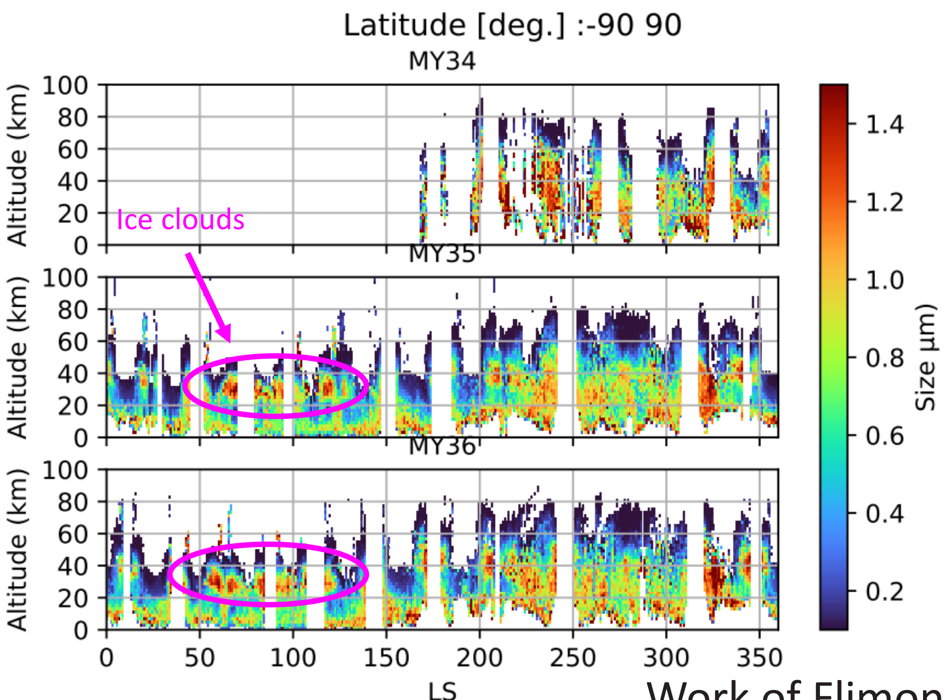
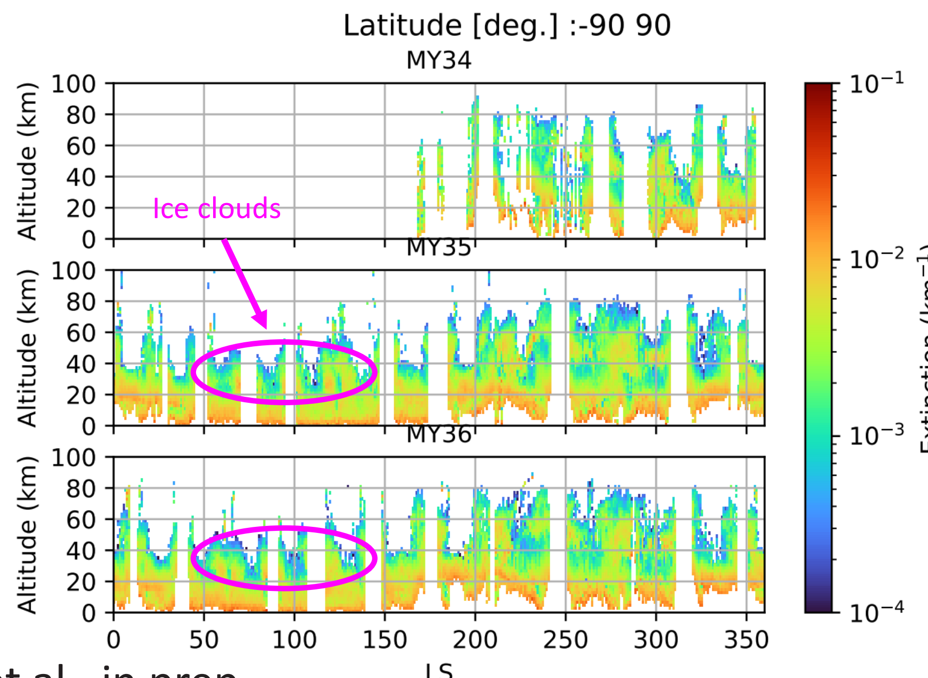
Particle size altitude distribution from NOMAD

Particle size is also deduced from TGO/NOMAD-UVIS occultations

Combining with NOMAD/SO will also improve the particle size retrieval and allow to detect larger particles



