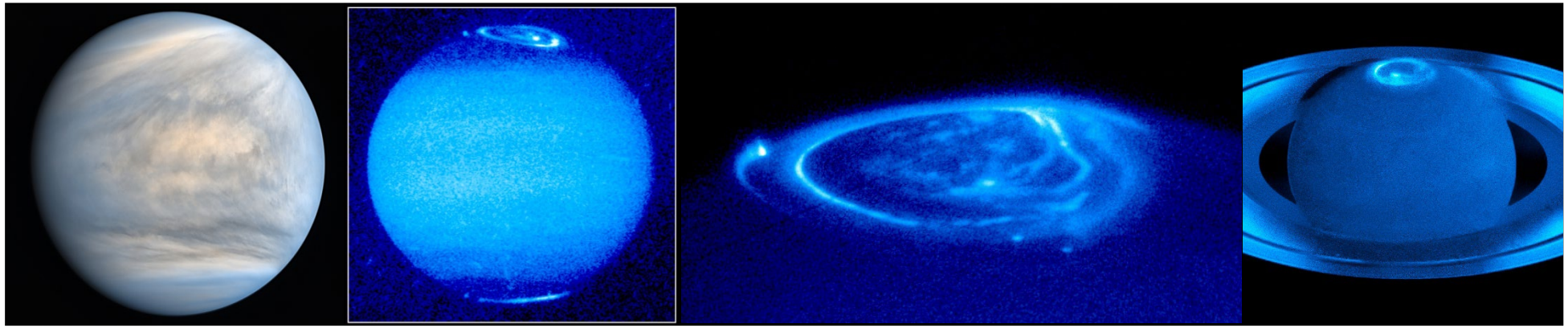
Universidad del País Vasco / Euskal Herriko Unibertsitatea

BILBOKO INGENIARITZA ESKOLA
ESCUELA DE INGENIERÍA DE BILBAO

Grupo de Ciencias Planetarias

Aula EspaZio Gela



The Solar System at UV wavelengths: Planetary Atmospheres

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Fundamentals

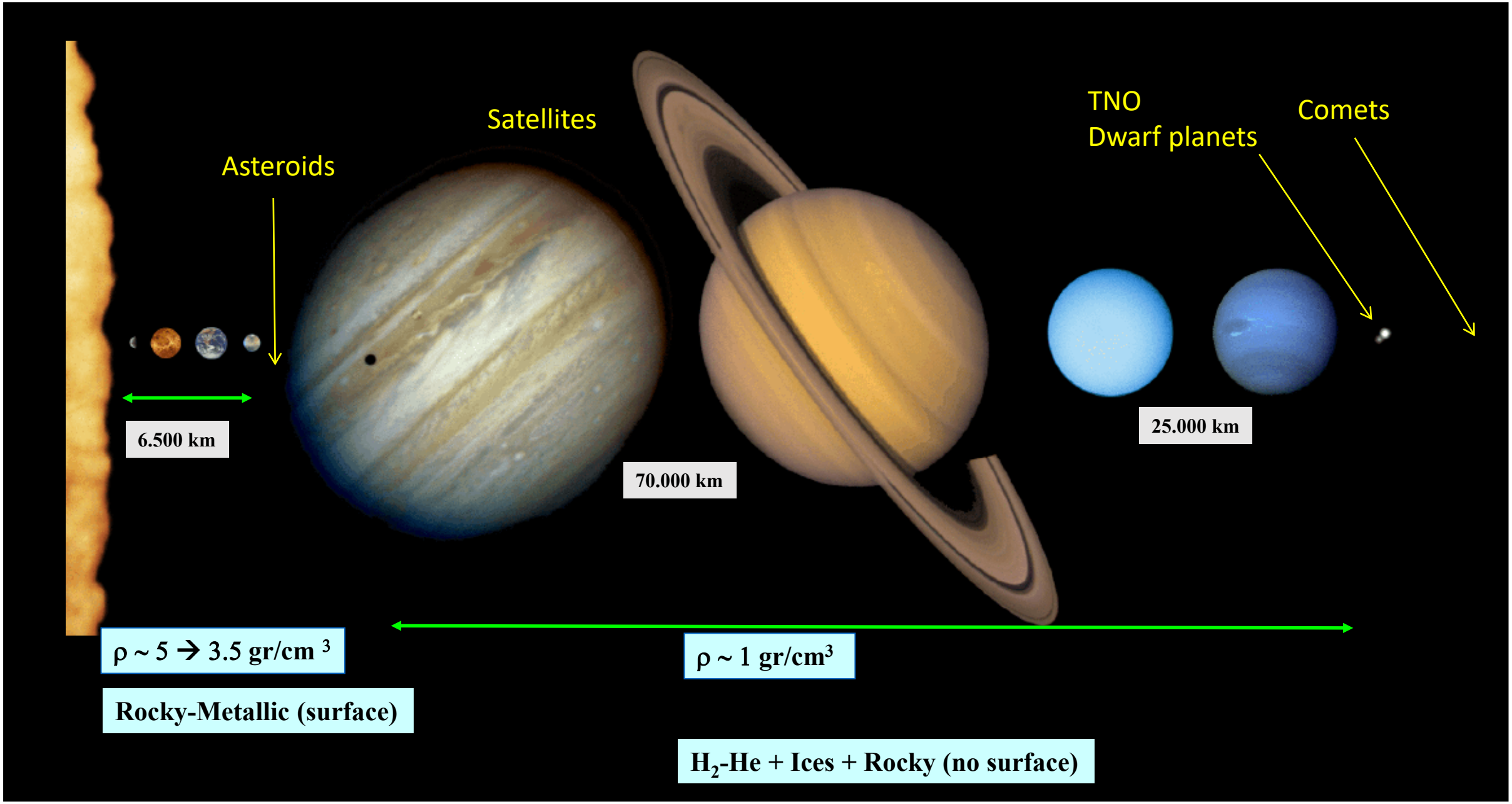
UV wavelength ranges:
Near-ultraviolet (NUV: 200–350 nm)
Far-ultraviolet (FUV: 100–200 nm)
Extreme-ultraviolet (EUV: 50–100 nm)

Energy output of the Sun:
Changes by a factor of 1000 between the EUV and NUV

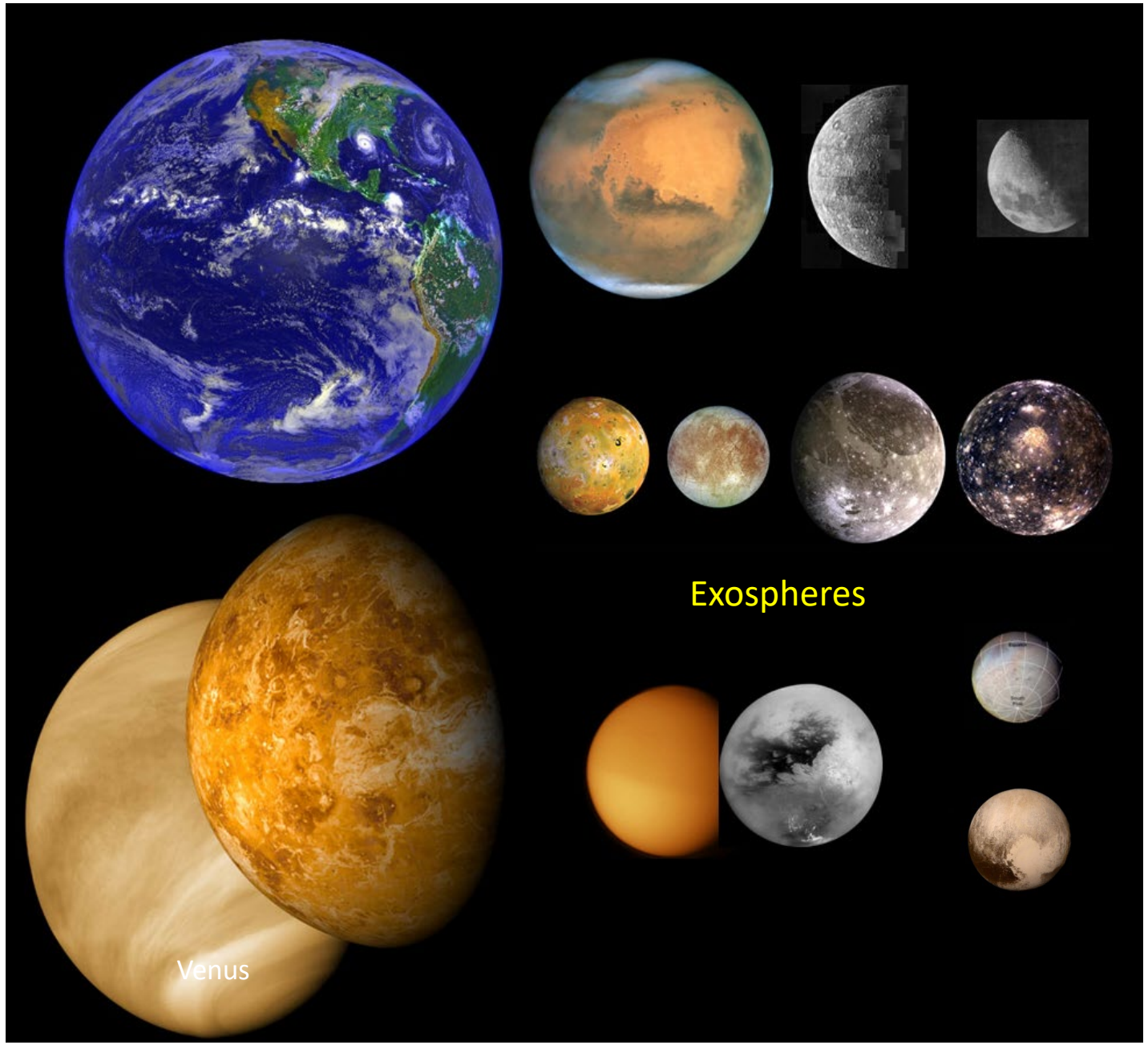
Earth-orbiting telescopes (e.g.):
International Ultraviolet Explorer (*IUE*) (1978-1996)
Hubble Space Telescope (*HST*) (1990-)

Planetary orbiting missions (UV instrumentation, a selection):
Mercury: *Mariner 10, Messenger, Beppi-Colombo*
Venus: *Pioneer-Venus, Venus Express, Akatsuki*
Mars: *Mariner, Mars Express, MRO, MAVEN, Emirates EMM*
Giants and icy planets: *Pioneer 10-11, Voyager 1-2, Galileo*, *Cassini*, *Juno*

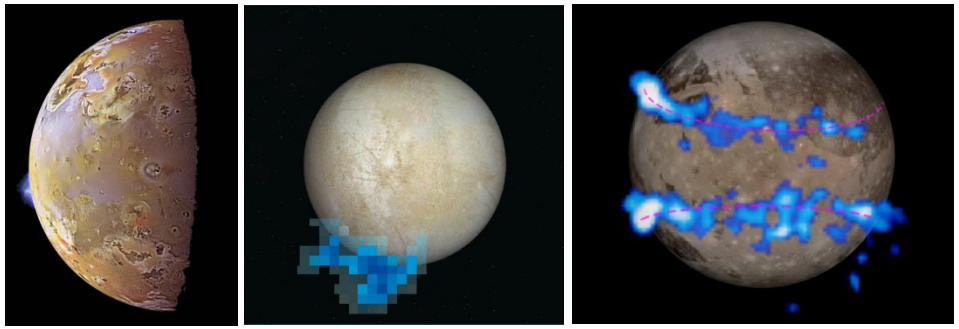
The solar system planets: an overview

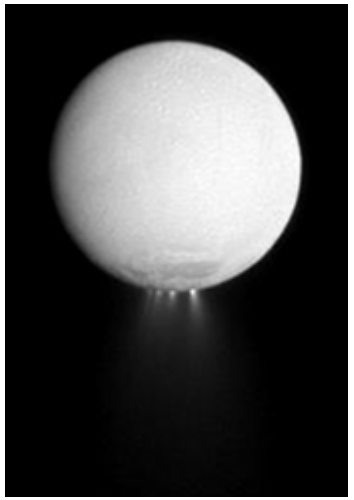


Terrestrial planets and major satellites



Satellite active interiors





Planetary Atmospheres

Mass/area = Pressure/gravity acceleration (Kg/m^2)

(1) Thin Atmospheres (Exospheres)

[Boundary surface: $Ps < 10^{-5}$ bar]:

Mercury, Moon, Galilean satellites (Io, Europa, Ganimedes, Callixto), Enceladus, Triton, Pluto

(2) Intermediate Atmospheres

[Boundary surface: Ps = 0.007 - 90 bar]:

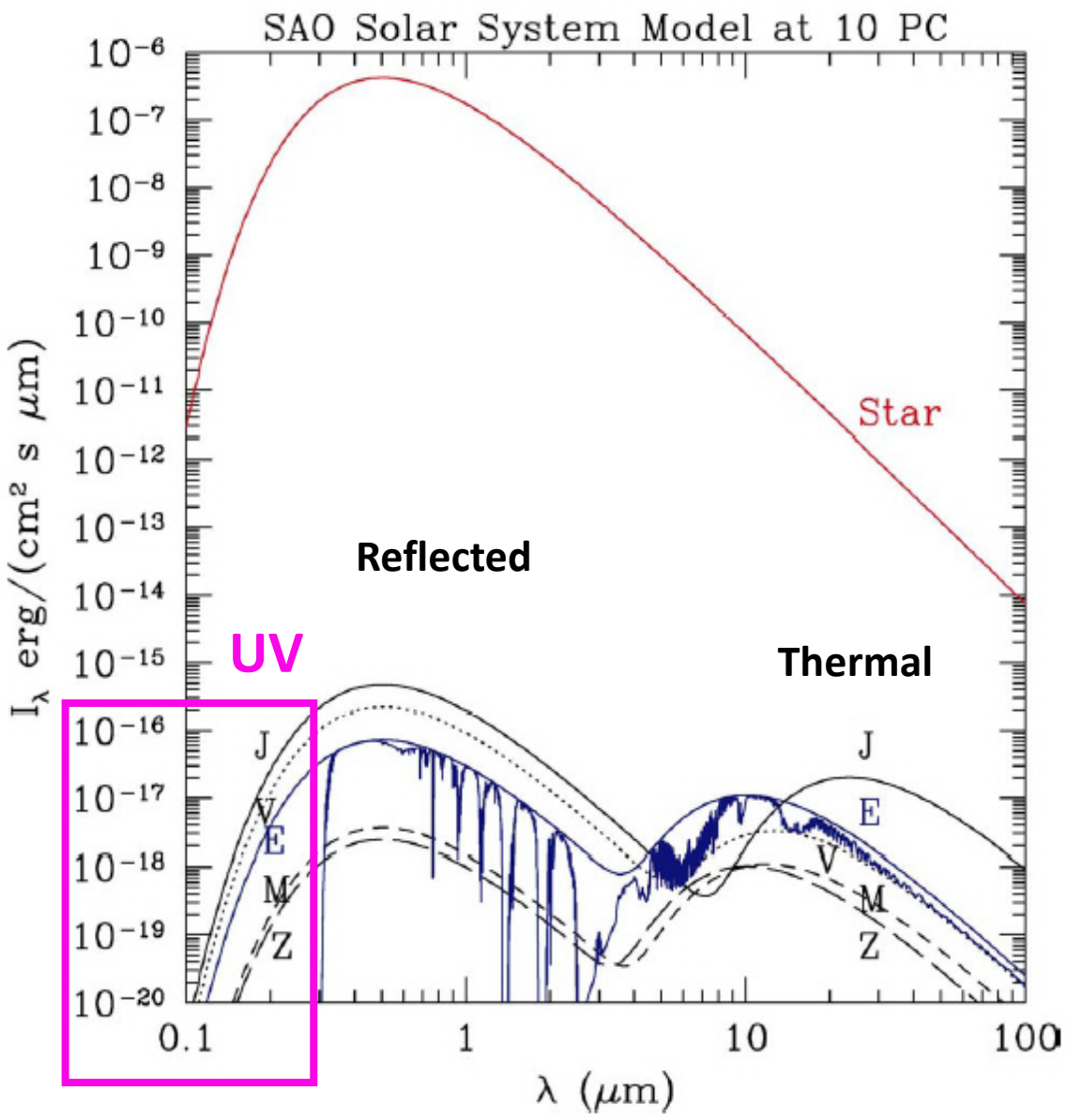
Venus, Earth, Mars, Titan.

(3) Massive and Deep Atmospheres

[No rigid boundary known: P > Kbar - Mbar]:

Jupiter, Saturn, Uranus, Neptune

Planetary Spectrum



UV phenomena drivers:
Solar radiation (limited photon penetration)
Solar wind and magnetospheric particles

Chemical compounds in the atmosphere:

→ Neutrals (scattering of solar radiation)

→ Radiative (sunlight: photochemistry, photoionization, photodissociation, absorption/emission processes) – Airglow - Nightglow

→ Radiative (excitation by solar wind and magnetospheric particles) – Aurora

→ Condensables (clouds and hazes → scattering, absorption/emission, latent heat release)

Atmospheres Terrestrial Planets and major Satellites

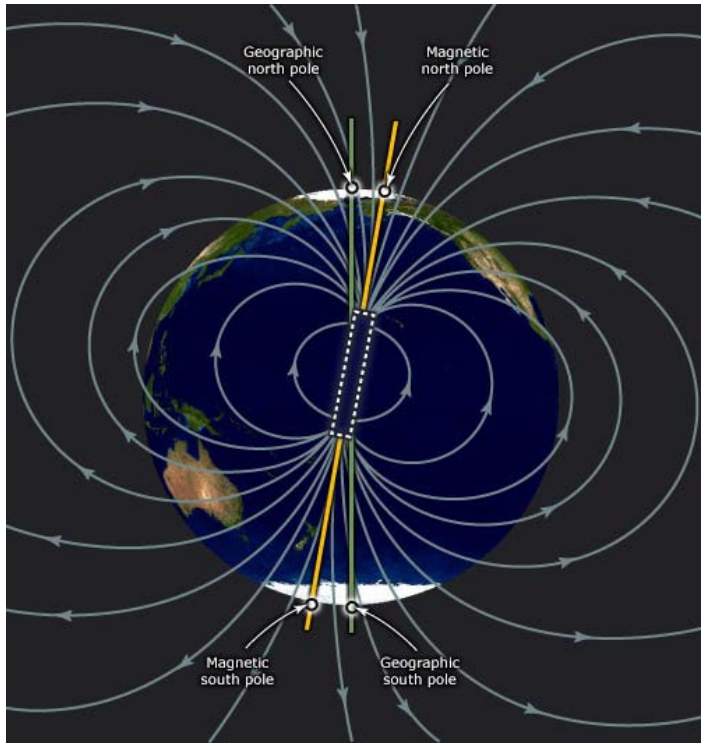
Planet Satellite	Composition (%)	Surface P_s (bar) , T_s (K)	Clouds	Aerosol optical depth
Mercury	He(42), Na (42) O (15), H, K	10^{-12}, 700 (day), 93 (night)	-	Exosphere
Venus	CO_2 (96), N_2 (3)	90, 730 *	SO_4H_2 (100% cover)	5-12
Earth	N_2 (77), O_2 (21) H_2O (100 ppm)	1, <288>*	H_2O + aerosols (50% coverage)	5-10 (100)
Moon	Na, K		-	Exosphere
Mars	CO_2 (95), N_2 (3), Ar (2)	0.007, <218>*	H_2O, CO_2, dust (10-100% cov.)	0.3 - 6
Io (J)	SO_2 (O_2, SO) (Na, K, S^+, …)	10^{-7}, 120	Volcanic dust	0.1
Europa (J) Ganimedes(J) Callixto (J)	O_2, (Na)	10^{-11}, ~ 100	-	Exosphere
Titan (S)	N_2 (90), Ar, CH_4	1.6, 92	CH_4 + C_nH_m	10
Triton (N)	N_2	10^{-5}, 38	N_2 (?) - CH_4	0.1-0.3
Pluto	CH_4, N_2	10^{-4}, 40	CH_4	> 0.15

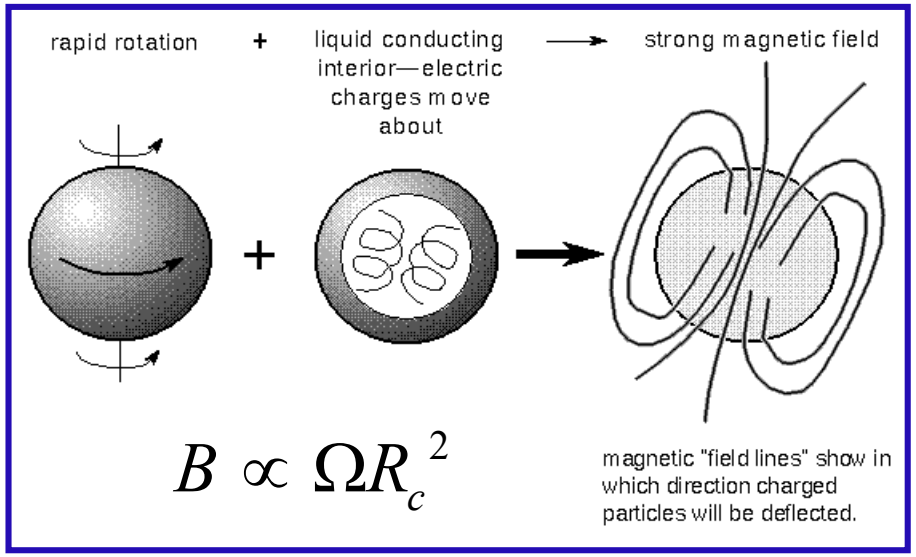
Atmospheres Giant and Icy Planets

Planet	Composition (%)	P_s (bar) T_s (K)	Clouds
Jupiter	H_2 (90), He (10)	1 bar→ Mbar 125 K → 2000 K	NH_3, NH_4SH, H_2O
Saturn	H_2 (90), He (10)	1 bar→ Mbar 100 K → 2000 K	NH_3, NH_4SH, H_2O
Uranus	H_2 (90), He (10)	1 bar→ Mbar 60 K → 1000 K	CH_4, NH_3, NH_4SH, H_2O
Neptune	H_2 (90), He (10)	1 bar→ Mbar 60 K → 1000 K	CH_4, NH_3, NH_4SH, H_2O

Planetary Magnetic Fields

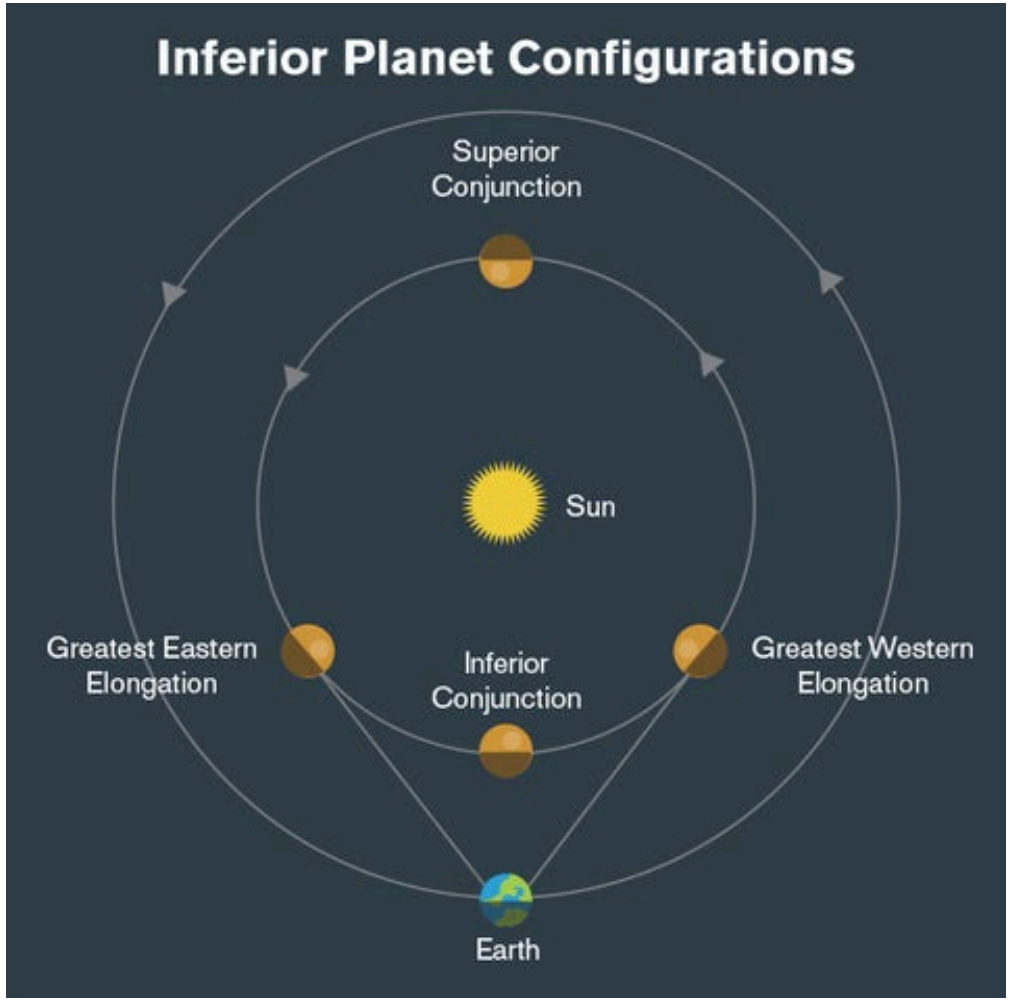
Planet	*Rotation Period (days)*	*Dipolar momentum (Earth = 1)*	*Equatorial magnetic field (Gauss)*	*Tilt angle (Ω - B)*
Mercury	58.65	0.0007	0.003	14
Venus	243.02(r)	<0.0004	<0.00003	-
Earth	1	1	0.305	10.8
Mars	1.03	<0.0002	<0.0003	-
Jupiter	0.41	20.000	4.28	9.6
Saturn	0.44	600	0.22	<1
Uranus	0.72 (r)	50	0.23	58.6
Neptune	0.67	25	0.14	47

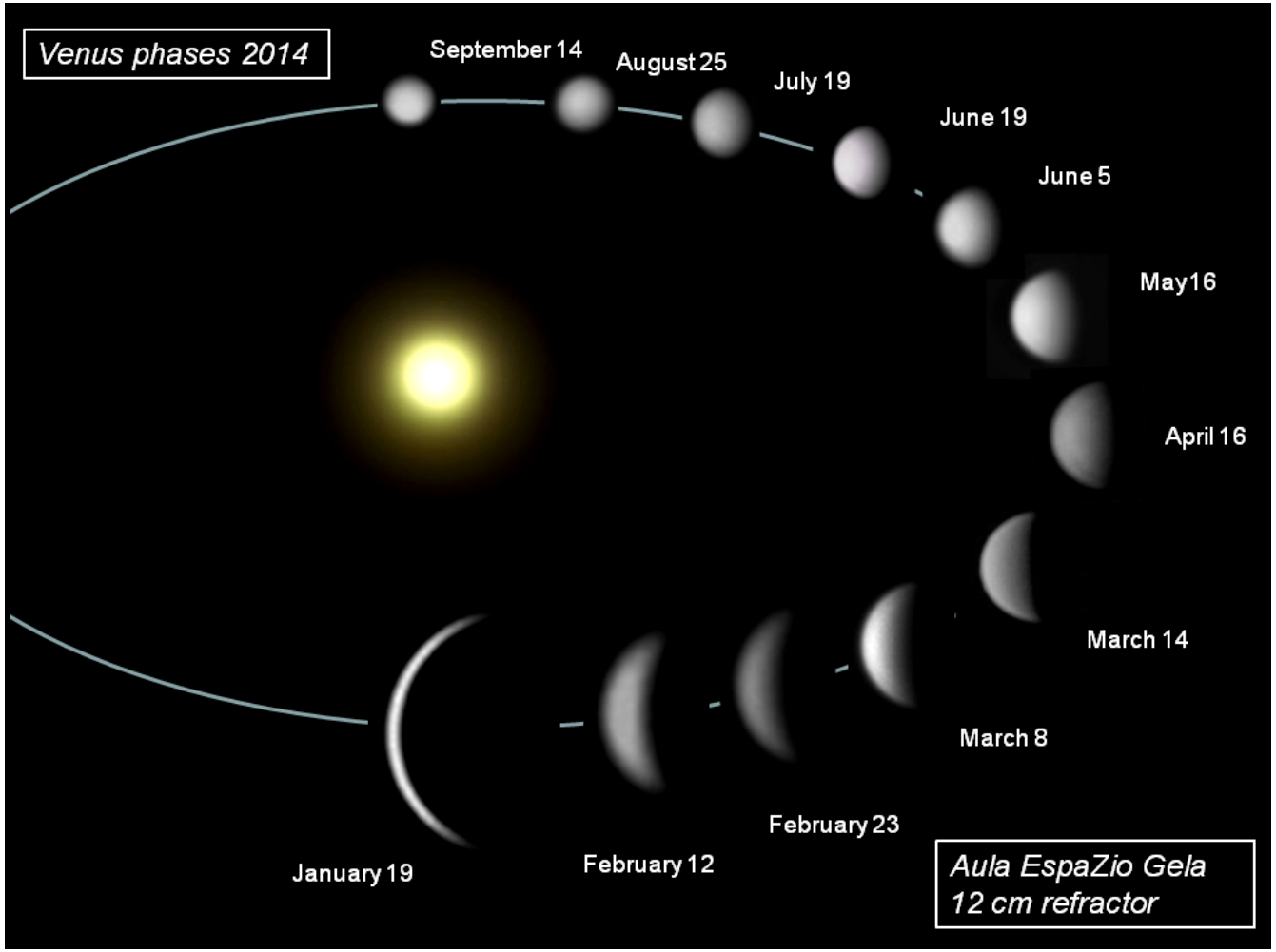




Venus

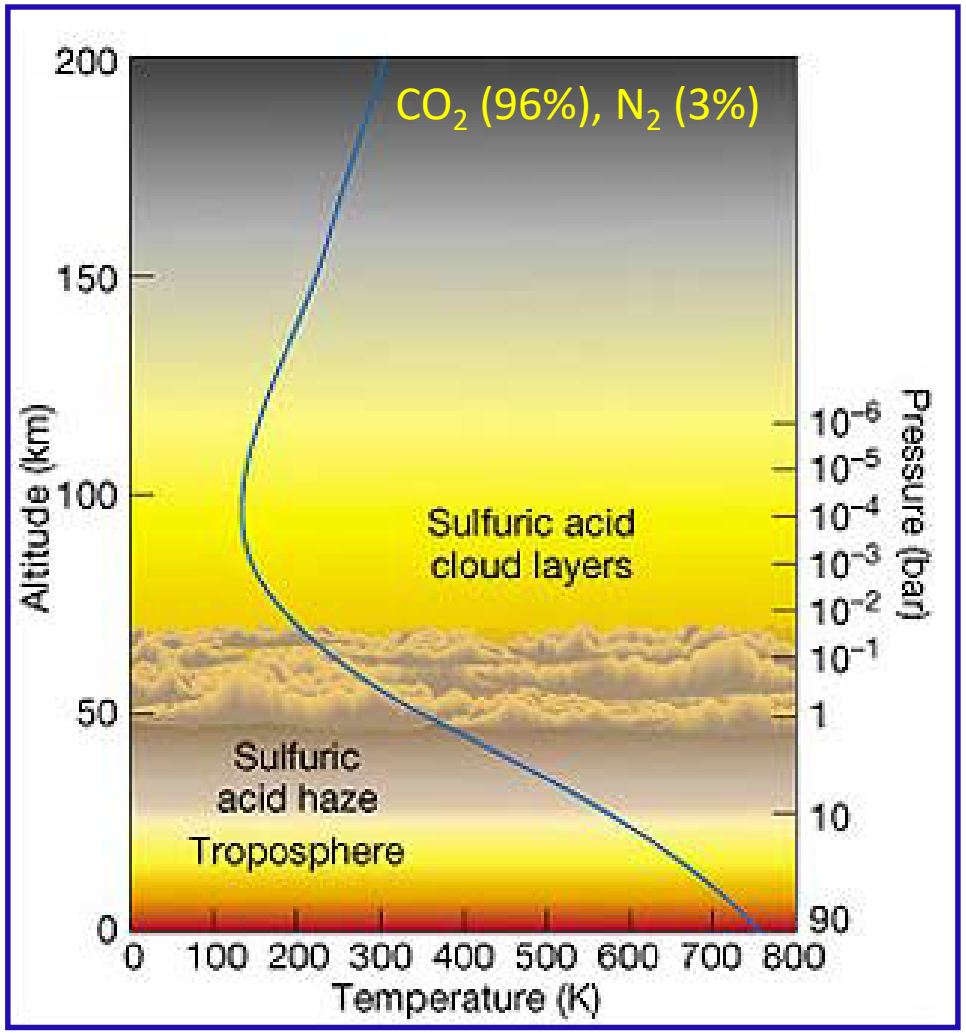
A planet difficult to observe from the ground or from Earth orbiting
Elongations from the Sun ~ 45°

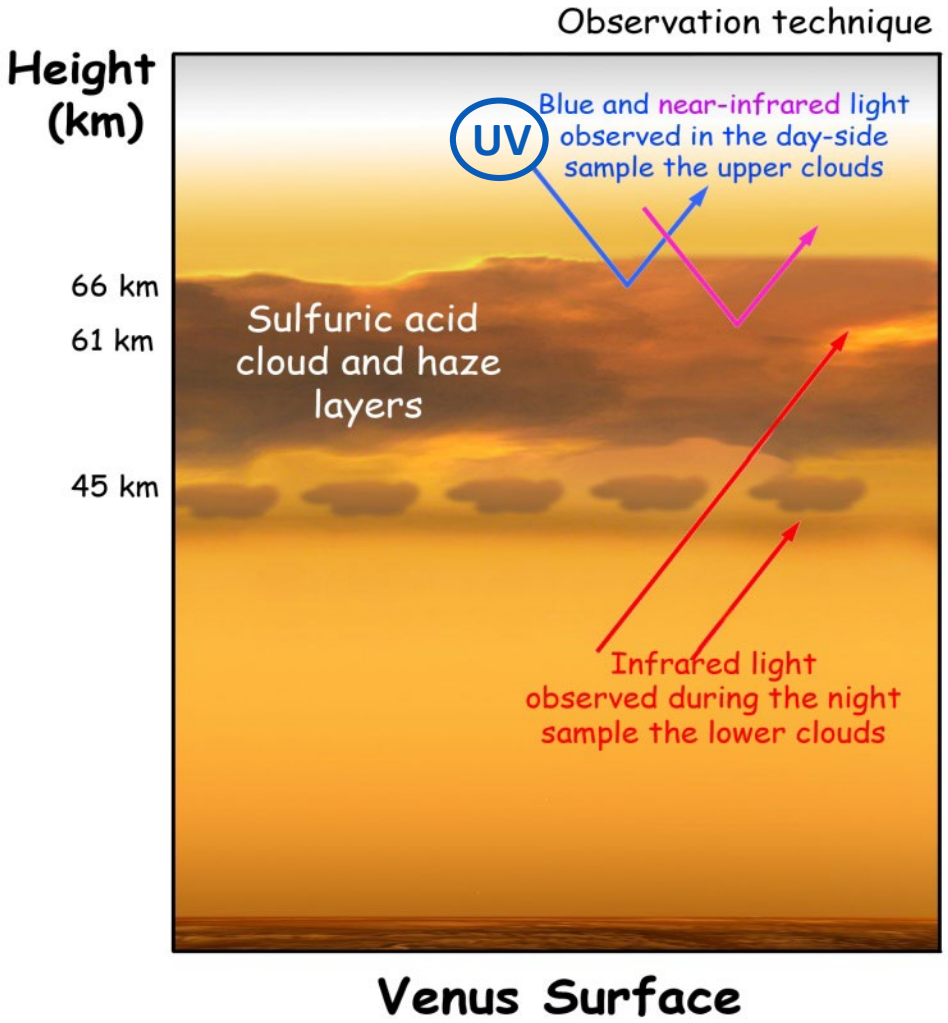




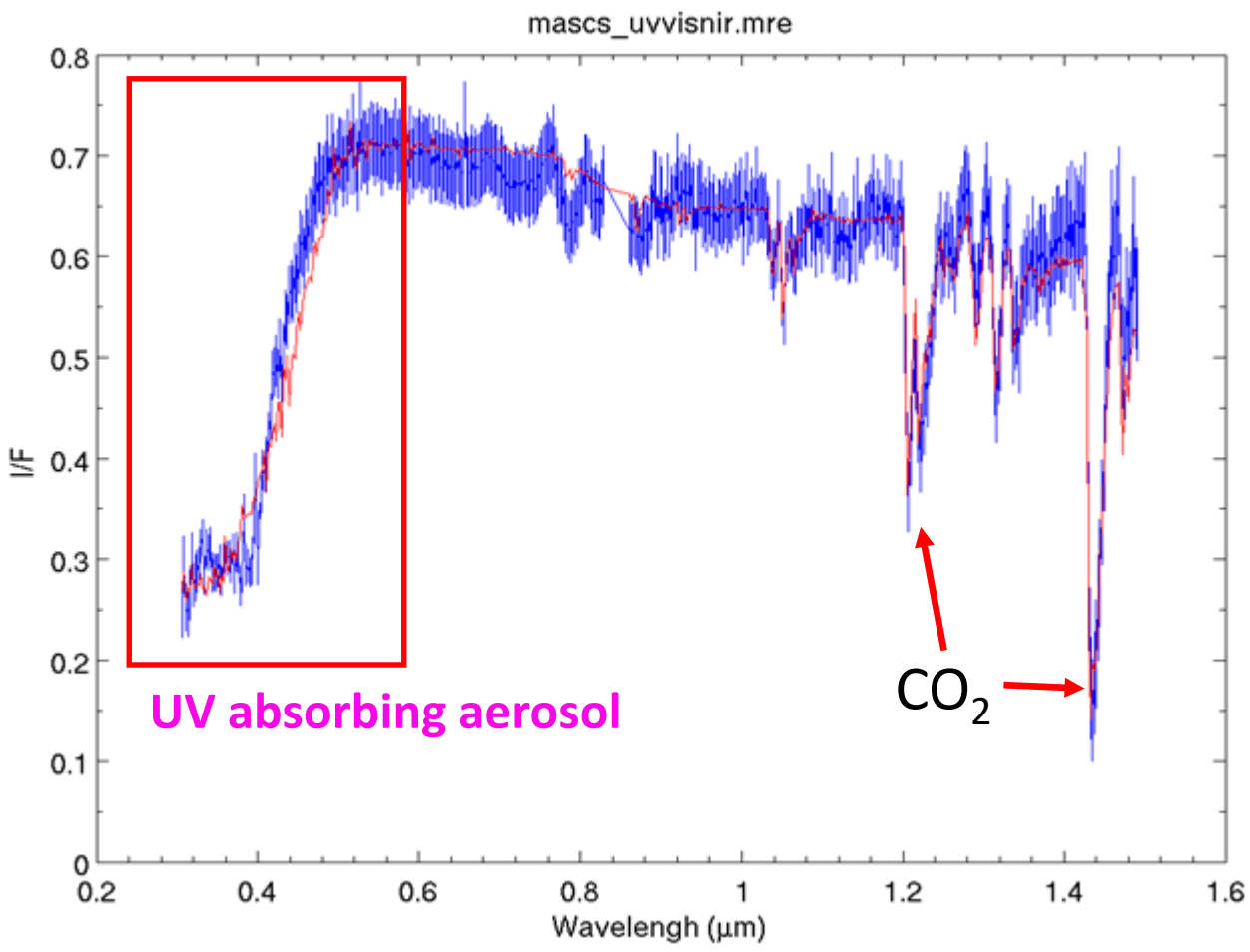
Venus clouds

Clouds → Chemical reaction and condensation:
$SO_2 + H_2O \rightarrow$ **SO_4H_2** (s,l)
Particle size = 0.5 - 3 µm **+ UNKWOWN UV AEROSOL ABSORBER**



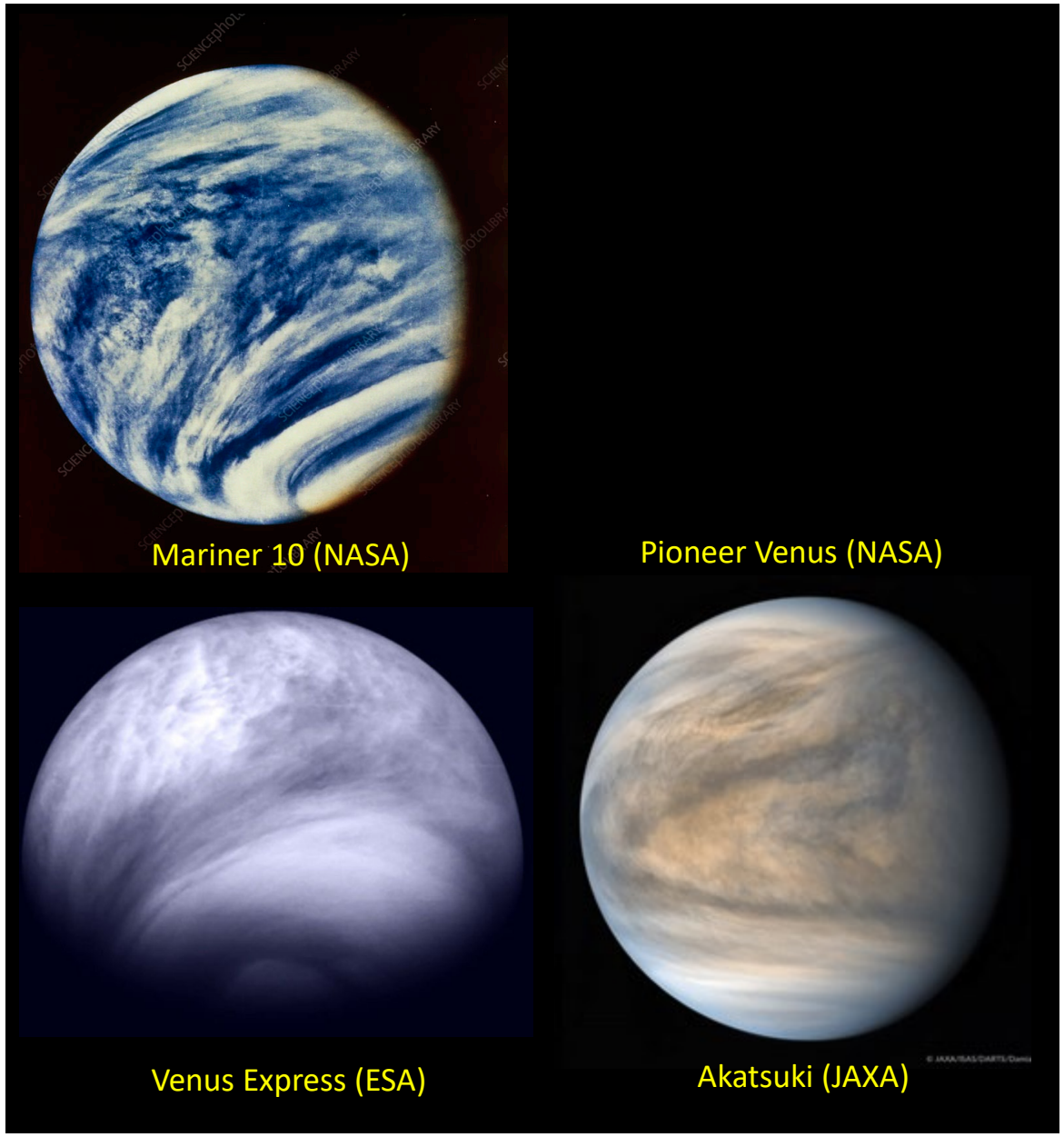


Venus optical spectrum



Pérez-Hoyos et al. (2018)

Venus UV absorber in the upper clouds (65 - 70 km)



Venus UV absorber candidates

Table 3
Candidates for UV Absorption

Candidate	Reference
S_3	Toon et al. (1982)
S_4	Toon et al. (1982)
S_8 (25°C)	Hapke and Nelson (1975)
S_8 (100°C)	Hapke and Nelson (1975)
S_2O	Hapke and Graham (1989)
OSSO	Frandsen et al. (2016)
SCl_2	Krasnopolsky (1986)
$(NH_4)_2S_2O_5$	Titov (1983)
$NOHSO_4$	Watson et al. (1979)
Cl_2	Pollack et al. (1980)
$FeCl_3$	Krasnopolsky (1985)
$C_5O_5H_2$	Hartley et al. (1989)

Our candidates:
→ Disulfur oxide (S_2O)
→ Dioxide disulfur (S_2O_2) (OSSO)

Pérez-Hoyos, Sánchez-Lavega et al. (JGR, 2018)

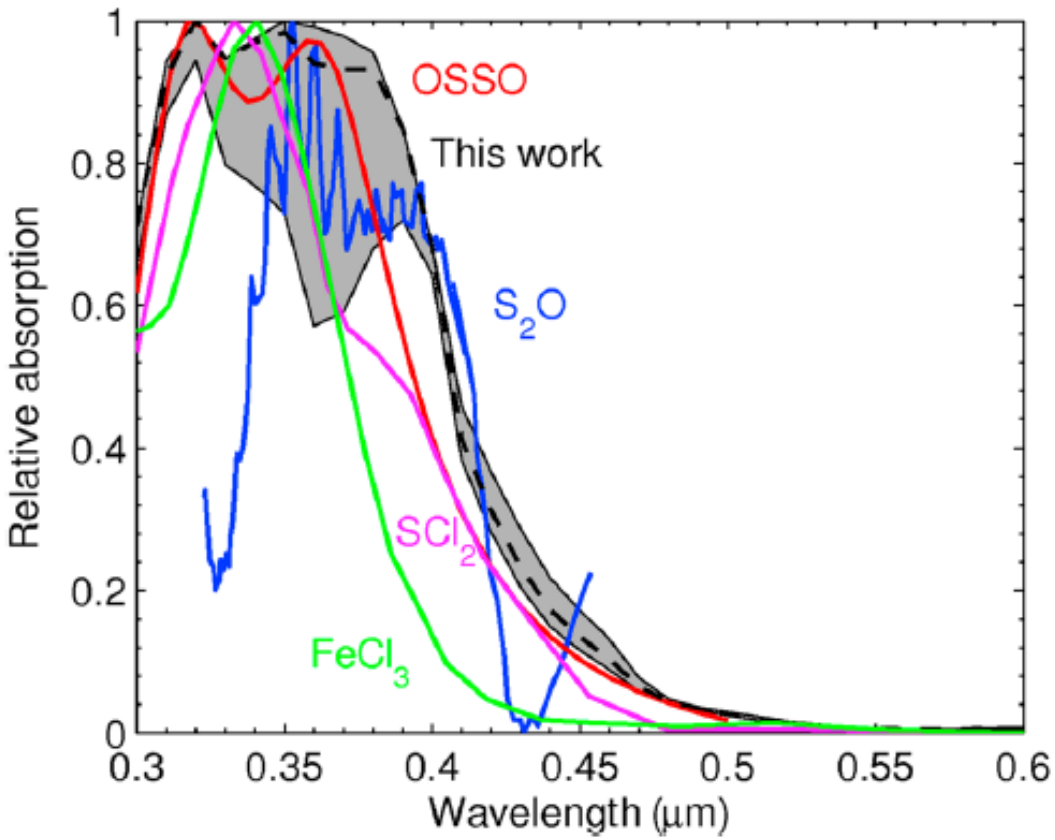
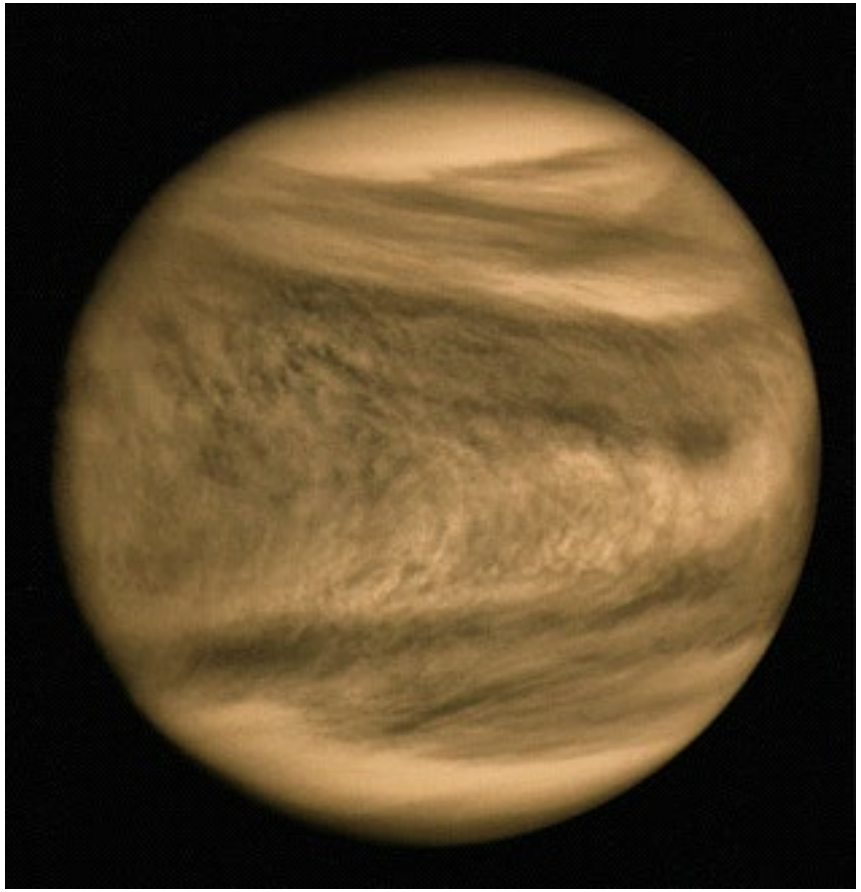


Figure 15. A comparison of the relative absorption (in arbitrary units) of some of the candidates for the UV absorber proposed so far with the model results obtained in this work. The gray area is used for our mode results, with the black dashed line being used for best fitting values, and maximum and minimum absorption values being indicated with solid black lines.