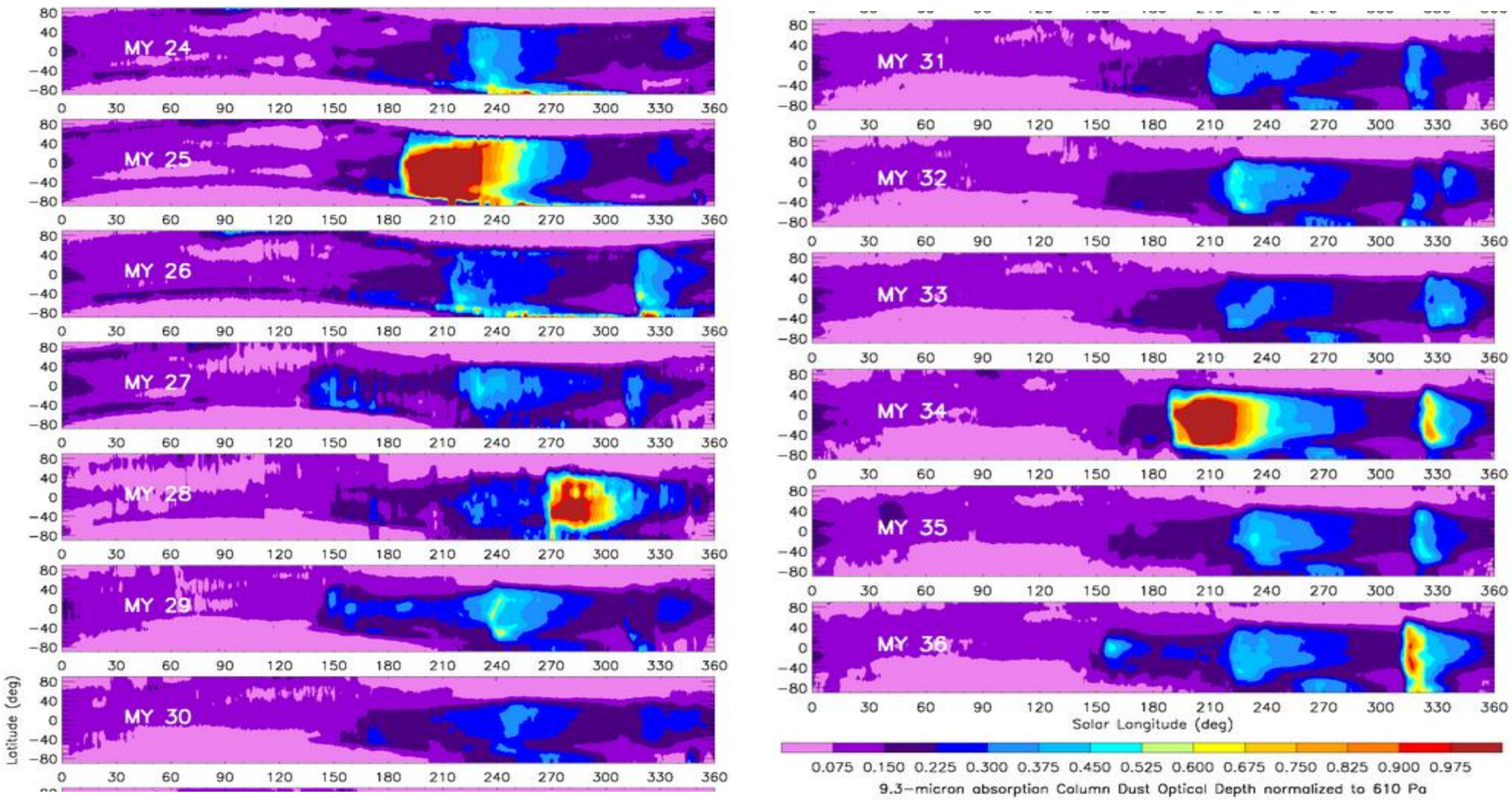


Work of Flimon et al., in prep

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101004052

Assimilated dust climatologies

The work of [Montabone et al. 2020] combines the retrieval of the several instruments to be assimilated in order to produce a complete seasonal climatology of the dust opacity on more than 13 MYs