MESSENGER/MASCS spacecraft

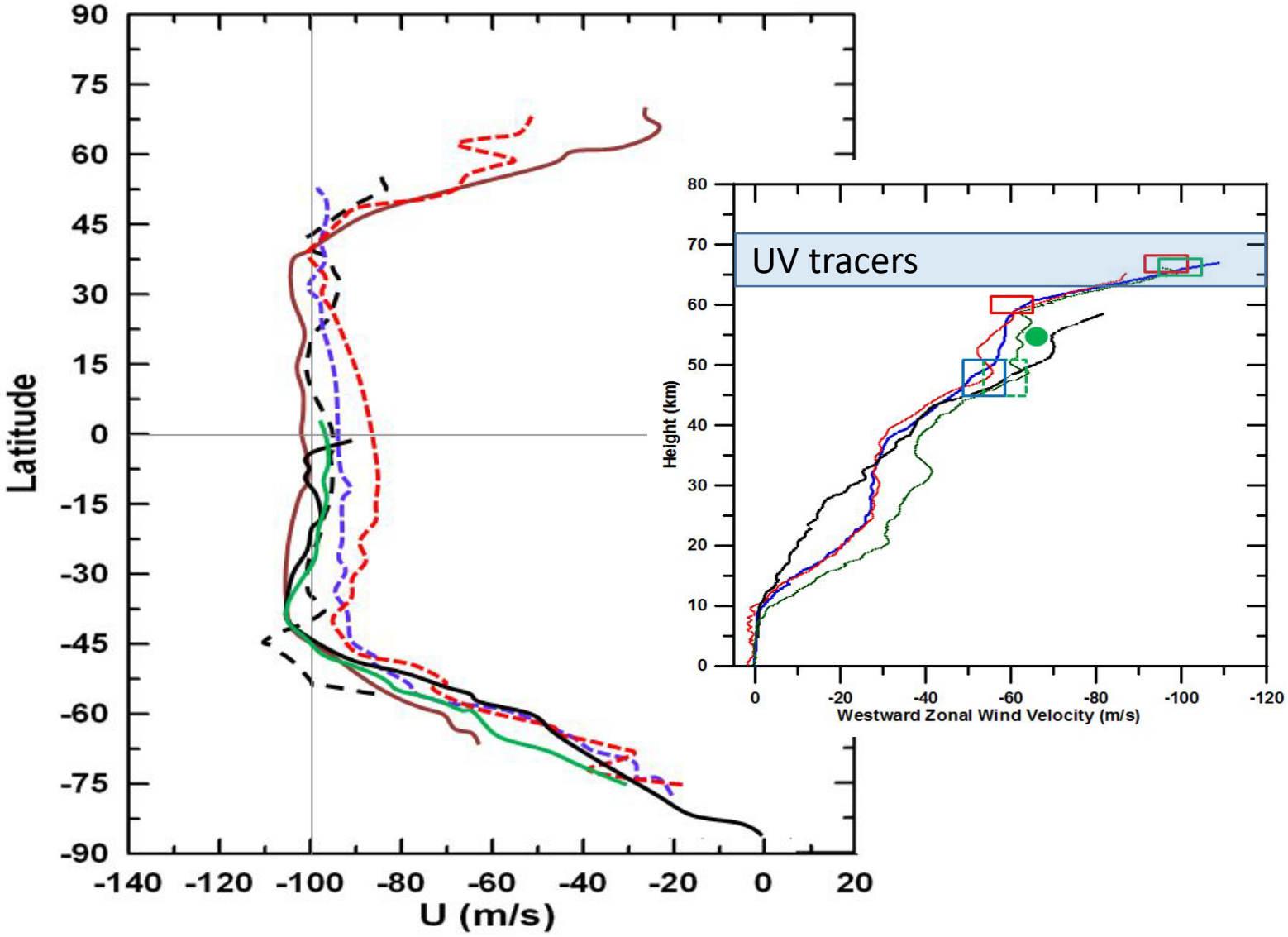
Venus Superrotation

Venus rotation period = 243 days
Atmosphere rotation (max) = 4 – 5 days
Supertotation → Atmosphere 60 x Surface



Waves in the upper clouds: Y, Psi shapes

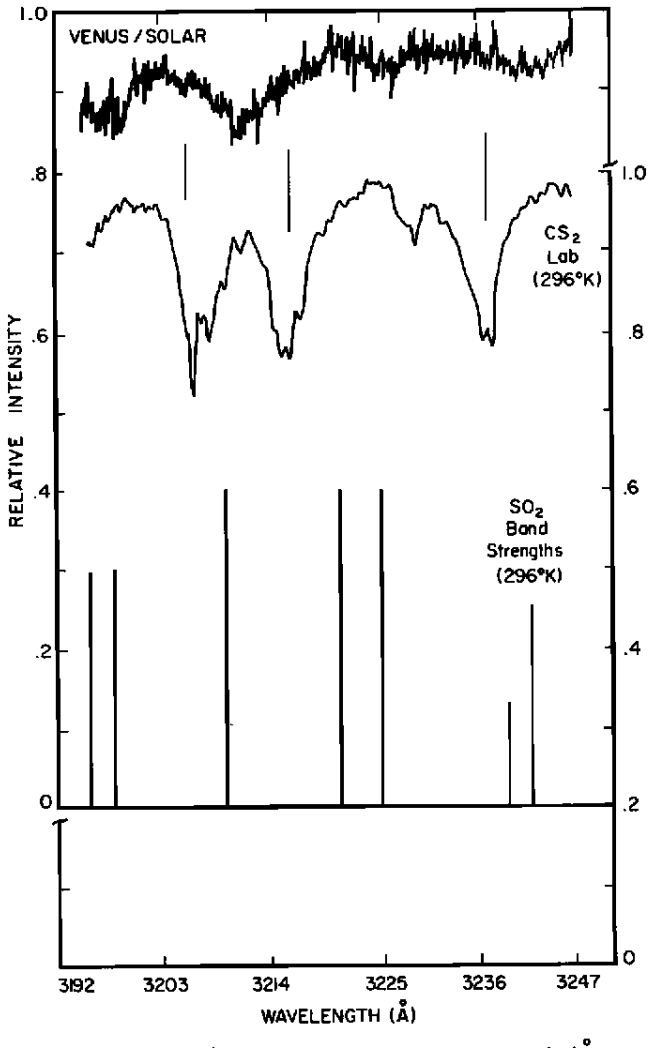
Cloud top level (UV absorbing aerosols)
Altitude above surface = 65-70 kms



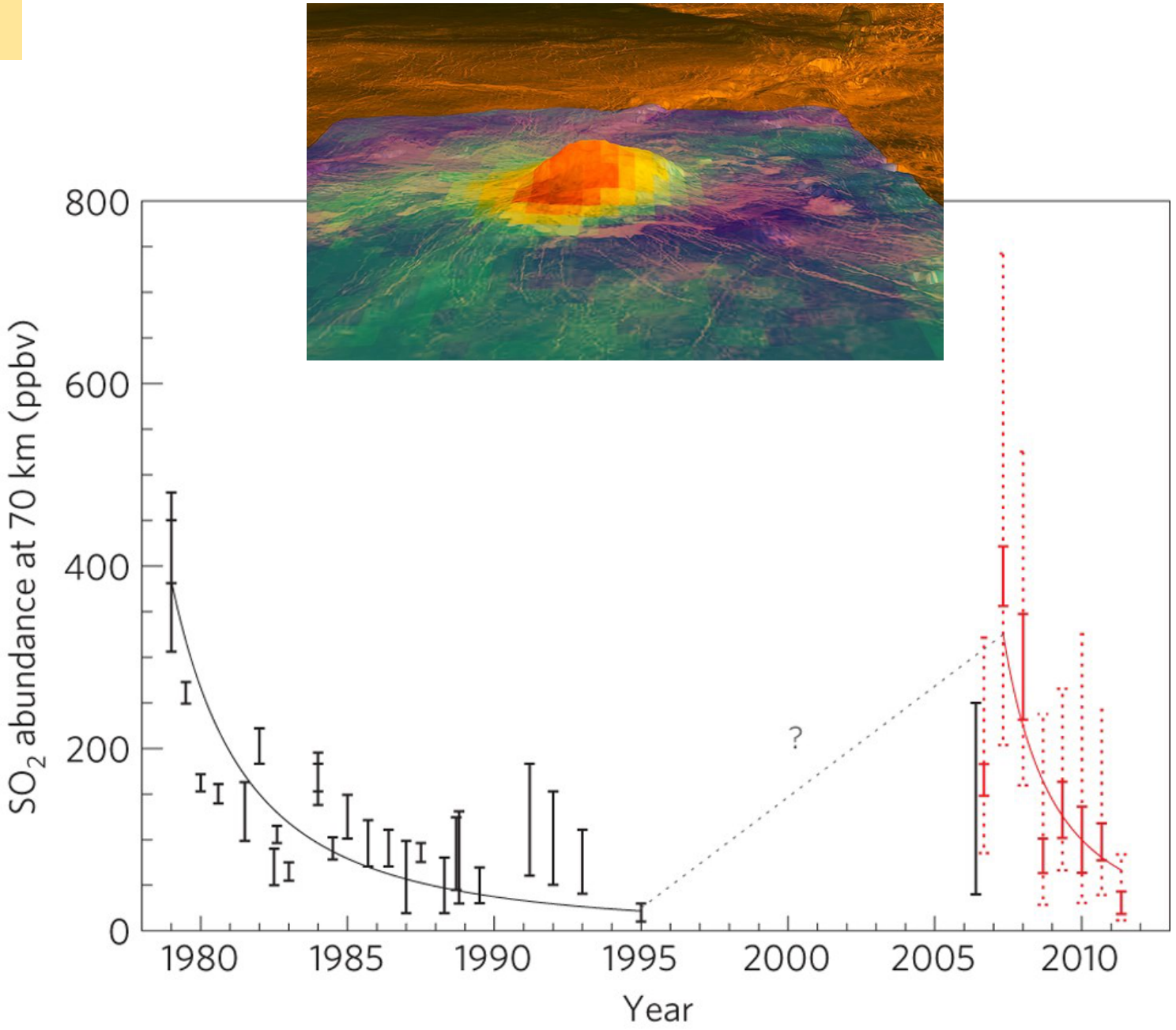
Sánchez-Lavega et al., Space Sci. Rev. (2017)

Venus: episodic, active volcanos?

SO_2 mixing ratio



Barker et al., GRL, 1979

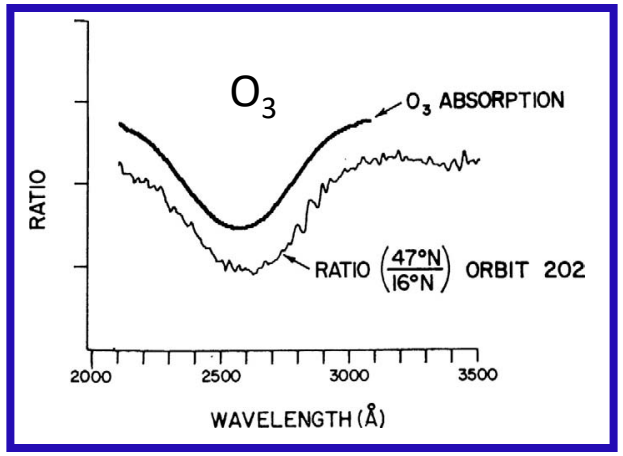


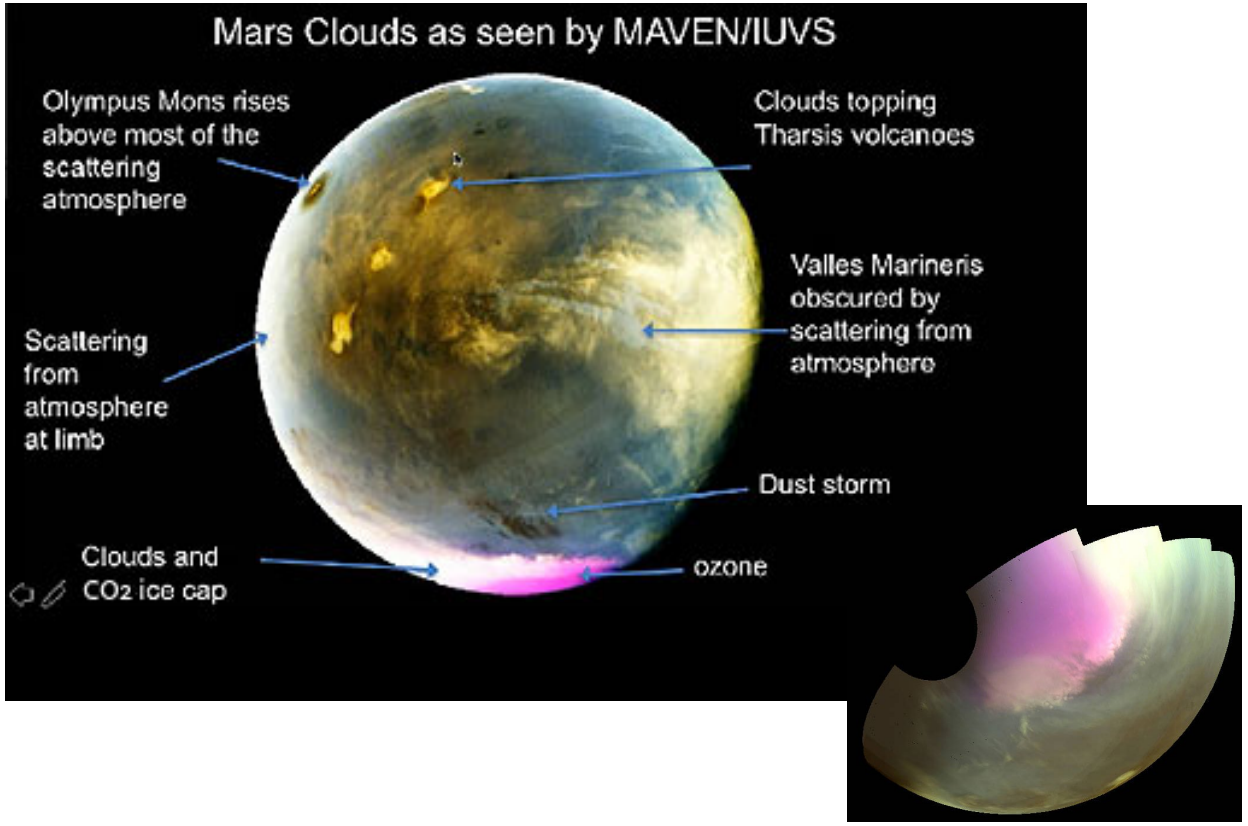
Marq et al., Nature Geos., 2012

Mars: ozone and water-ice clouds

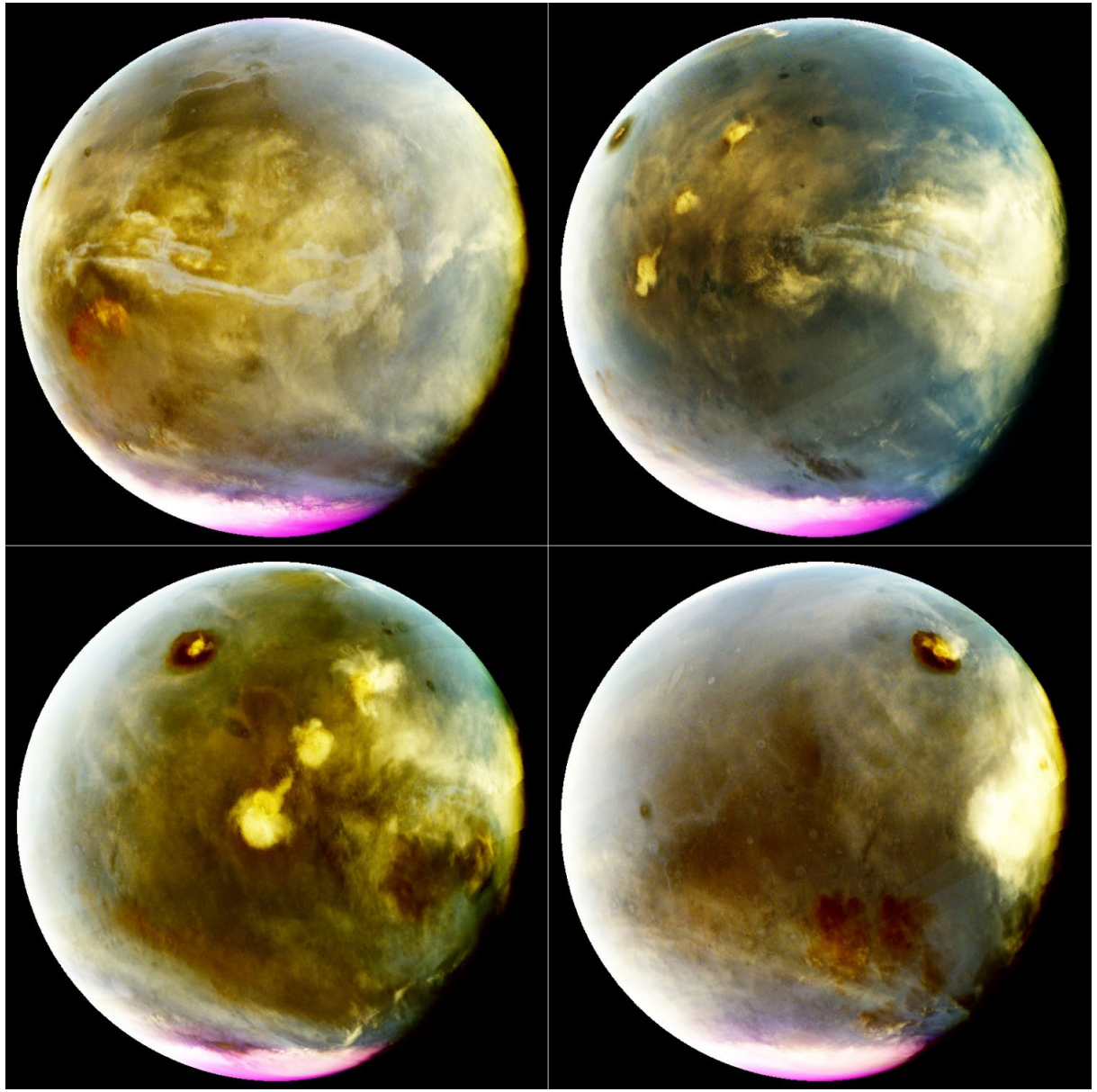
H_2O ice clouds
size: 1-2 μm

- Seasonal variability
- Dynamics (winds)





Imaging: 200-350 nm (MAVEN/IUVS)

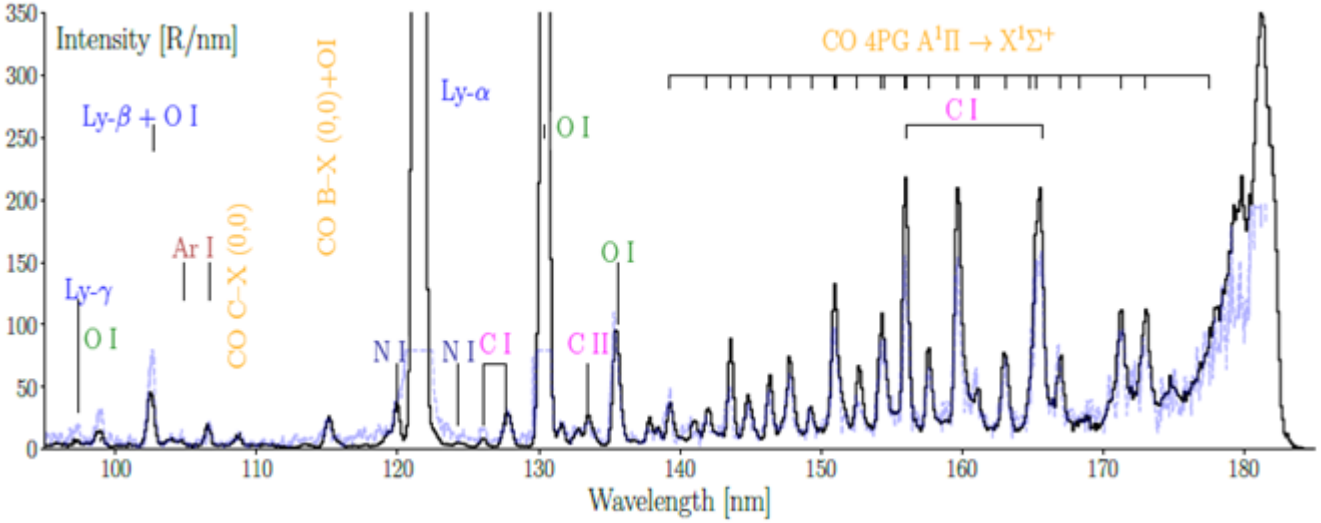


Mars UV emission spectrum

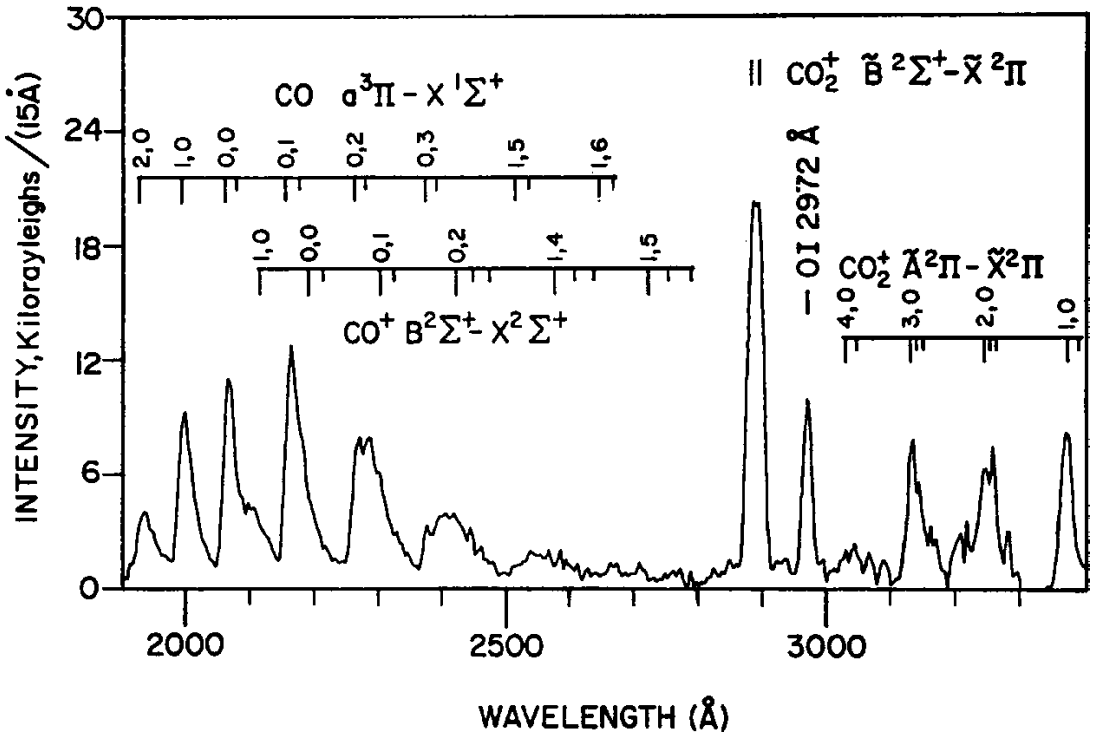
Complex UV spectrum: aurora, nightglow and airglow

Lyman-alpha
CO (110 - 175 nm), Oxygen OI, Carbon, Nitrogen

Cameron bands
CO (190 - 270 nm), UVD (CO2+transition at 289 nm), the oxygen OI forbidden emission at 297.2 nm

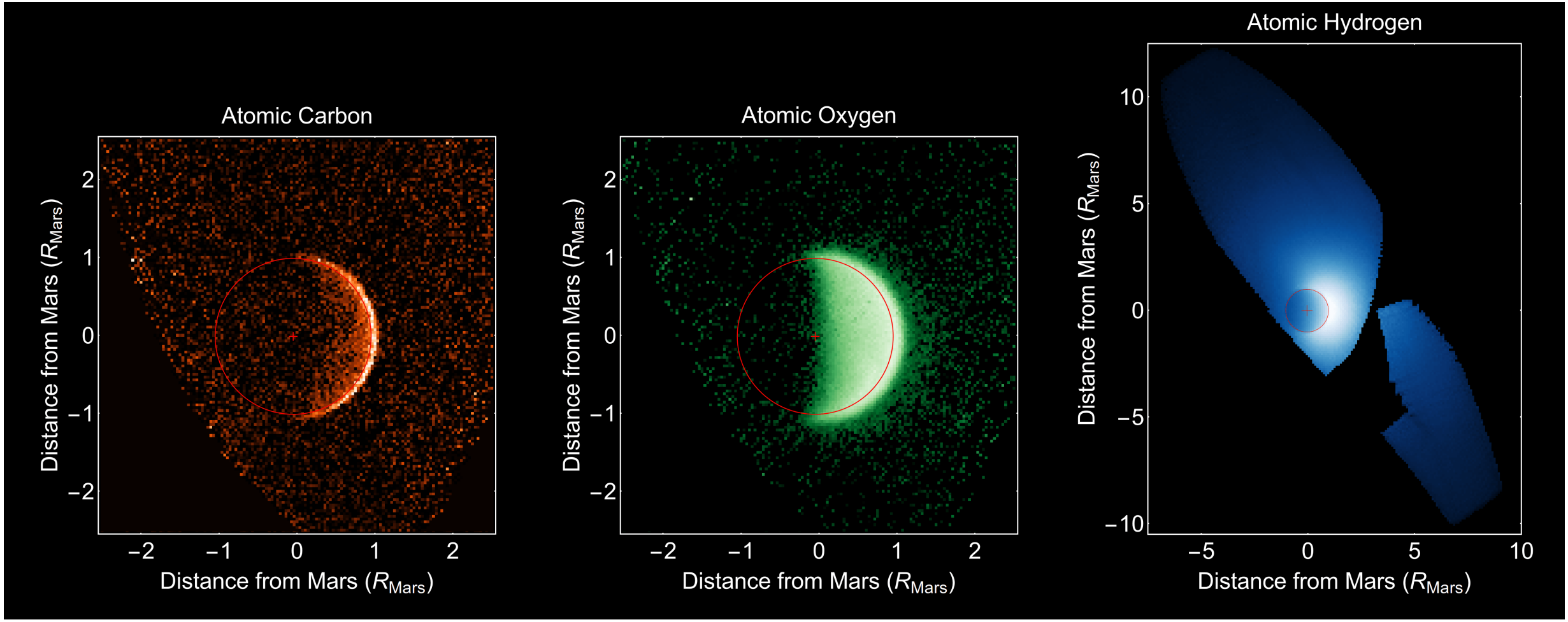


Jain et al., GRL, 2022



Bertaux et al., (2005)

Mars atomic emission coronas

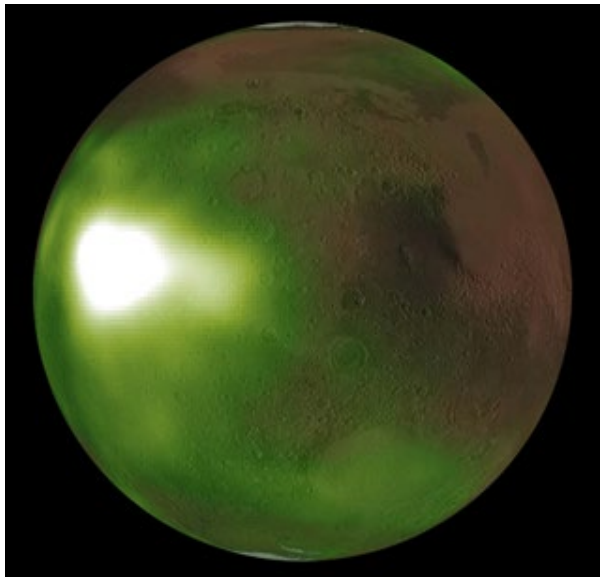


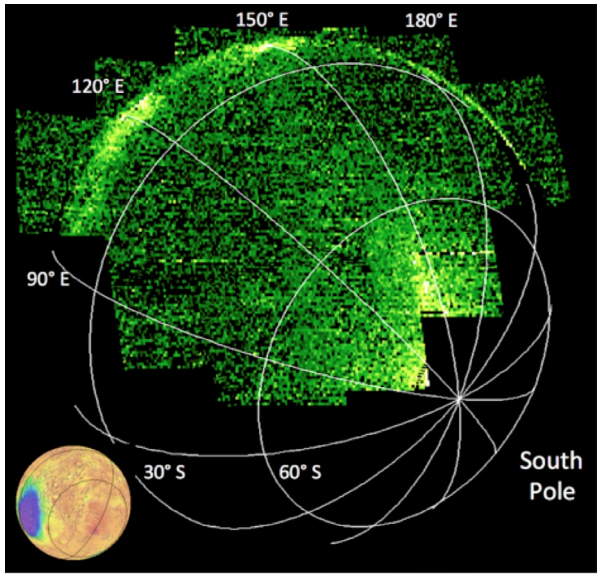
MAVEN /IUVS

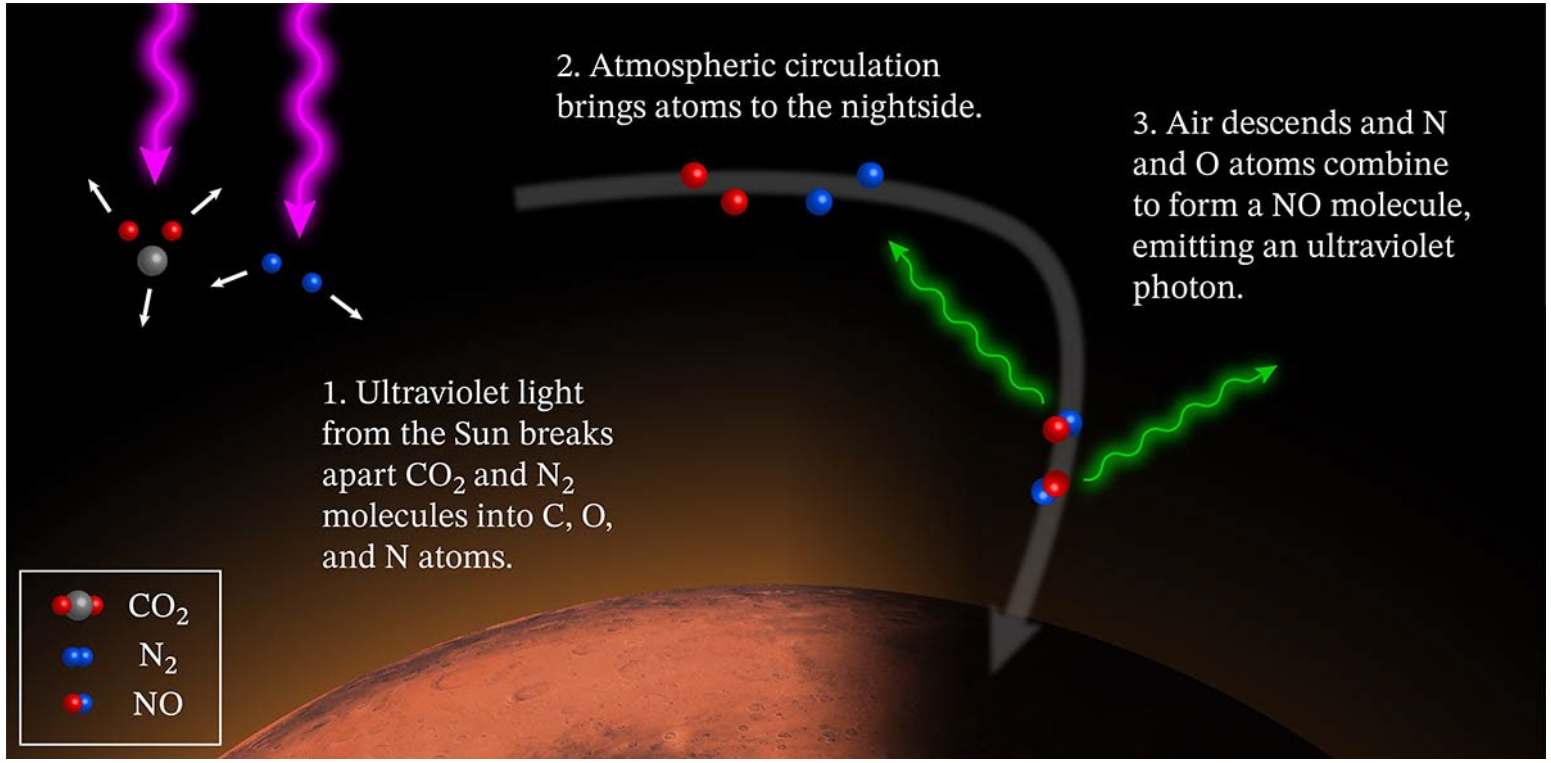
Mars: Nitric Oxide emission

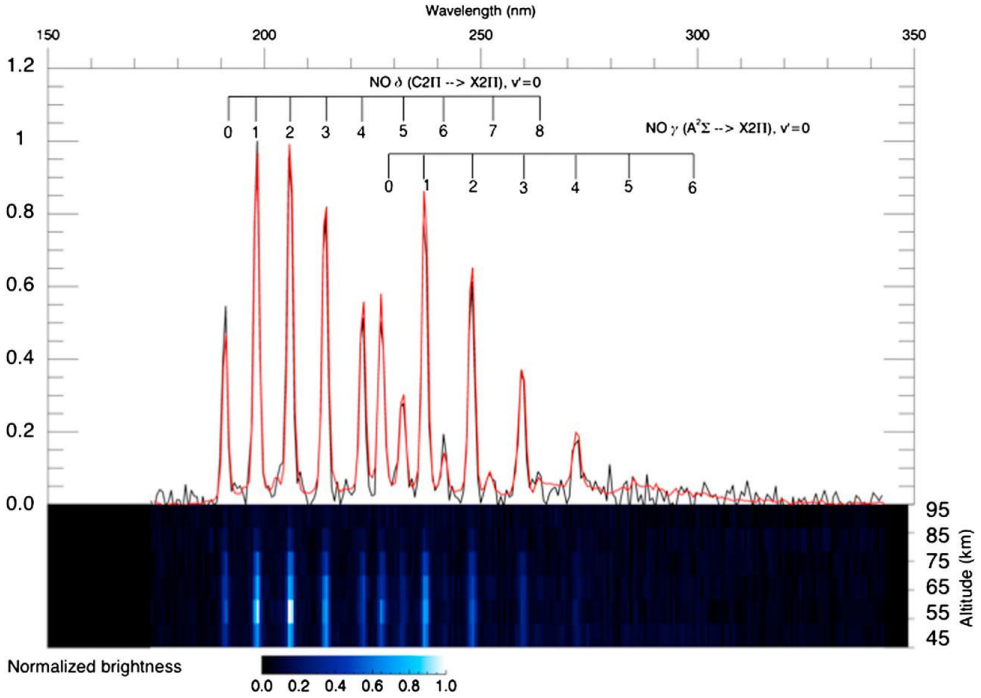
Nightglow
Nitric Oxide (NO) emission
190 - 270 nm bands

→Measure winds at high altitudes
(z = 40 to 115 km)





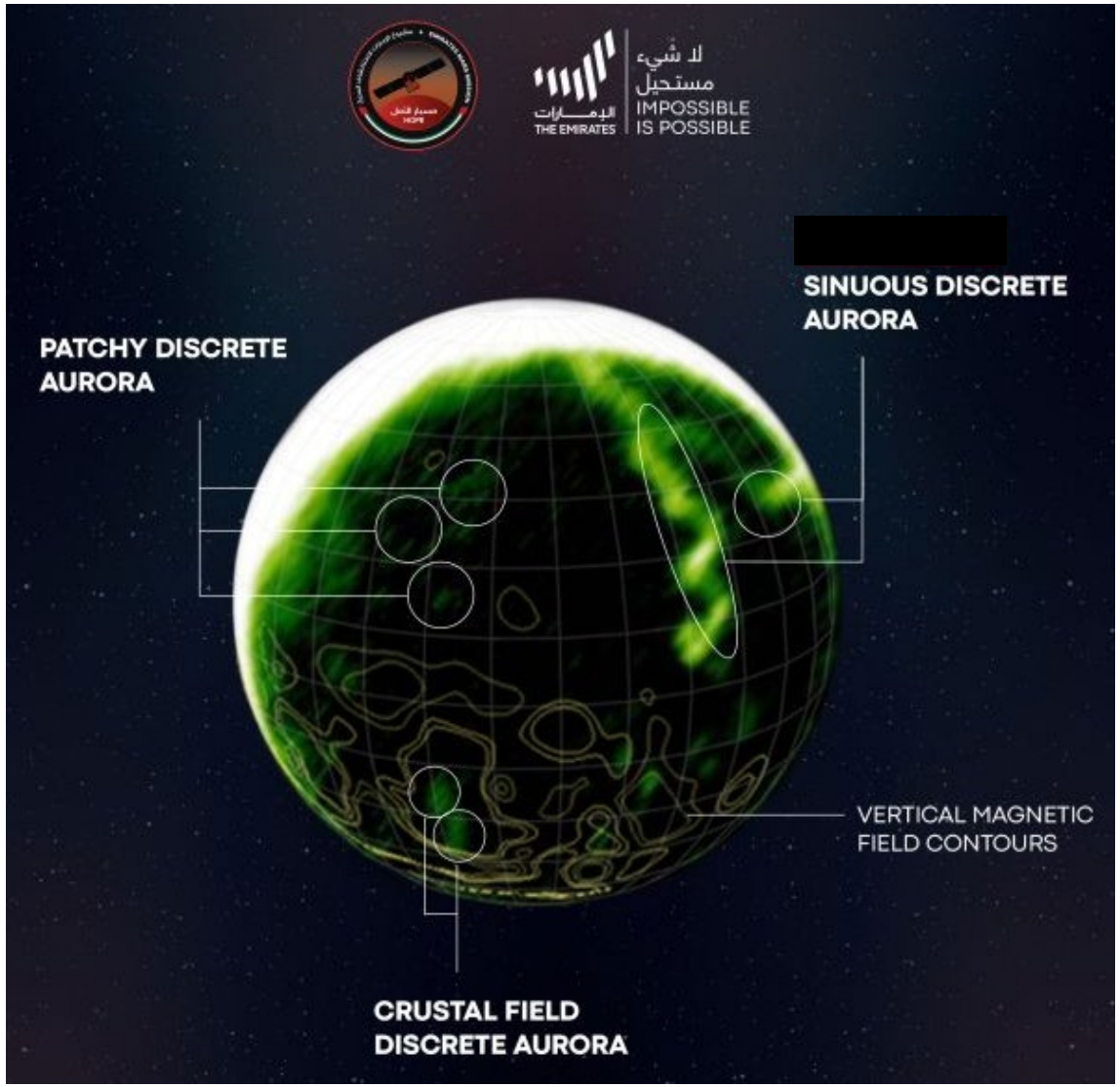


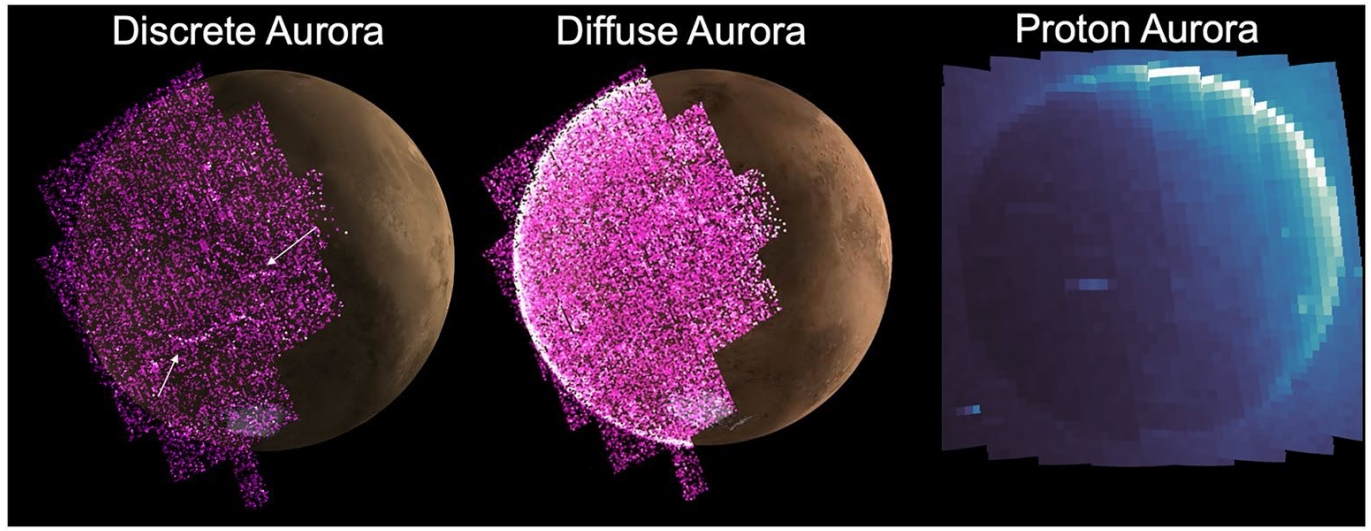


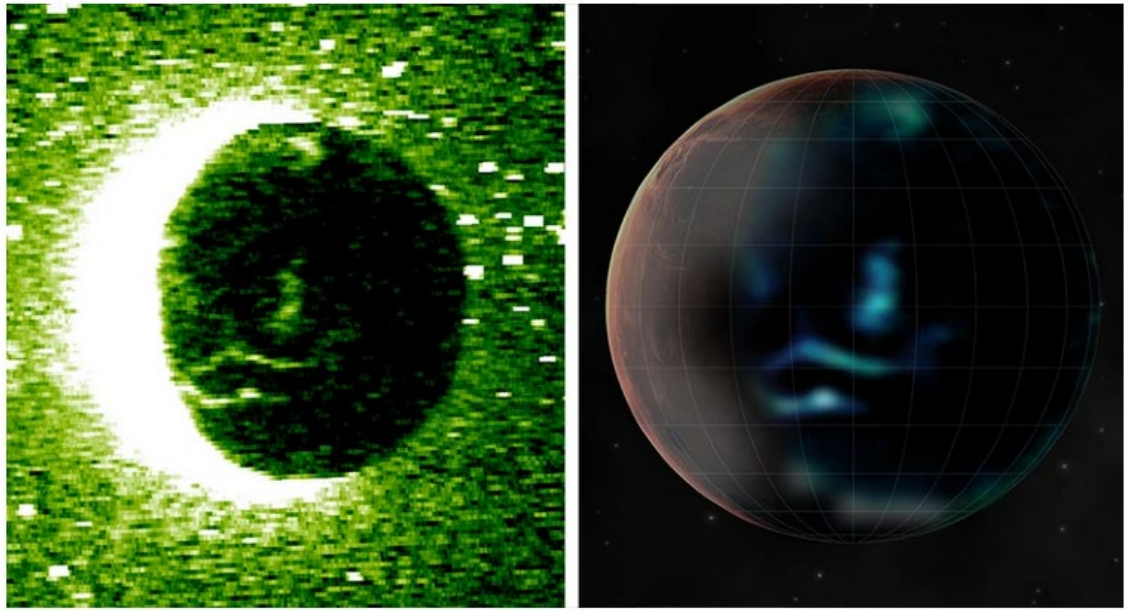
NASA/University of Colorado-LASP/MAVEN-IUVS

Stiepen et al., JGR, 2017

Mars: Aurora variety

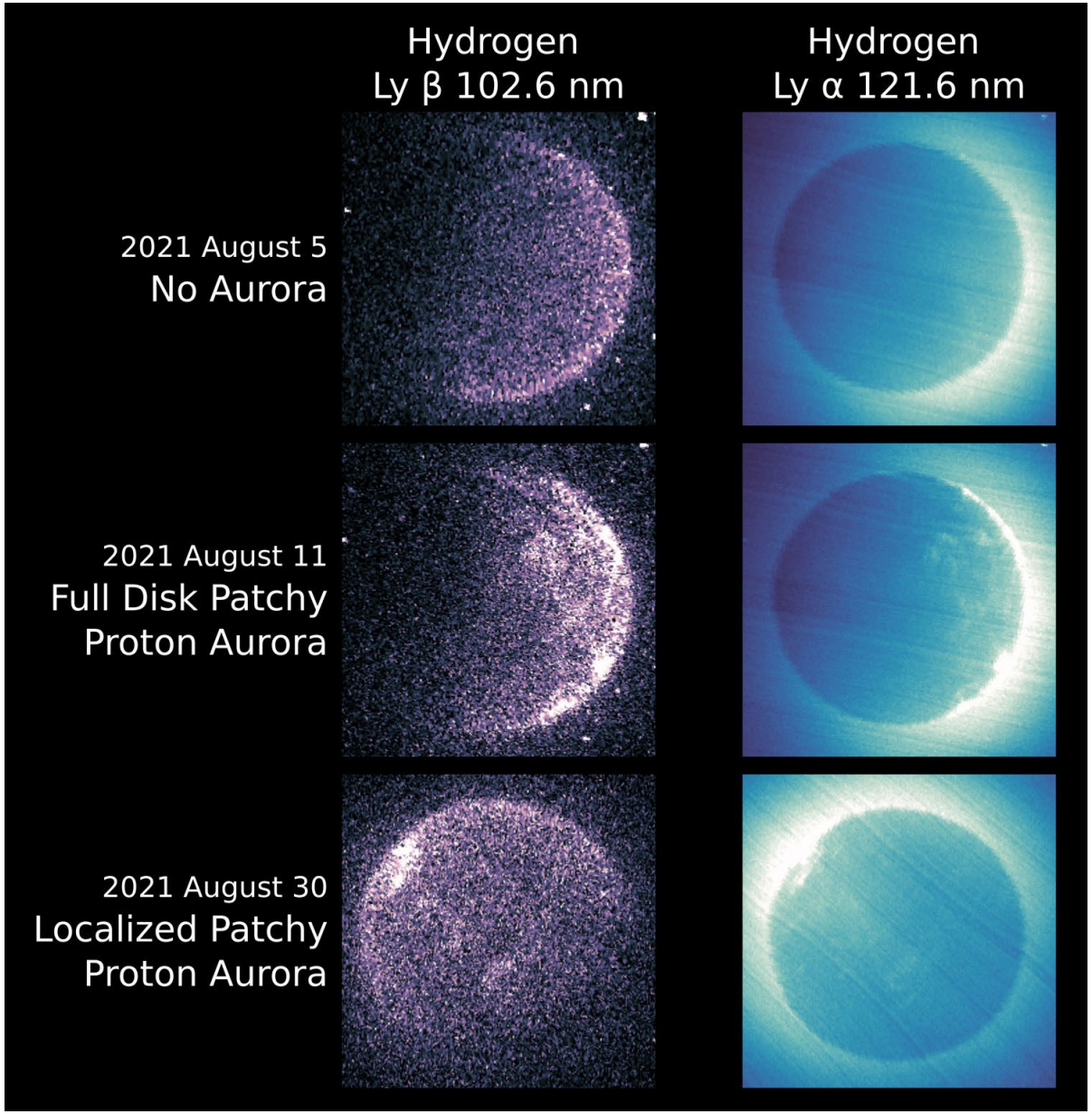






Images taken by Hope's onboard spectrometer (left-hand panel) and an artist's impression (right) show discrete auroras on Mars's night side. Credit: Emirates Mars Mission

Mars proton aurora

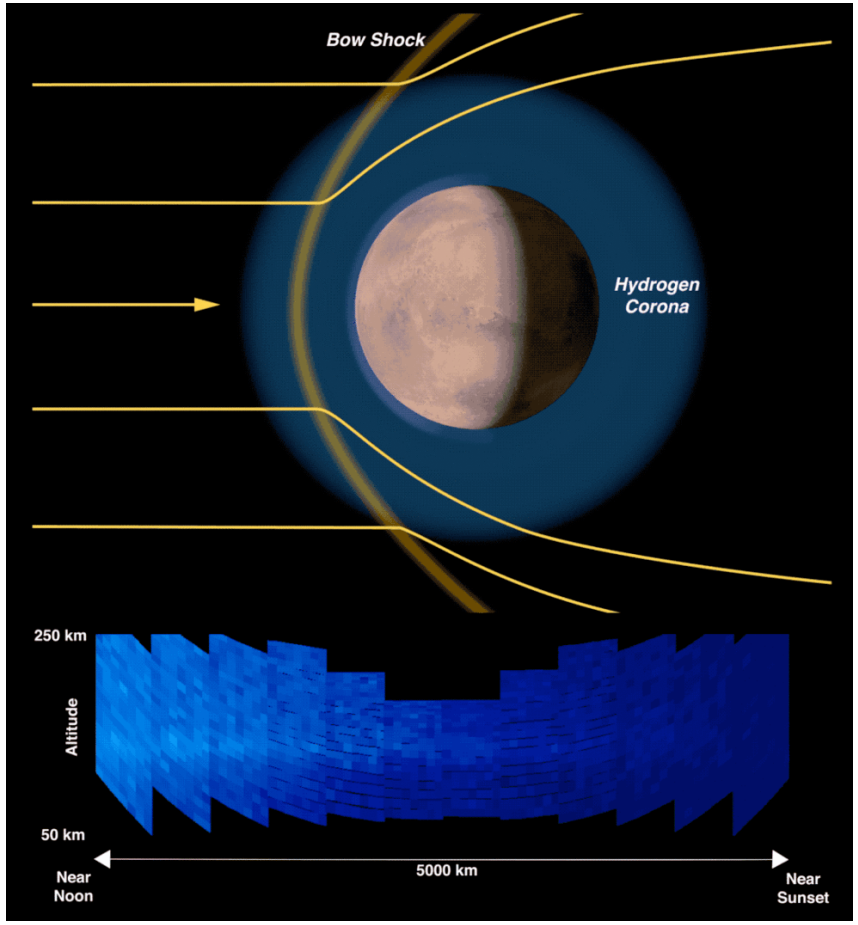


Al Amal (EMM/EMUS) – MAVEN/IUVS

PATCHY PROTON AURORA: H^+ emission

DIFFUSE PROTON AURORA: Charge-exchange H^+ rip e^- off atoms to form H → H emission

Altitudes = 110 – 130 km



Mars night-time crustal (localized) aurora

CO - CO_2 + O_2 emissions (190 – 297 nm)

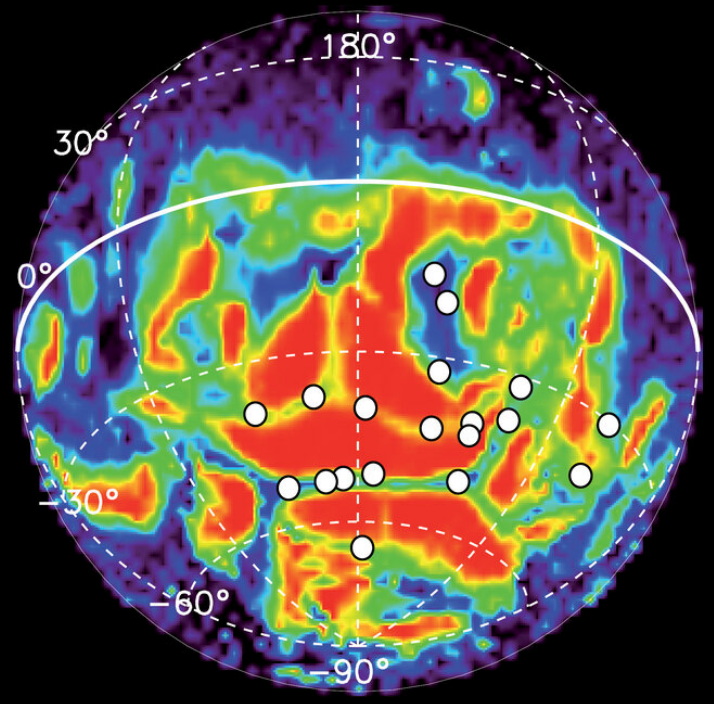
→ MARS' NIGHT–TIME AURORA

Using 10 years of data from Mars Express, scientists have for the first time combined all remote sensing observations of localised ultraviolet aurora with in situ measurements of electrons hitting the atmosphere, finding these rare light emissions only occur under special magnetic field conditions.