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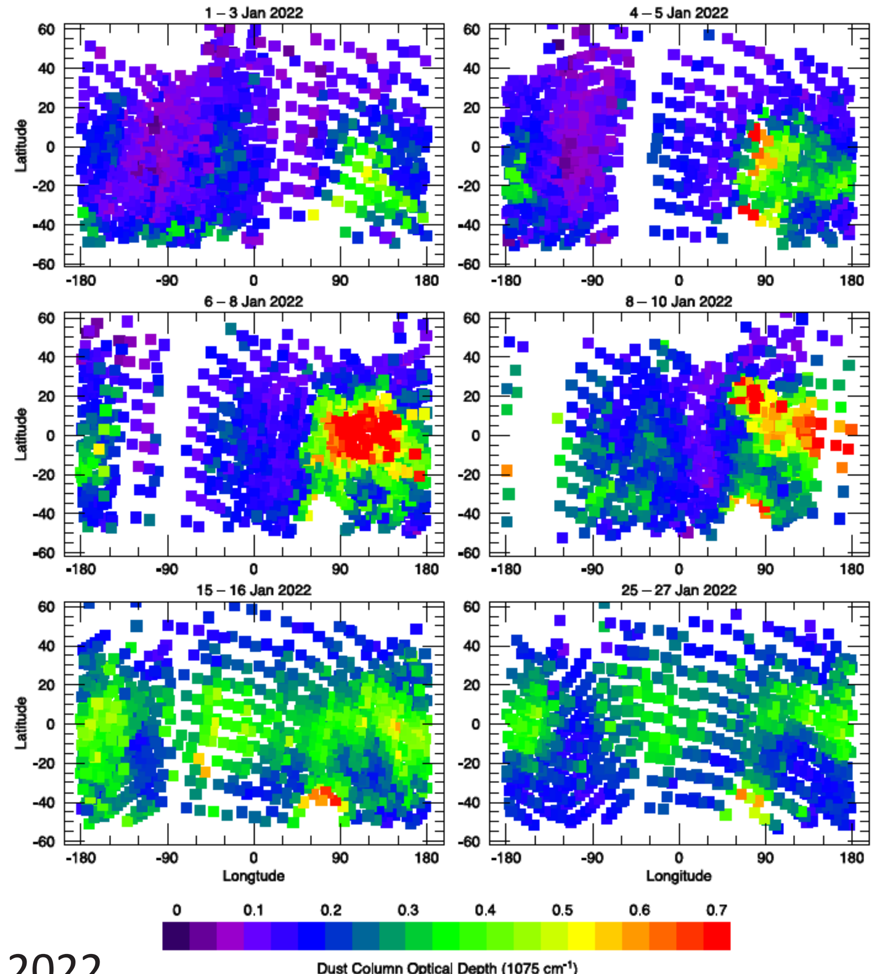
Dust column from EMIRS

EMM/EMIRS TIR spectrometer

- Dust OD at 9.3 μm
- Provide global synoptic view at all local times (day & night)

Allowed to observe the initiation, growth, and decay of the early regional dust storm of MY 36

Early regional dust storm Ls = 151°–164°



Work of Smith et al., 2022

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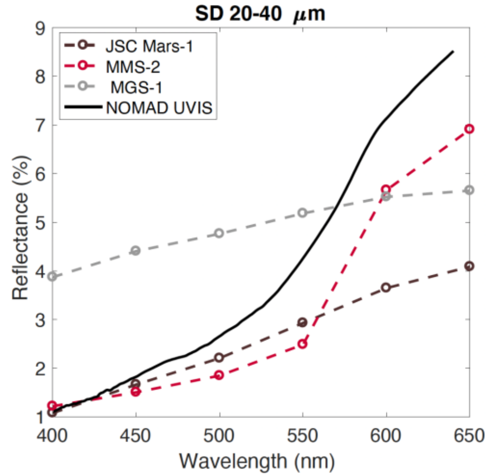
Dust properties from lab measurements

In the frame of roadmap, laboratory experiments were performed on 3 Martian dust analogues to measure the:

- Phase functions & polarization
- Complex refractive index

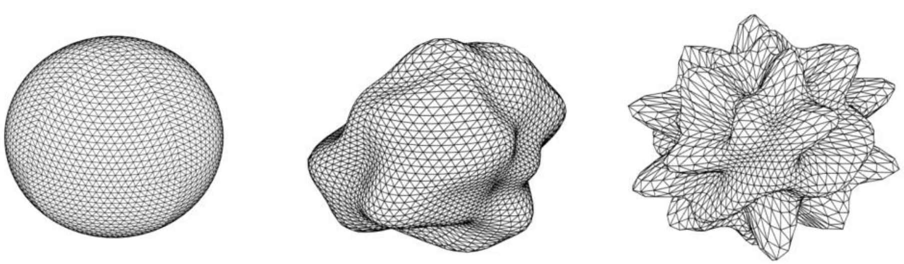
Then combined with realistic particle shapes

=> New set of scattering properties were calculated



Comparing results:

- Analogues don’t seem suitable for UV range were calculated (SSA>0.9, appear too bright)
- Better agreement for visible