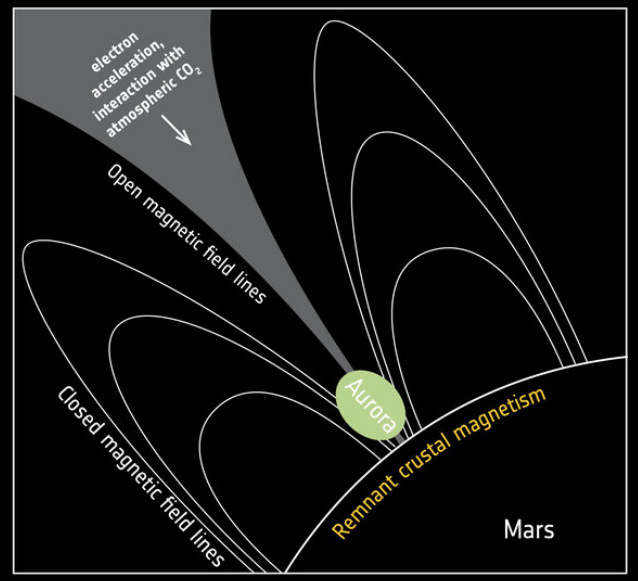
Locations of the 19 auroral detections (white circles) by SPICAM on the Mars nightside in the southern hemisphere, over locations already known to be associated with residual crustal magnetism (centre). The data are superimposed on the magnetic field line structure (from NASA's Mars Global Surveyor), where red indicates closed magnetic field lines, grading through yellow, green and blue to open field lines in purple.

The auroral emissions are very short–lived, they are not seen to repeat in the same locations, and only occur near the boundary between open and closed magnetic field lines (also visualised top right).

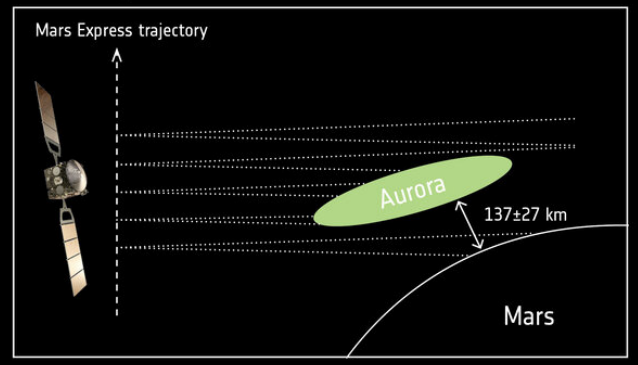
SPICAM limb observations enabled the altitude of some of the auroral events to be determined as 137±27 km (bottom right).



→ Magnetic field structure near Mars aurora



→ Measuring aurora altitude



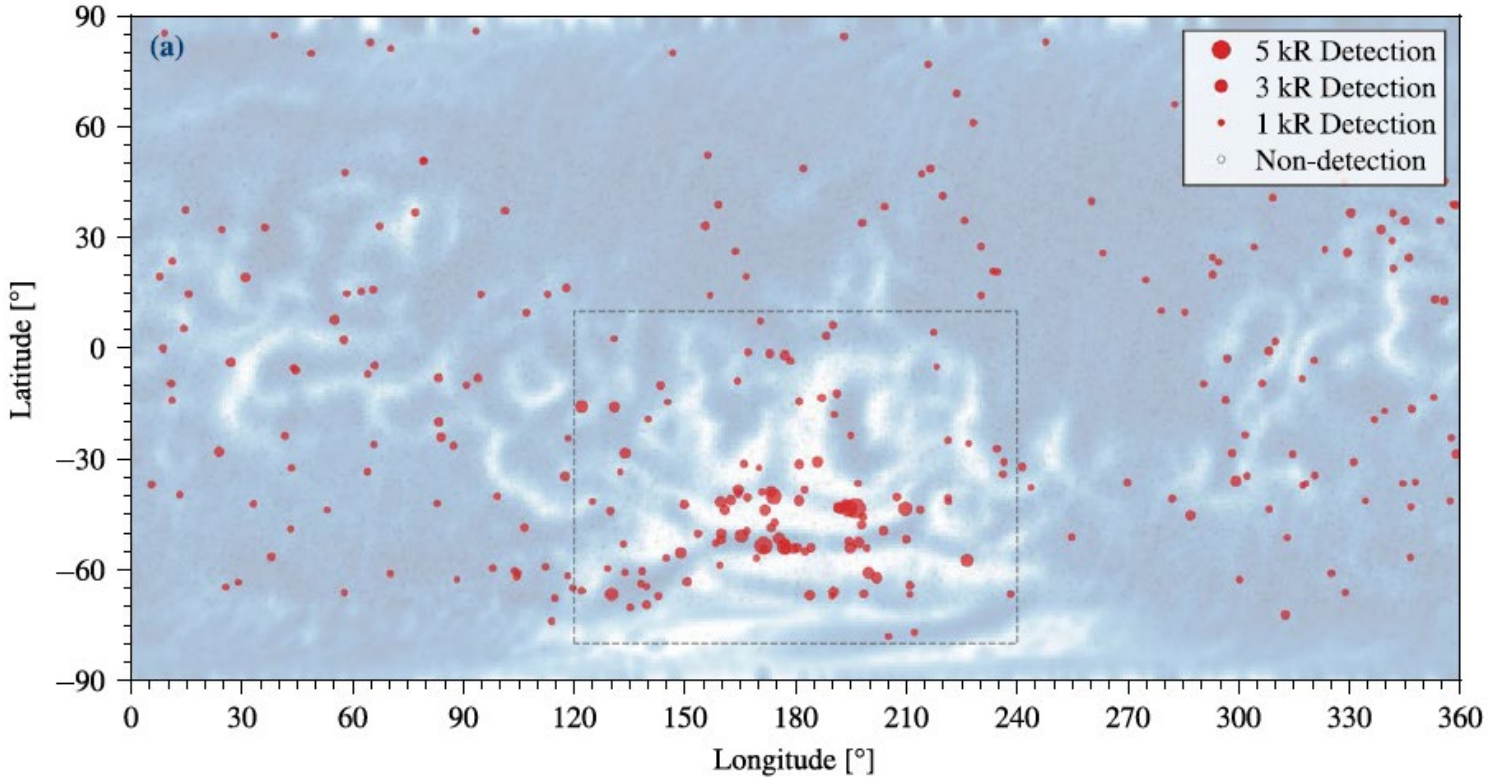
www.esa.int

ESA/ATG medialab, J.-C. Gérard & L. Soret (2015)

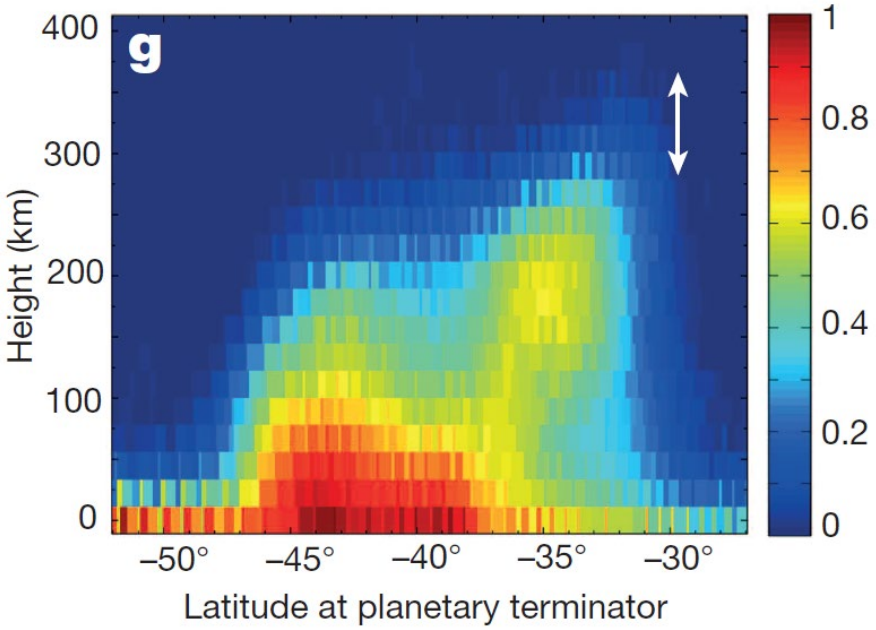
European Space Agency

Mars night-time crustal (localized) aurora

CO - CO_2 + O_2 emissions (190 – 297 nm)



Schneider et al., JGR (2021)

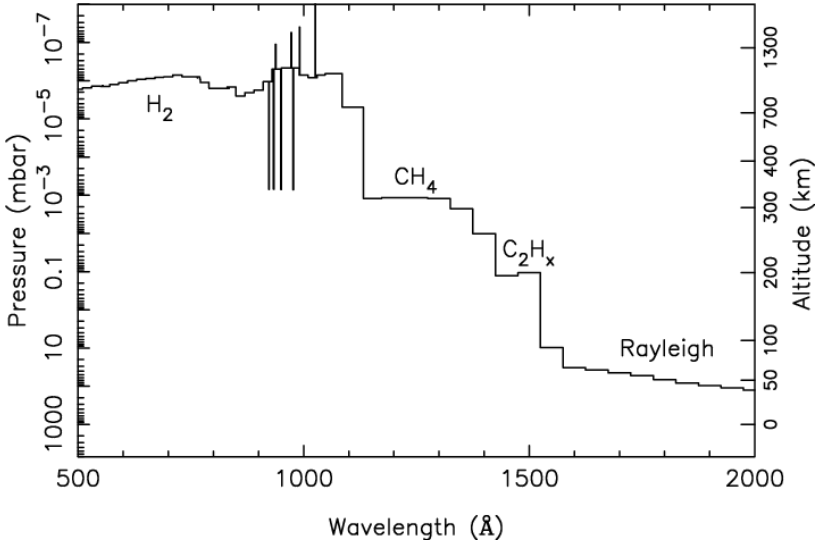


High altitude “plume “ on Mars in 2012
Over magnetic anomaly
Relation to aurora phenomena?

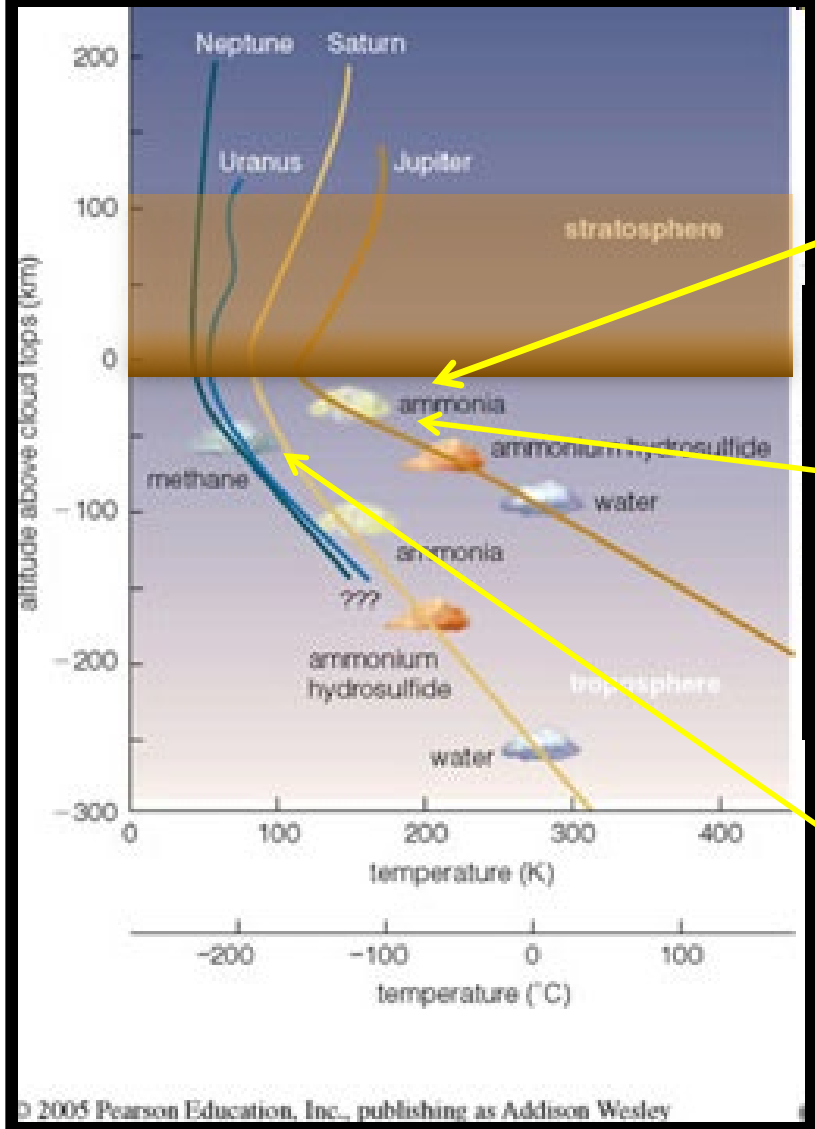
Sánchez-Lavega et al., Nature (2015)

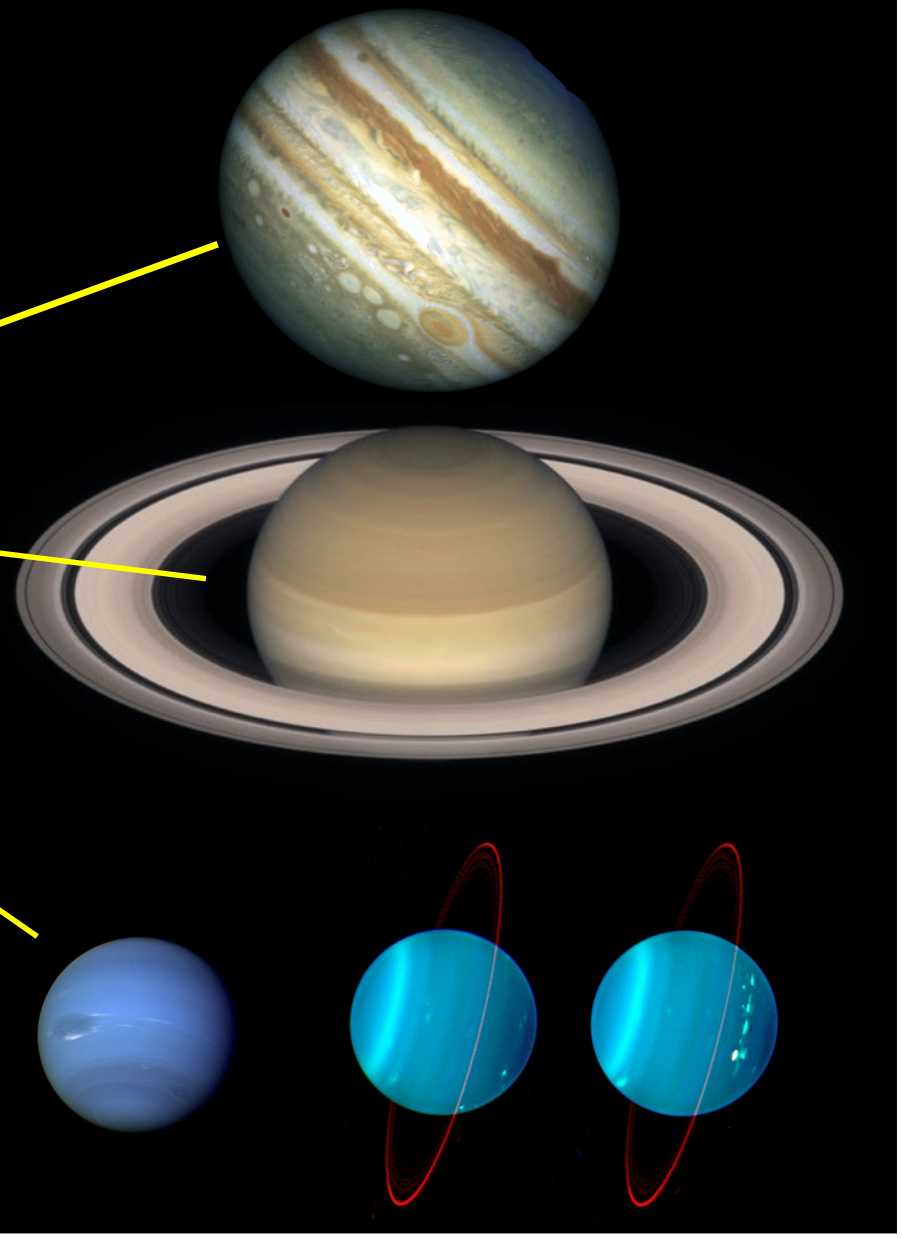
Giant and icy planets visible atmospheres

UV radiatin penetration
in the giant and icy planets



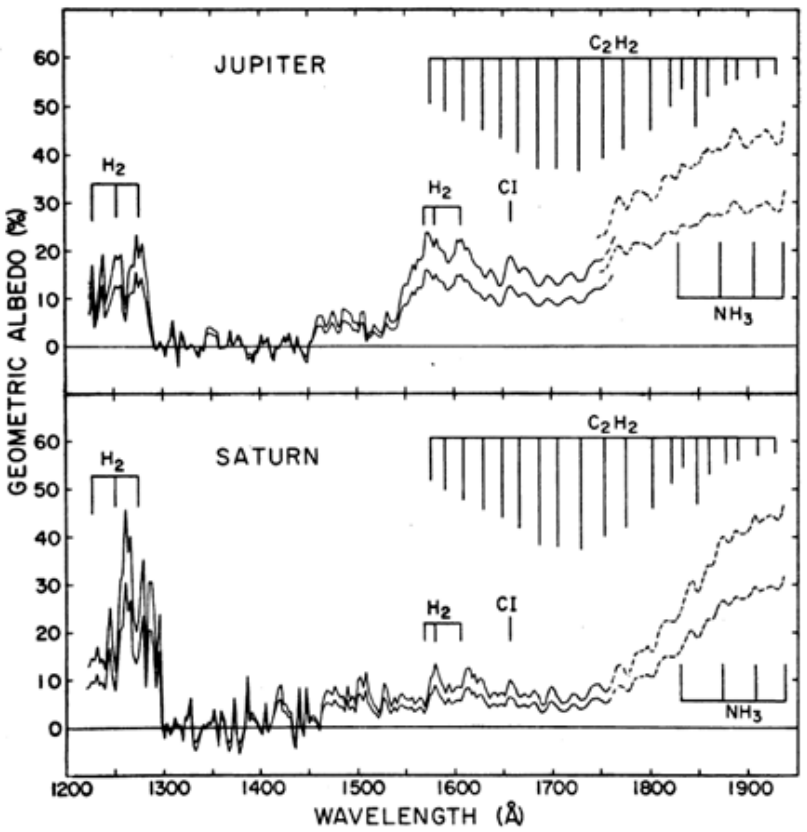
Visible upper cloud P ~ 1 bar
Tropopause P~ 0.1 bar





Reflected spectra giant and icy planets, and Titan

UV absorbing-emitting gases
120 - 195 nm

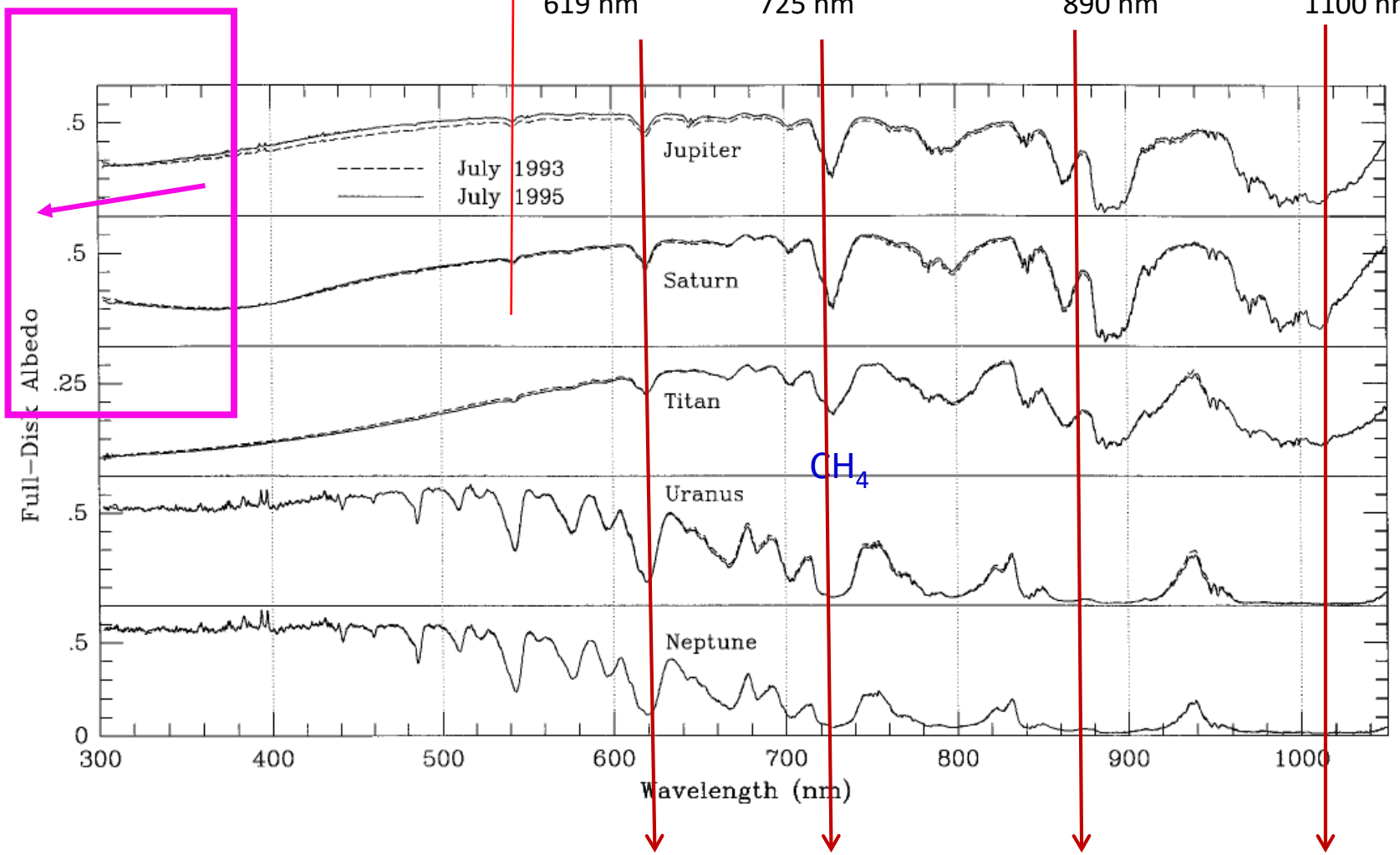


Unknown
UV absorbing
aerosols

NH_3

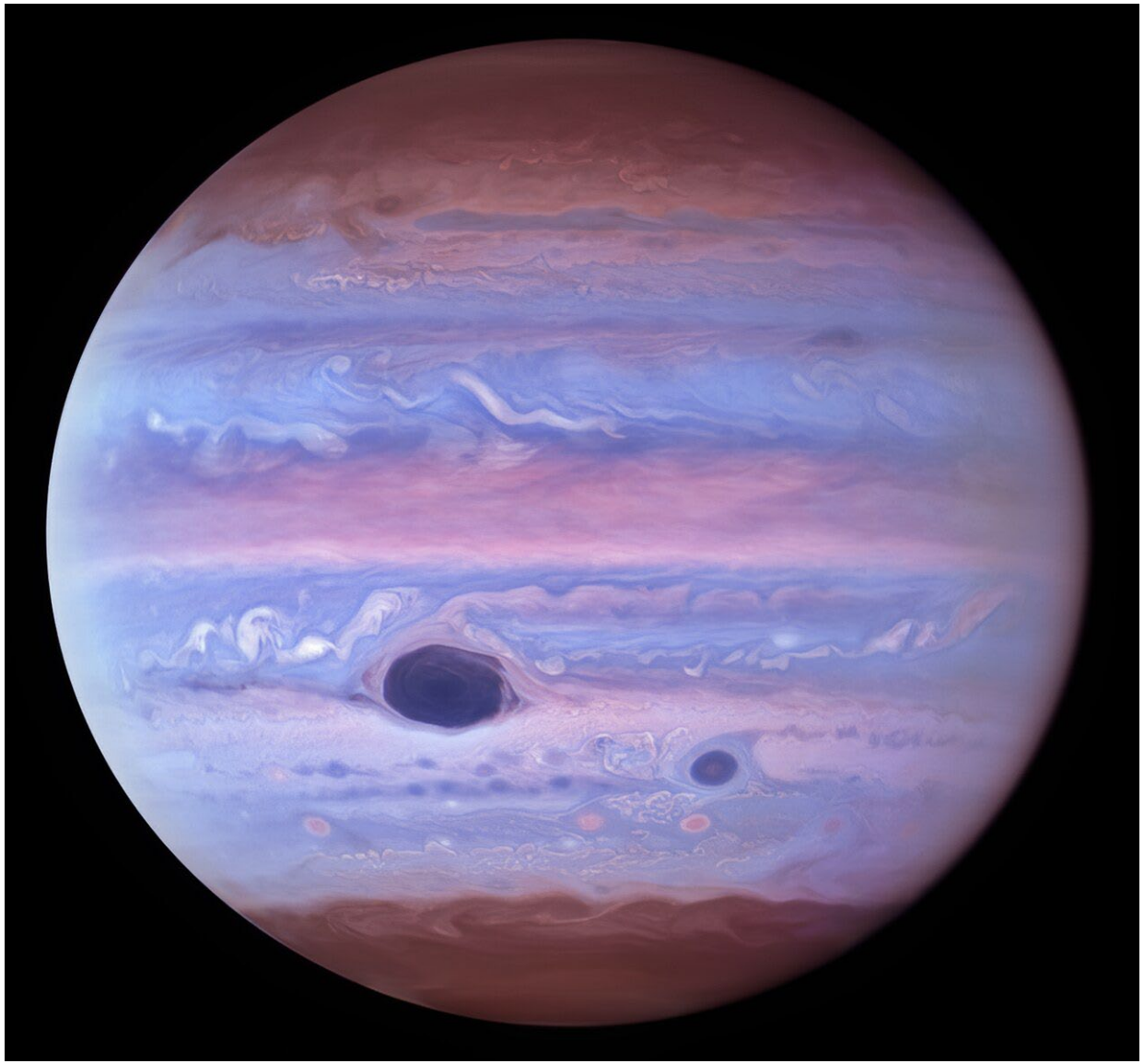
CH_4 absorption bands

619 nm
725 nm
890 nm
1100 nm



Jupiter dark aerosols in UV

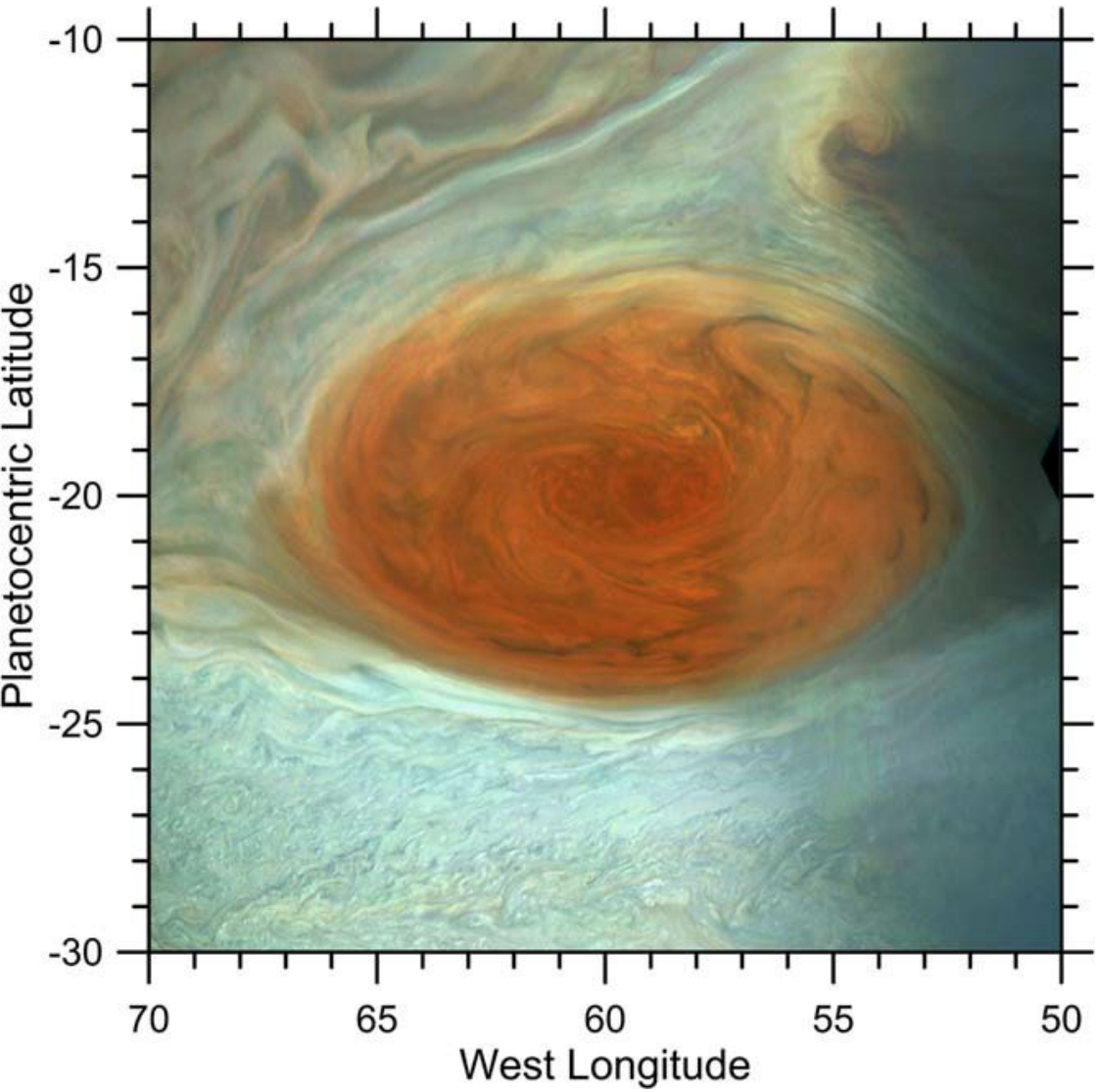
UV absorbing aerosols concentrated in the GRS, BA and poles

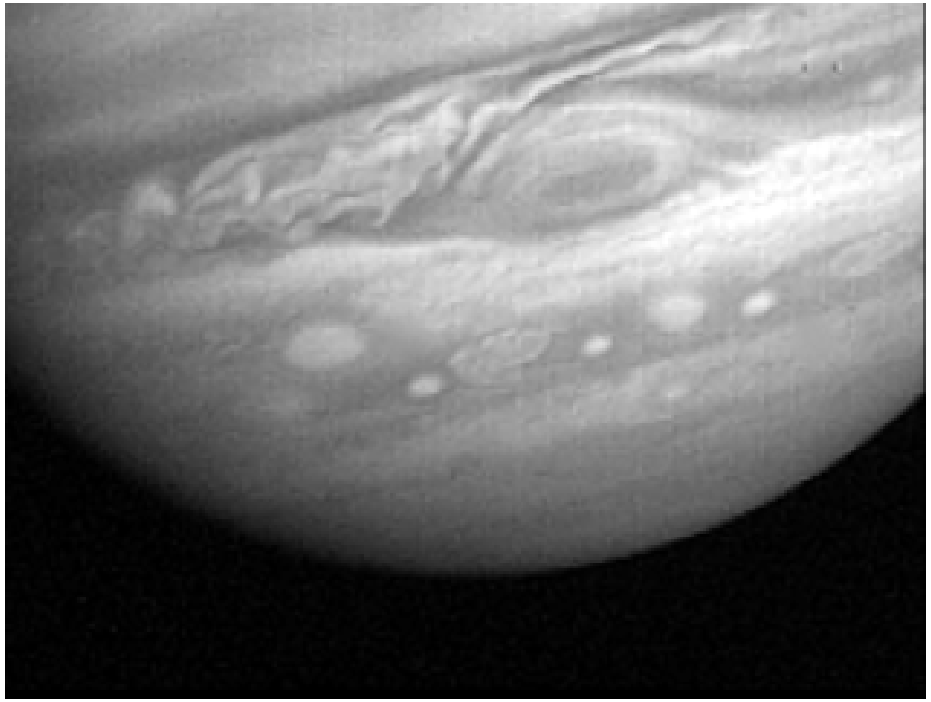


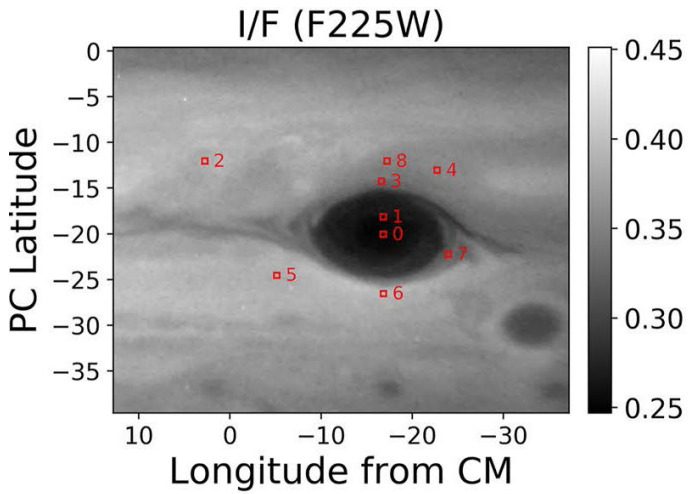
SL 9 impacts in July 1994
UV absorbing debris

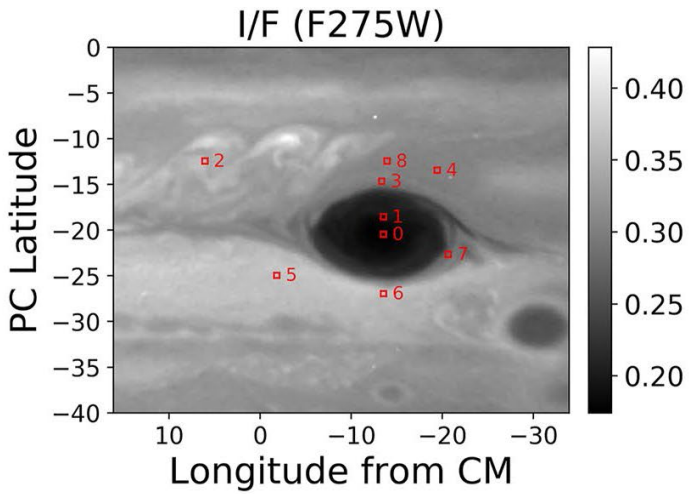
Jupiter's Great Red Spot

Anticyclone ~ 15,000 km , V_{rot} ~ 120 ms^{-1}





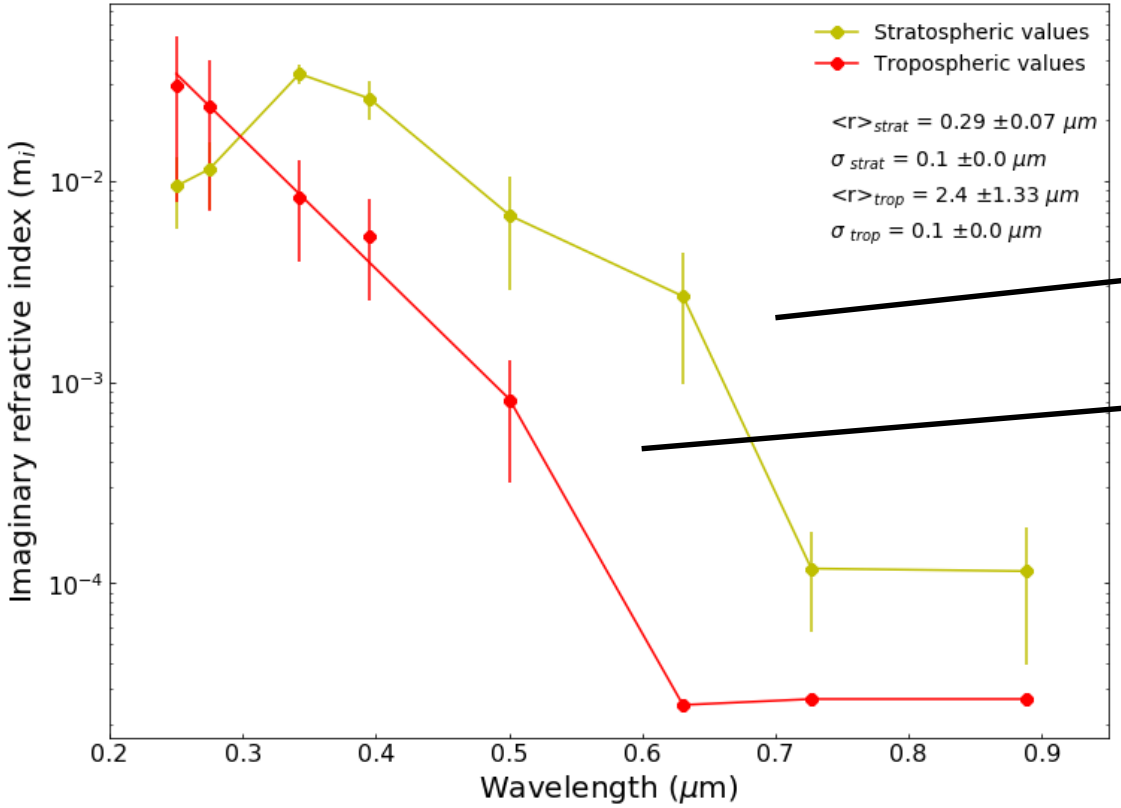


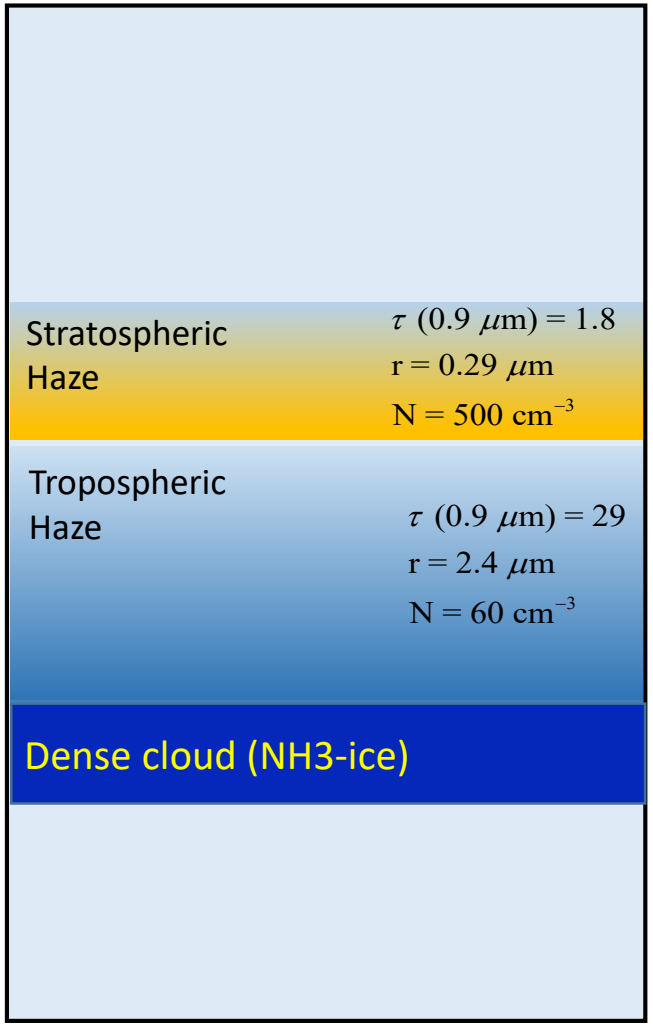


Sánchez-Lavega et al., Astron J. (2018)

Jupiter's Great Red Spot chromophores

Radiative transfer models
→ aerosol absorption (refractive imaginary index





Anguiano-Arteaga et al., JGR (2021)

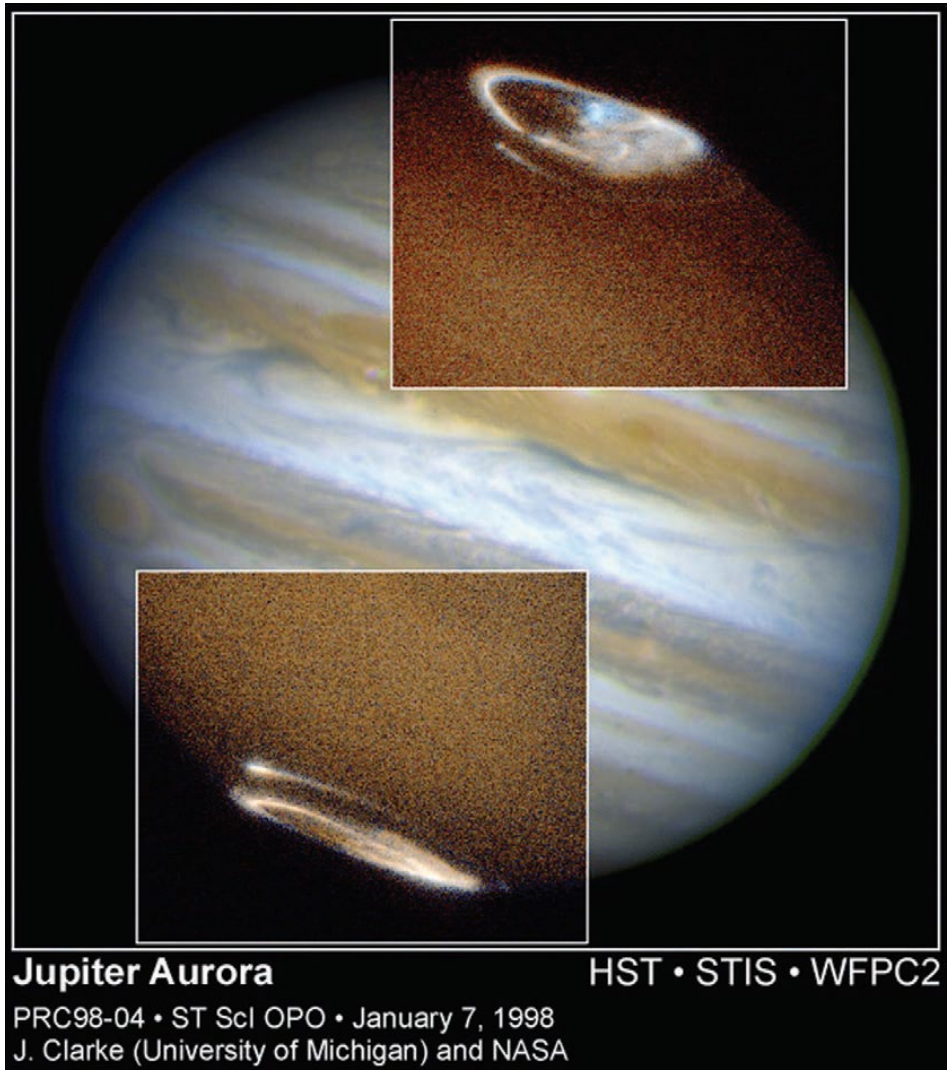
Laboratory experiments:
Aerosols (radius 0.25-µm) formed when acetylene reacts with photolytic products of ammonia produced by ~ 0.2-µm UV radiation
(Carlson et al., Icarus, 2016

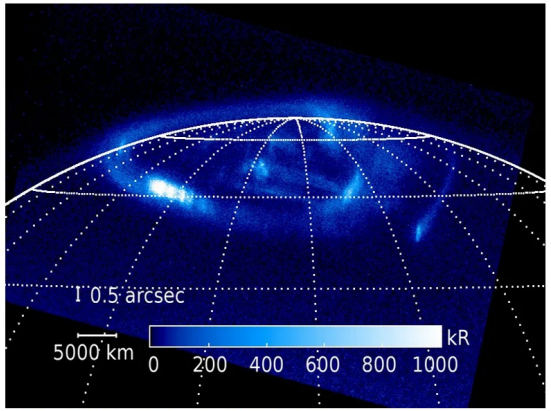
Jupiter's auroras

FUV auroral images (130 – 160 nm)

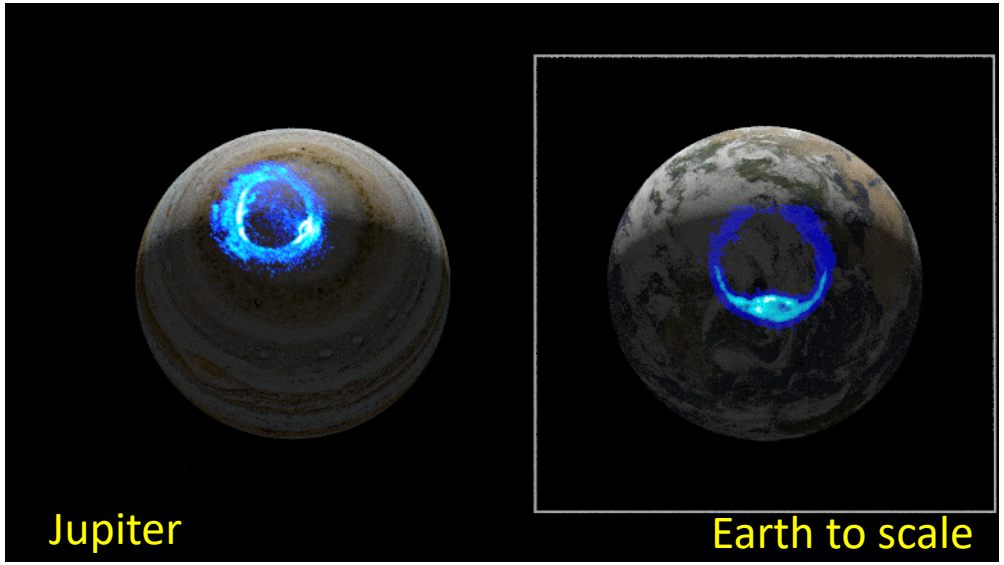
H_2 Lyman and Werner band series band emissions, H Lyman α line (H-Lyα)

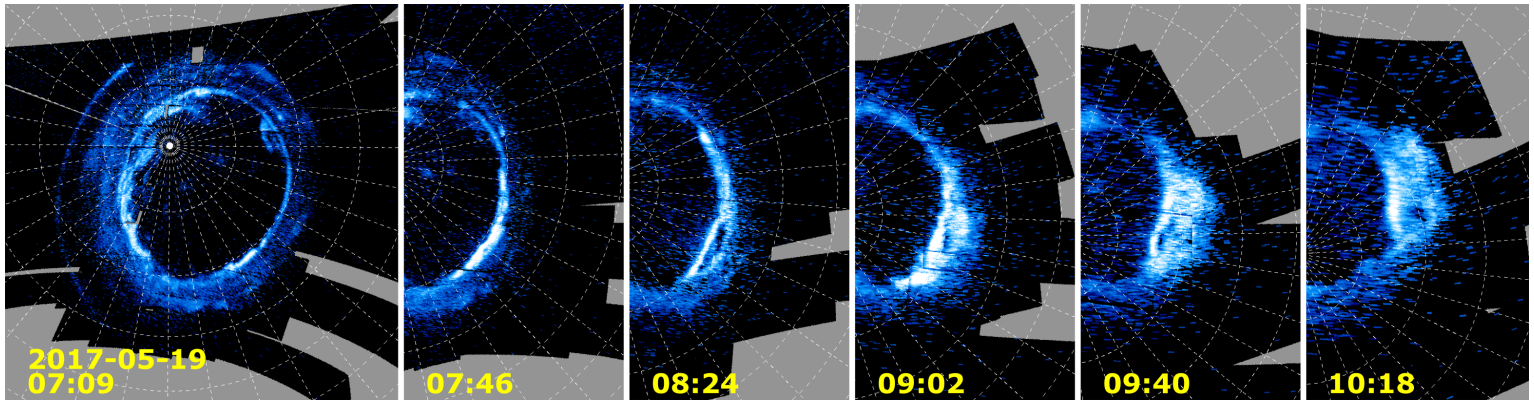
Oval altitudes above tropopause (0.1 bar):
Z = 50 km altitude (0.1 bar pressure) at 210 nm
Z =300 - 400 km (1 to 10 pbar) at < 145 nm





A Hubble image depicting Jupiter's ultraviolet aurora at the planet's north pole. Credit: Adapted from Gérard et al.