Work from Martikainen et al., 2022

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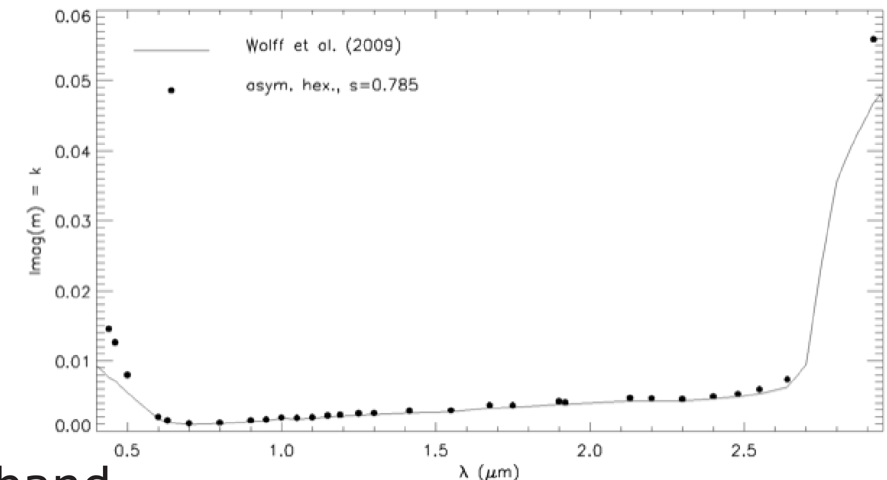
Improving dust properties

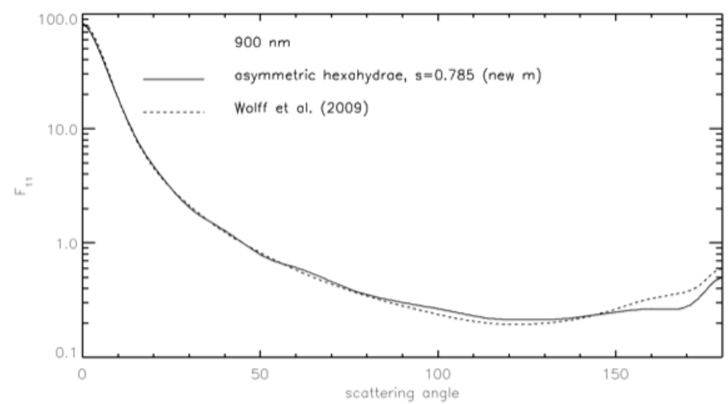
Current work assesses the impact of using more realistic "hexahydra" particle shapes in comparison with cylinder shapes of [Wolff et al. 2009]



⇒ Absorption

Primary impact <0.4 μm & 2.9 μm band

(new shapes with many edges induce additional scattering => require more absorption)



⇒ Phase function

- Very limited impact for phase angles <150°
- Relatively limited at larger angles

Wolff et al., 2023, in prep

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Current open questions

- What physical processes control the initiation, growth, and decay of dust storms?
- What physical processes control the interannual variability of global dust storms?
- What is the current global dust budget and how has it evolved over time?
- How do dust particle size distributions evolve over time in different conditions (storms, dust devil injection, etc.)?

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Some resources to consider

- Dust climatology of [Montabone et al., 2015,2020]
  https://www-mars.lmd.jussieu.fr/mars/dust_climatology/
  - Montabone, L., Forget, F., Millour, E., Wilson, R.J., Lewis, S.R., Cantor, B., Kass, D., Kleinböhl, A., Lemmon, M.T., Smith, M.D., Wolff, M.J.,
    Eight-year Climatology of Dust Optical Depth on Mars.
    Icarus 251, pp. 65-95 (2015), doi: https://doi.org/10.1016/j.icarus.2014.12.034
  - Montabone, L., Spiga, A., Kass, D. M., Kleinböhl, A., Forget, F., Millour, E.,
    Martian Year 34 Column Dust Climatology from Mars Climate Sounder Observations: Reconstructed Maps and Model Simulations.
    J. Geophys. Res. - Planets (2020), doi: https://doi.org/10.1029/2019JE006111

- Hexahydrae shape database
  https://zenodo.org/record/4711247#.YhYXbS1Q3RU
  Saito, M., P. Yang, J. Ding, and X. Liu,
  A comprehensive database of the optical properties of irregular aerosol particles for radiative transfer simulations.
  J. Atmos. Sci., in press, doi: https://doi.org/10.1175/JAS-D-20-0338.1

- DISORT radiative transfer software
  http://www.rtatmocn.com/disort/
  + python wrappers (https://github.com/kconnour/pyRT_DISORT)

- "Scattering by Particles & Surfaces" softwares of M. Mishchenko
  https://www.giss.nasa.gov/staff/mmishchenko/brf/

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THANK YOU!
MORE INFO?

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