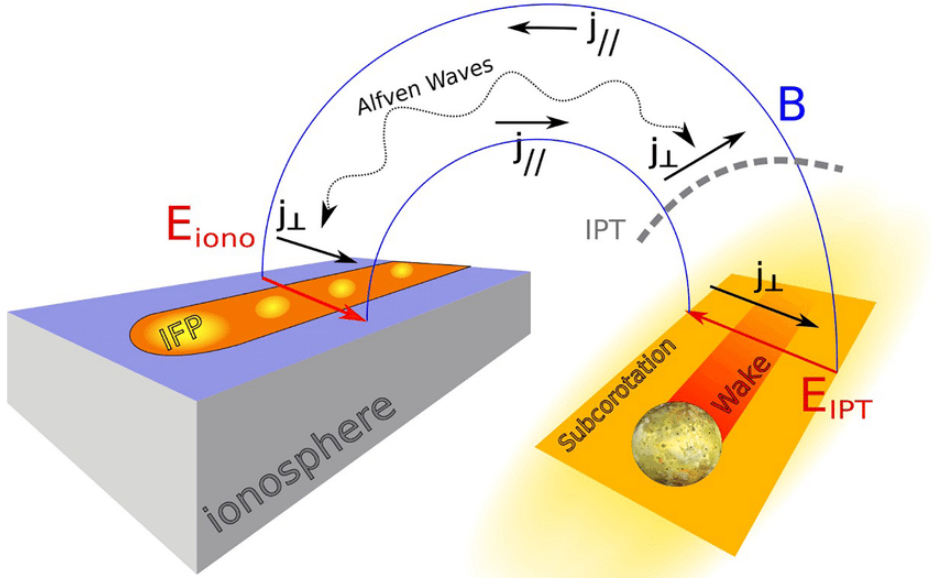


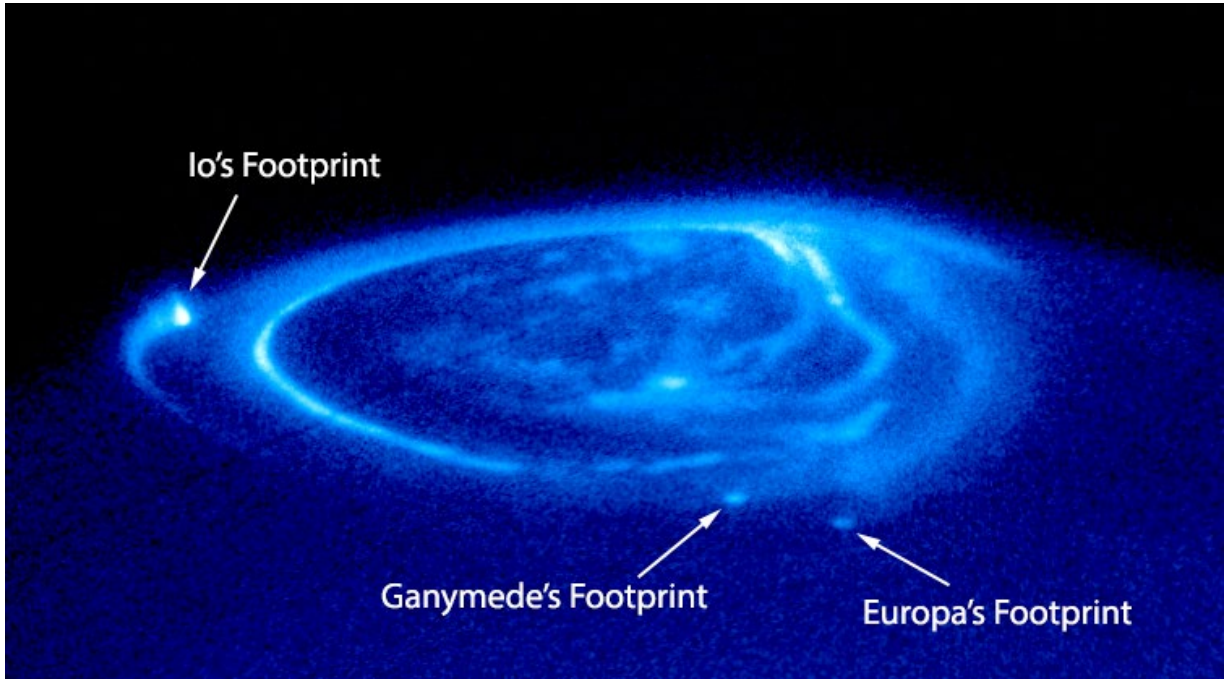
Juno/UVS

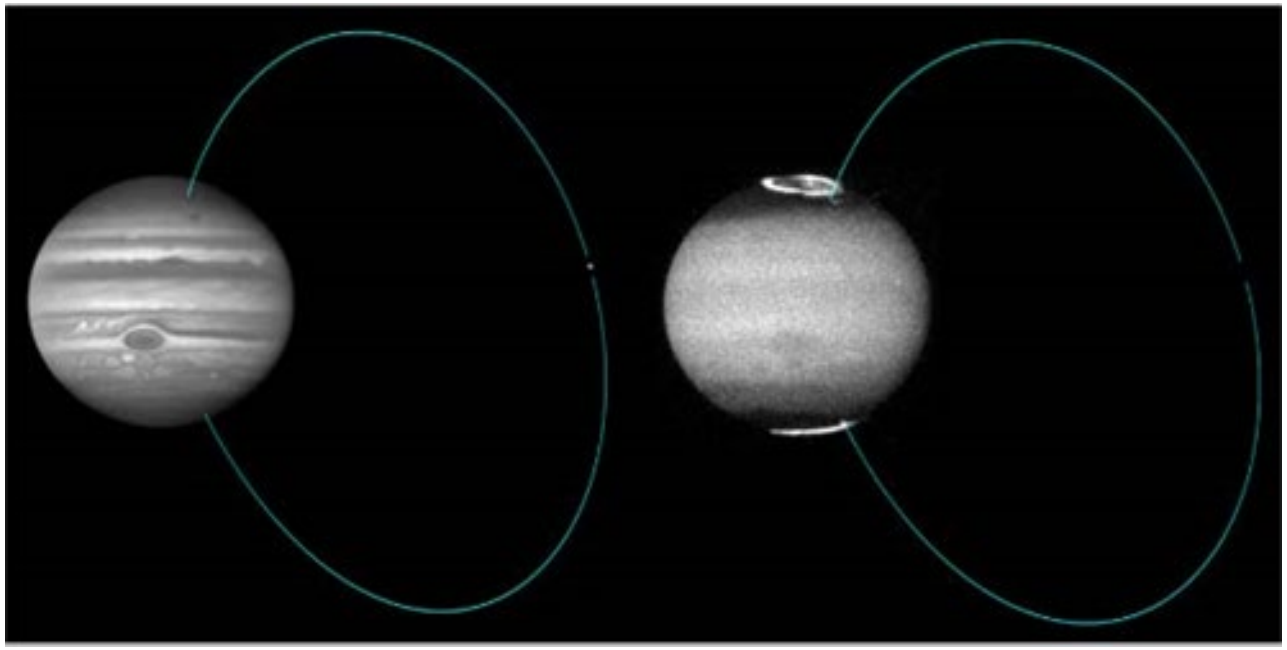
Jupiter’s oval aurora and satellites “footprints”

The IFT "footprint" produced by electron currents in and out of Jupiter's upper atmosphere

* Io is electrically conducting by virtue of its ionosphere
* Power ~ 10^{11} W
* Io plasma flow (electrons) = 3×10^{6} Amper







Io, Europa and Ganymedes emissions

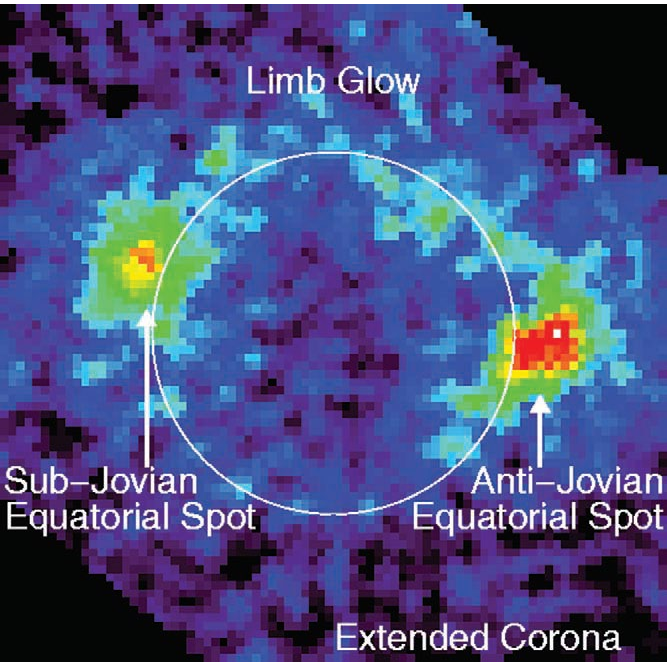
Io at 135.6 nm (*HST* STIS)
Atmosphere-volcanos

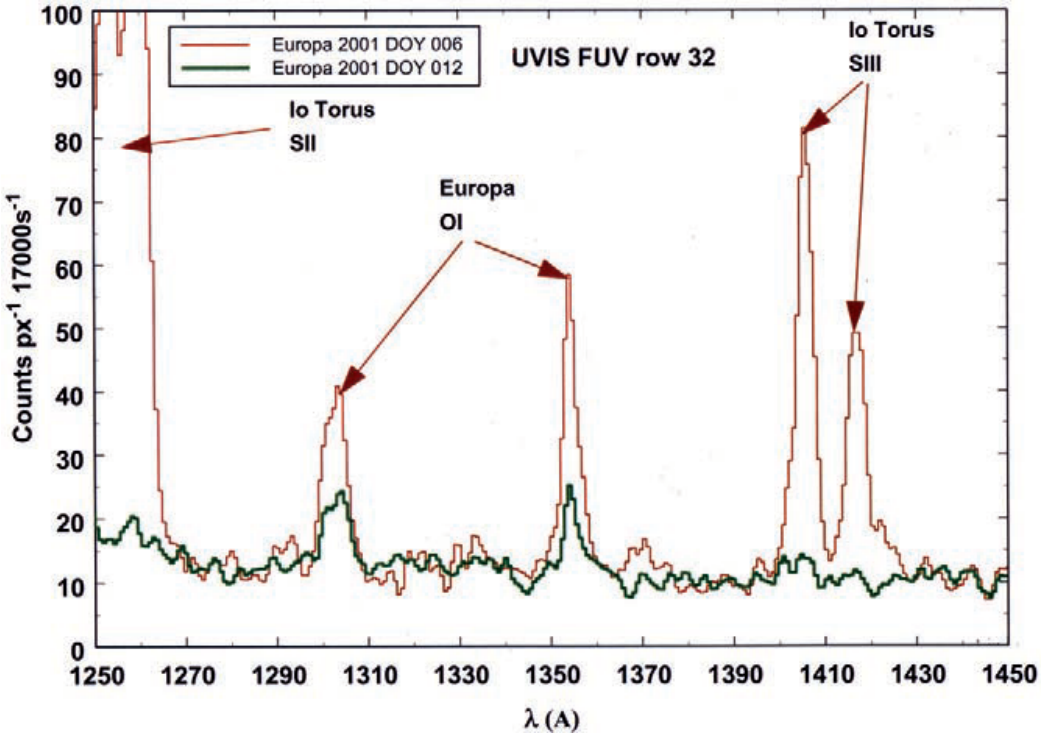
Equatorial “spots”:
electrons flowing along the Io flux tubes with Io’s SO_2 atmosphere

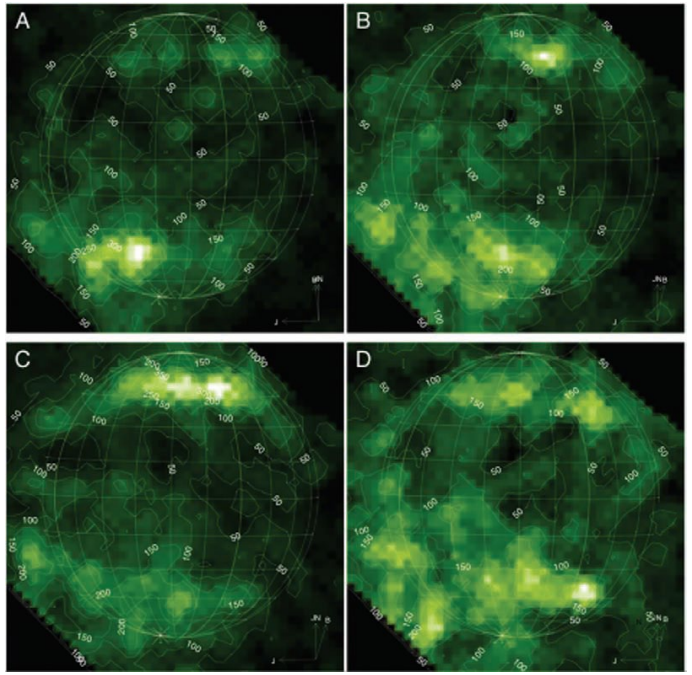
FUV spectrum of Europa (*Cassini* UVIS)
Europa: plumes and atmosphere
Neutral oxygen emissions at **130.4** and **135.6 nm**
OI features due to electron dissociation and excitation of a tenuous O_2 atmosphere

Io torus emission from ionized sulfur.

Ganymede’s UV aurora.
(*HST* STIS)
Atmosphere
Magnetic field
Neutral oxygen at **135.6 nm**







Saturn UV aerosol absorption

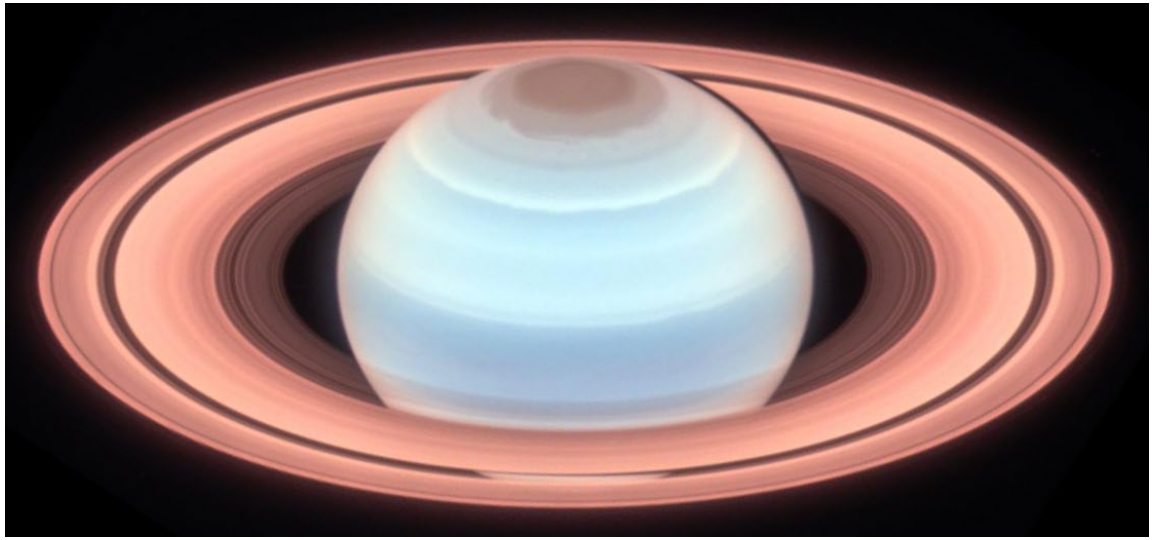
* Stratospheric aerosols P < 0.1 bar
  Thin particles sizes < 1 μm

* Rayleigh scattering

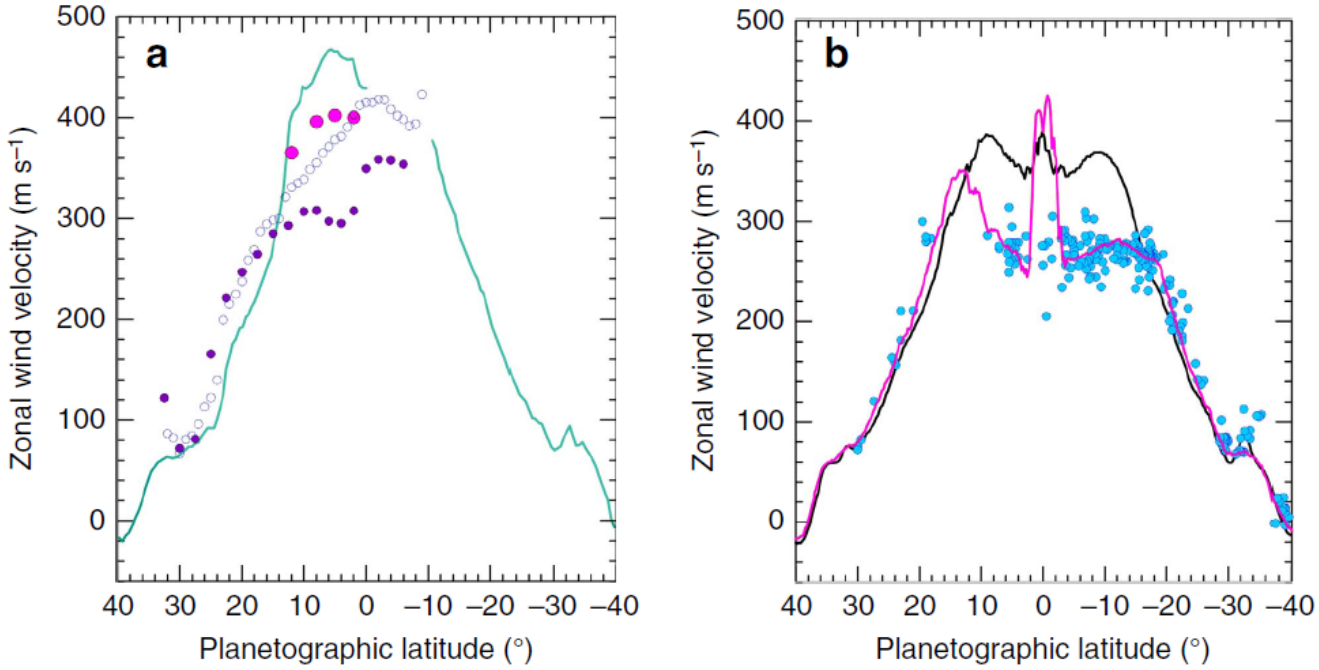
* Higher concentration in the Equatorial Zone

Aerosols UV absorbers → tracers of motions

Altitude and temporal dependence of the Equatorial Jet



HST WFPC2/ACS; wavelengths 225 - 345 nm

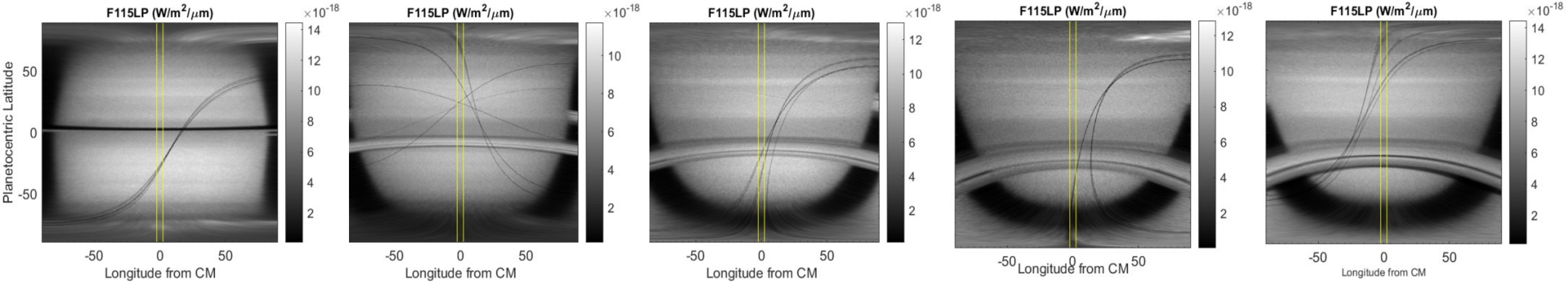


Sánchez-Lavega et al., Nat. Comm. (2021)

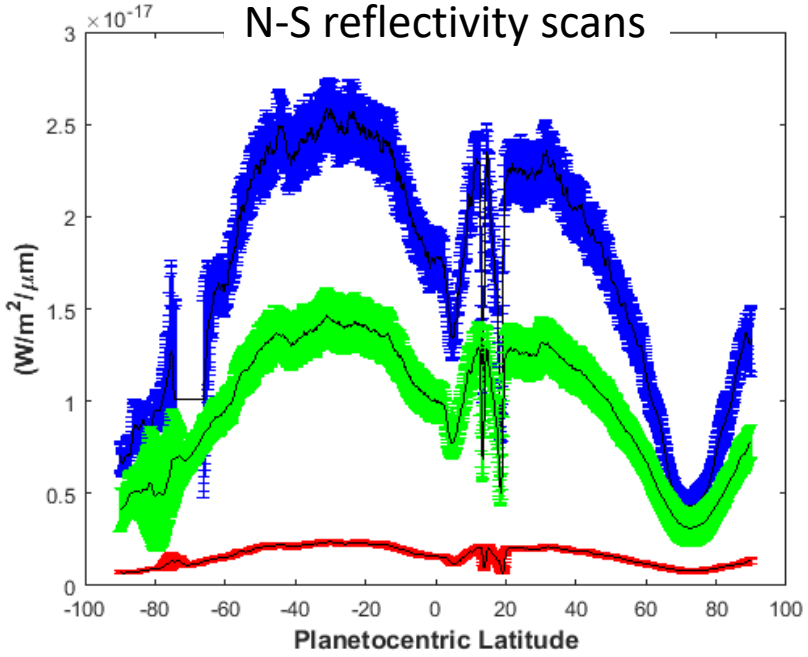
Saturn aerosol-compounds long-term changes

Years: 2009 – 2013 (HST - wavelengths: 115 nm – 125 nm – 140 nm)

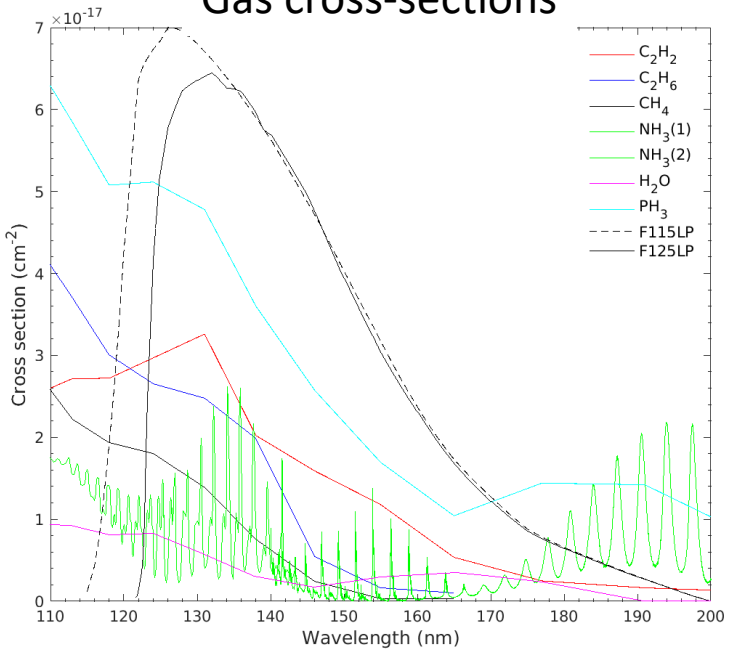
Aerosol and gas absorptions

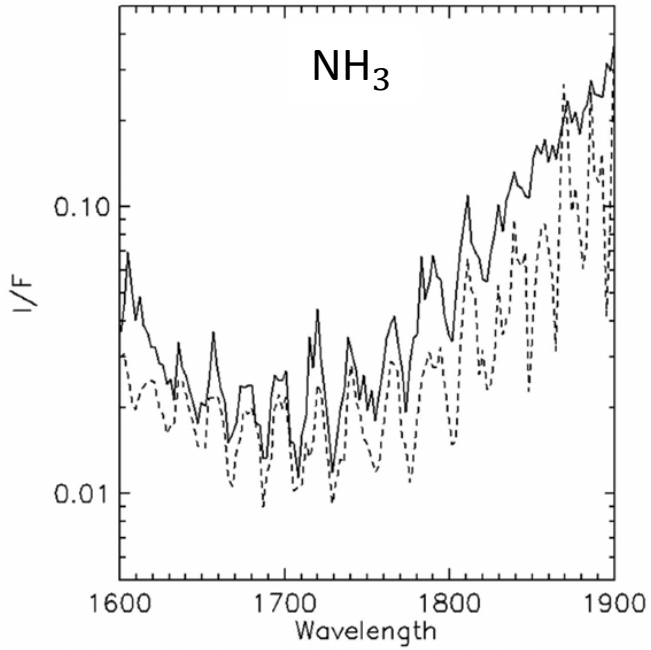


N-S reflectivity scans



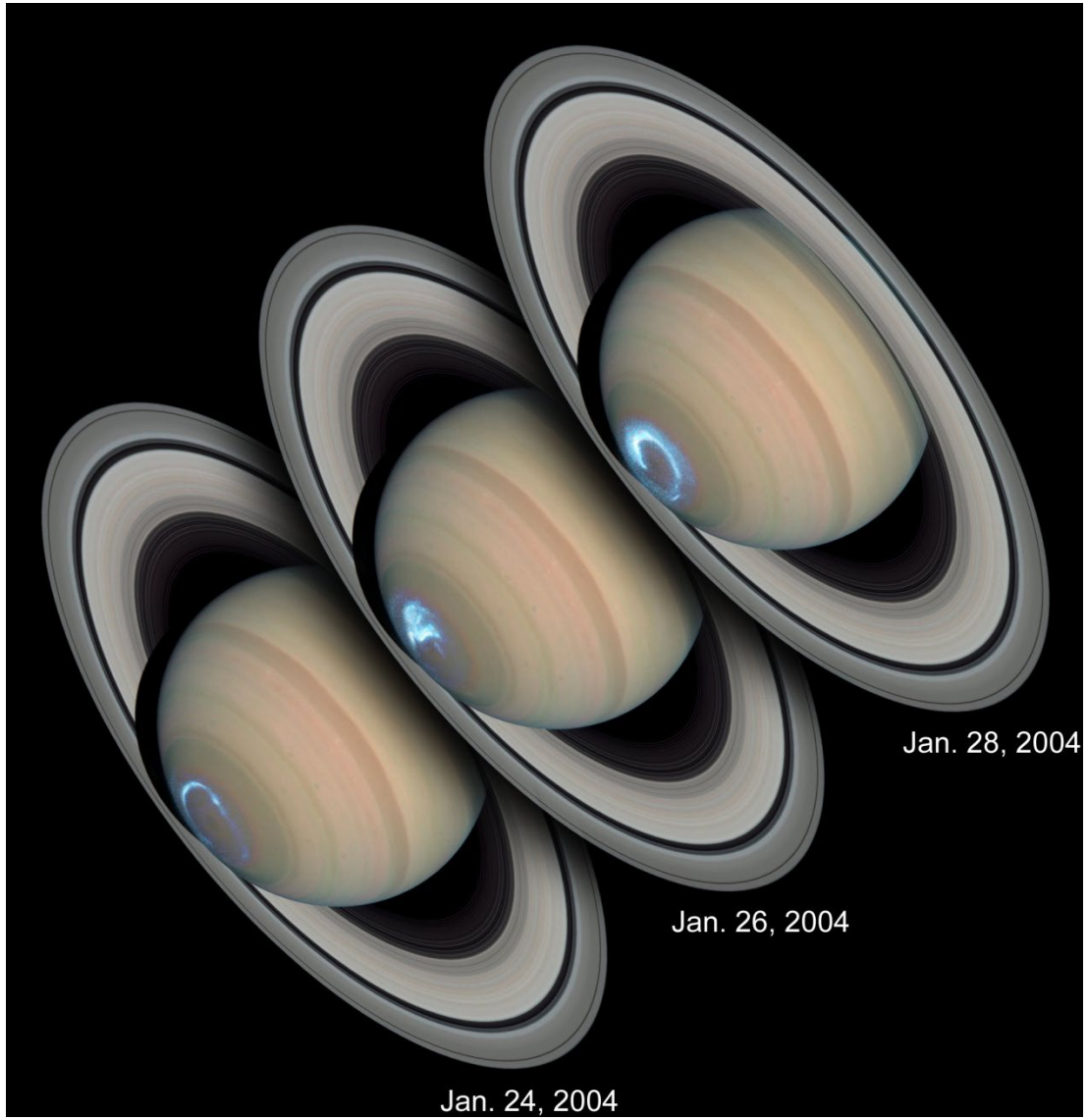
Gas cross-sections

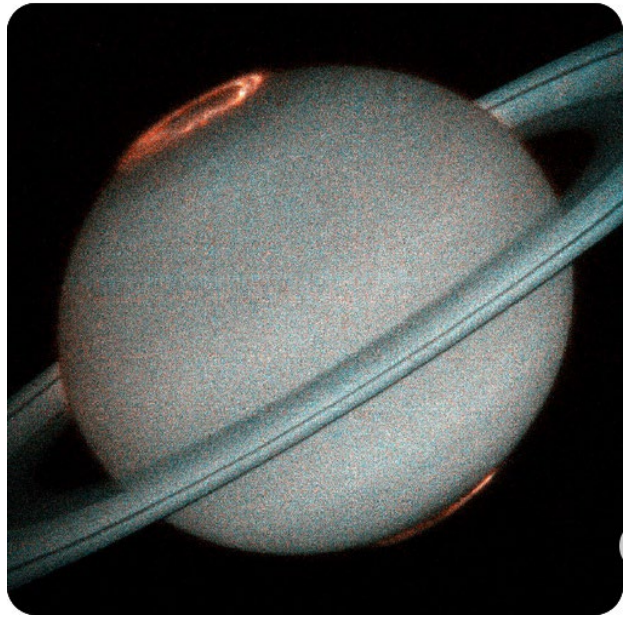


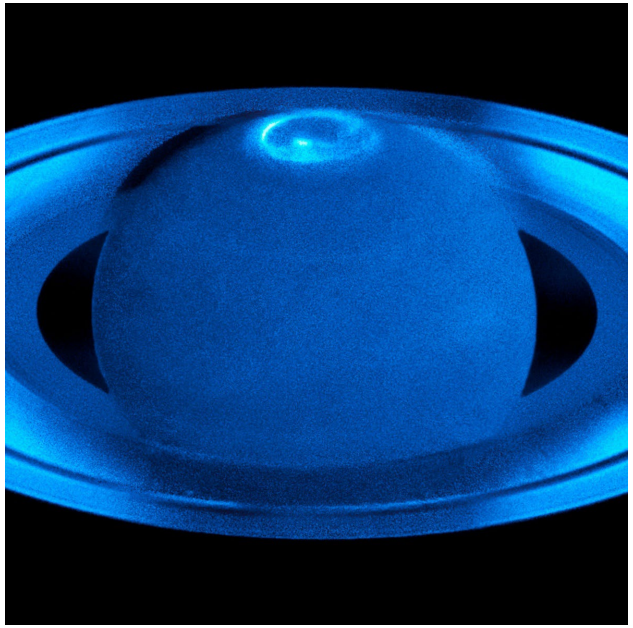


Saturn's aurora

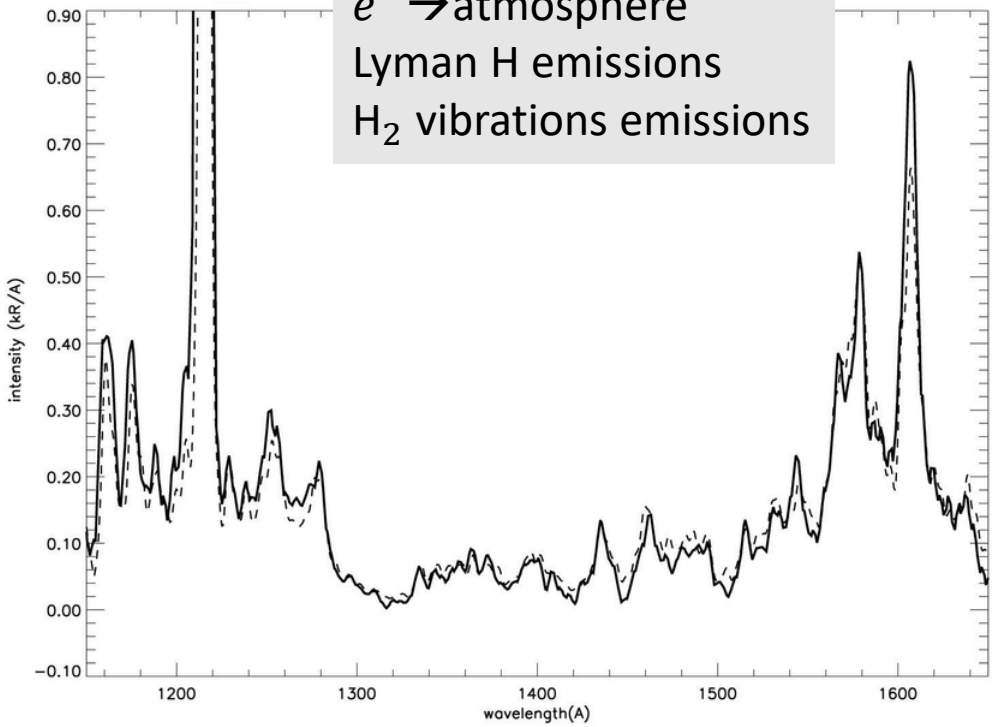
FUV: 80 nm – 190 nm





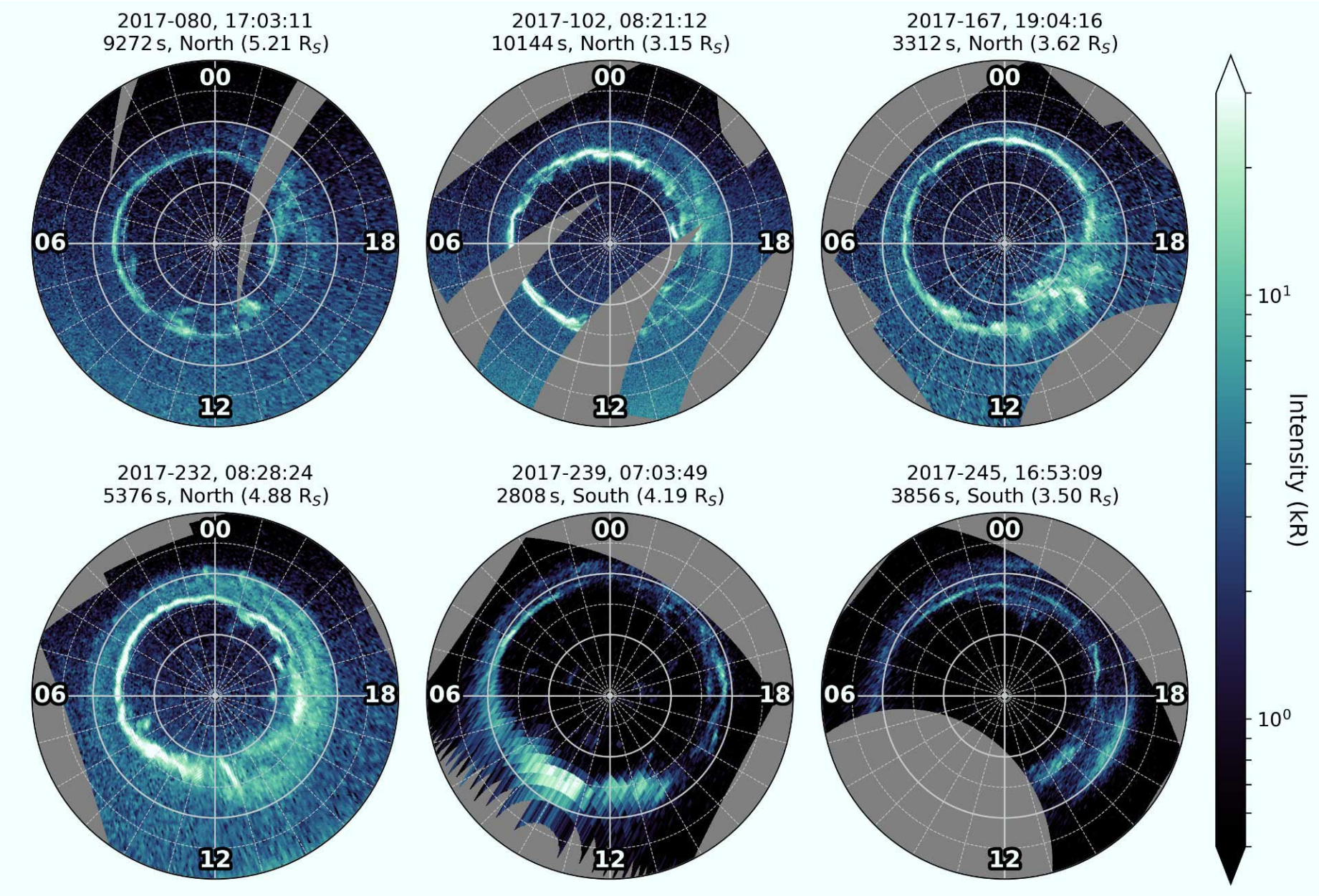


$e^- \rightarrow$ atmosphere
Lyman H emissions
H_2 vibrations emissions



Kurth et al. (2009); Stallard et al. (2019)

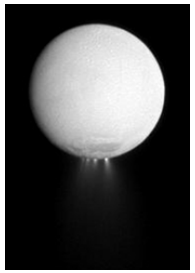
Saturn’s oval aurora changing morphology

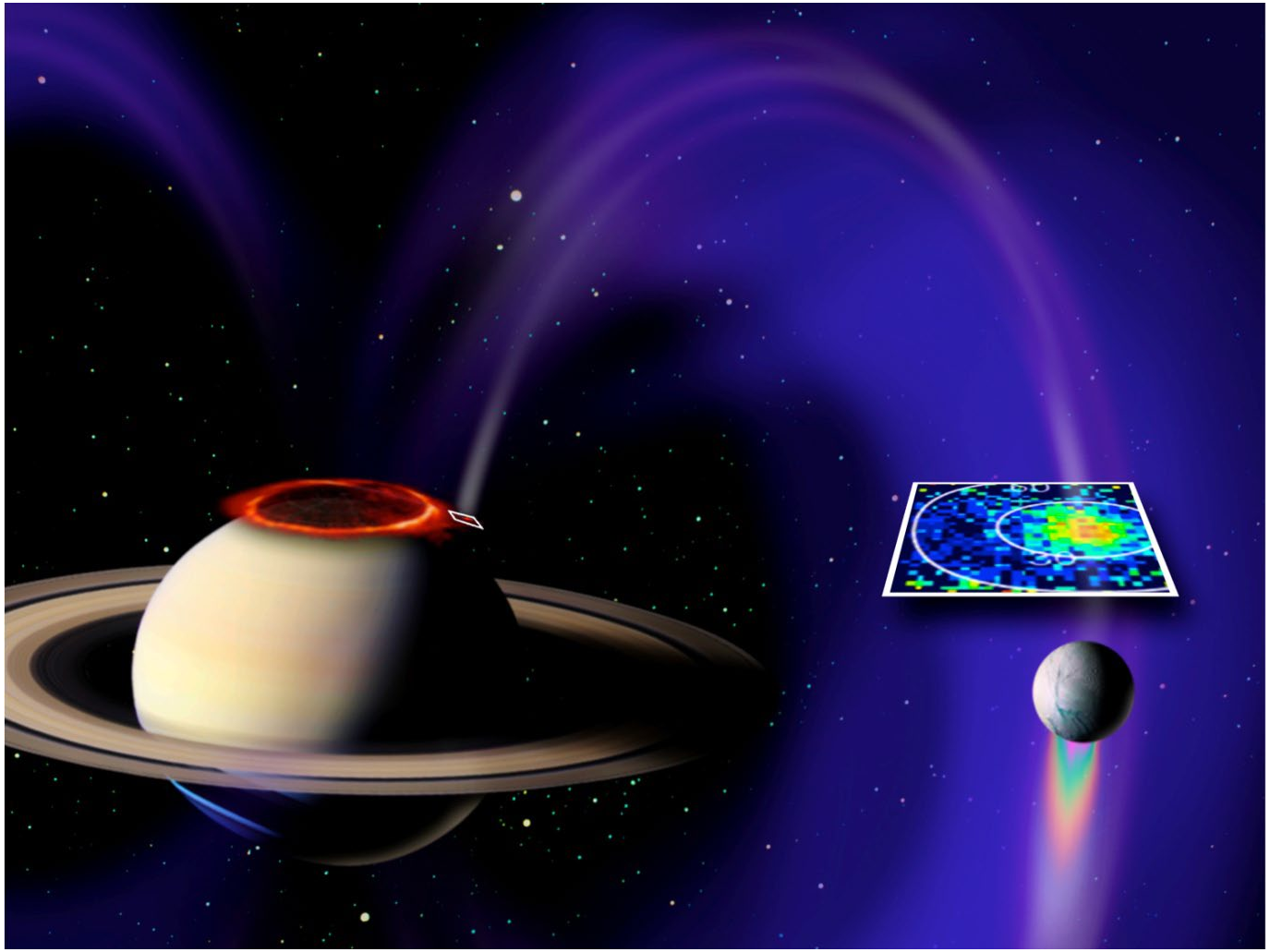


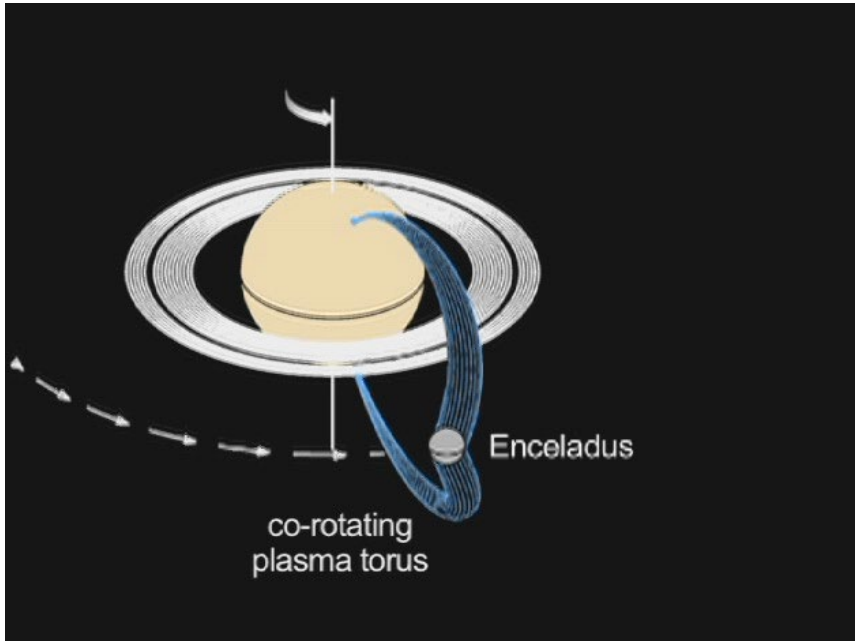
Cassini UVS

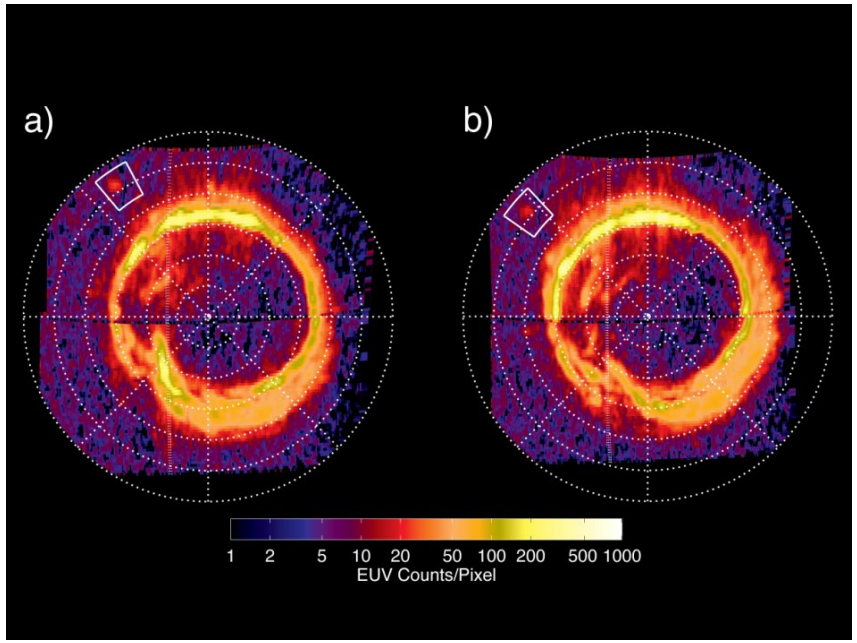
Enceladus footprint

Active cryovolcanism and geyser-like plumes
→ Plasma torus (electrons, ions)
→ Footprint (auroral)







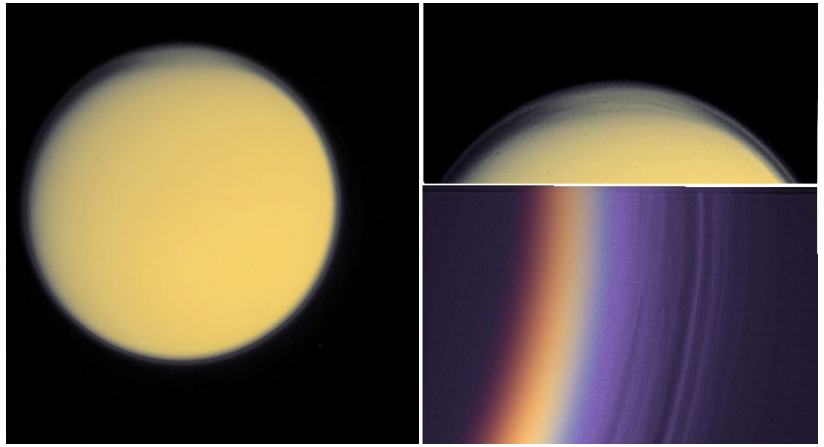


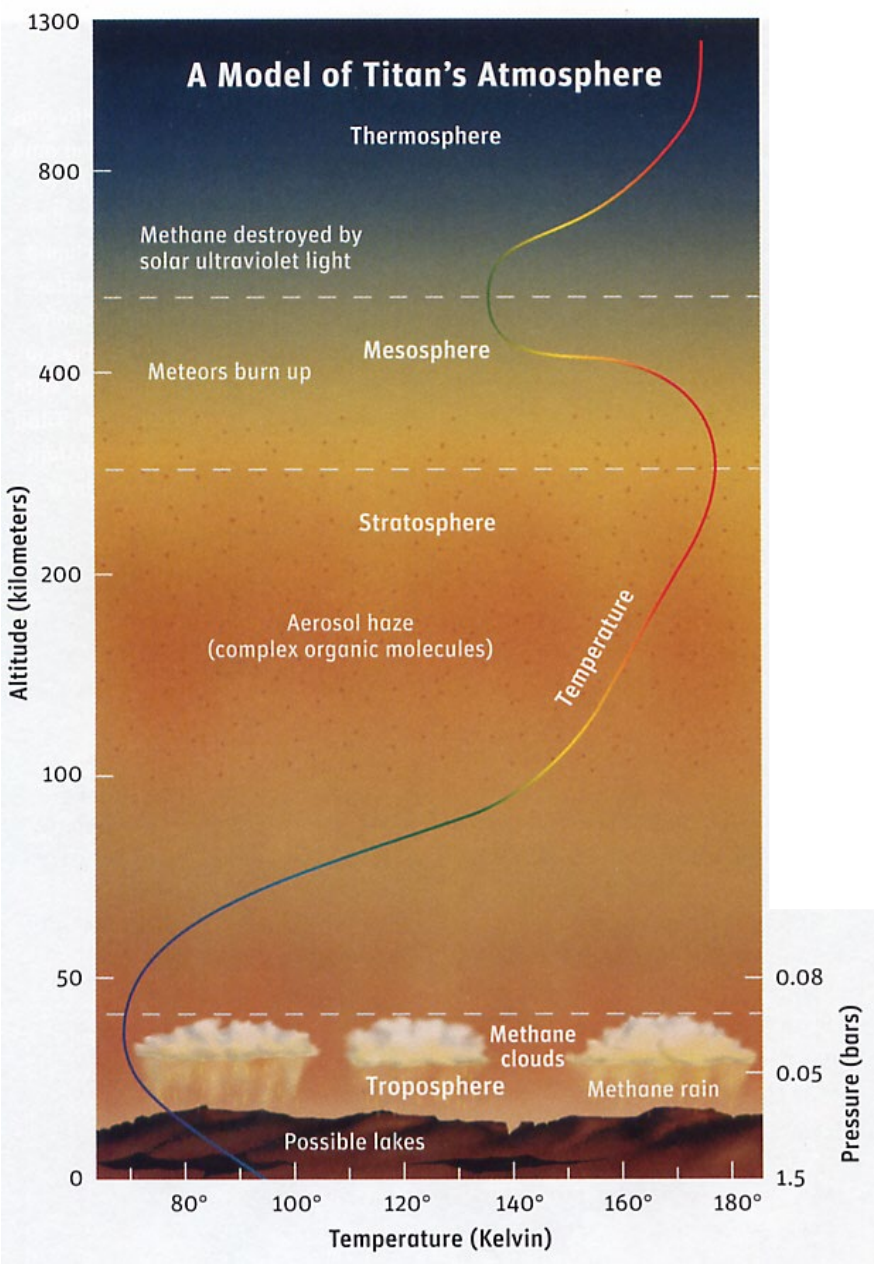
Pryor et al. (2011)

Titan clouds and hazes

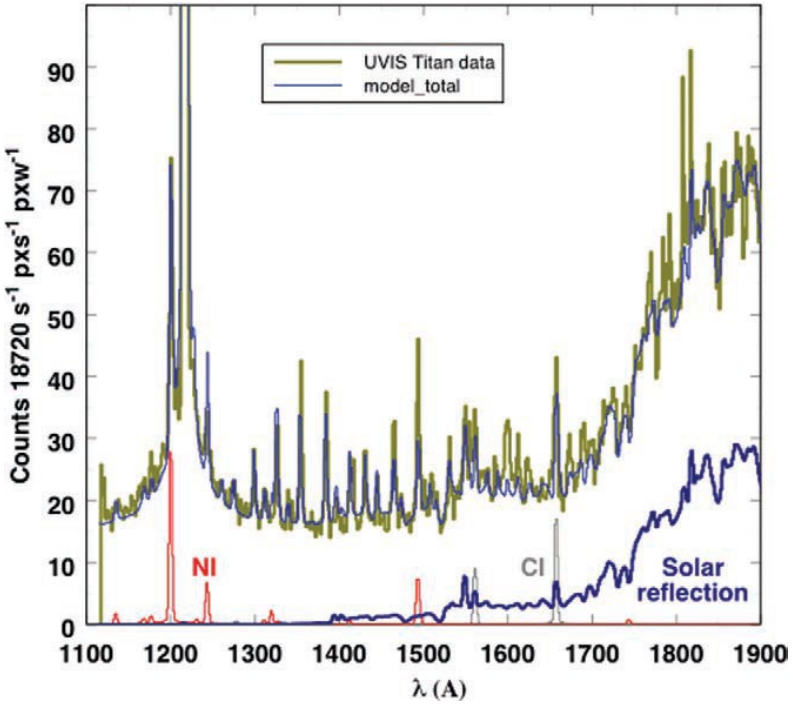
Composition (%): N_2 (98), CH_4 (1.6)

Condensation: CH_4 (s)
Photochemistry → Hazes C_nH_n (s)

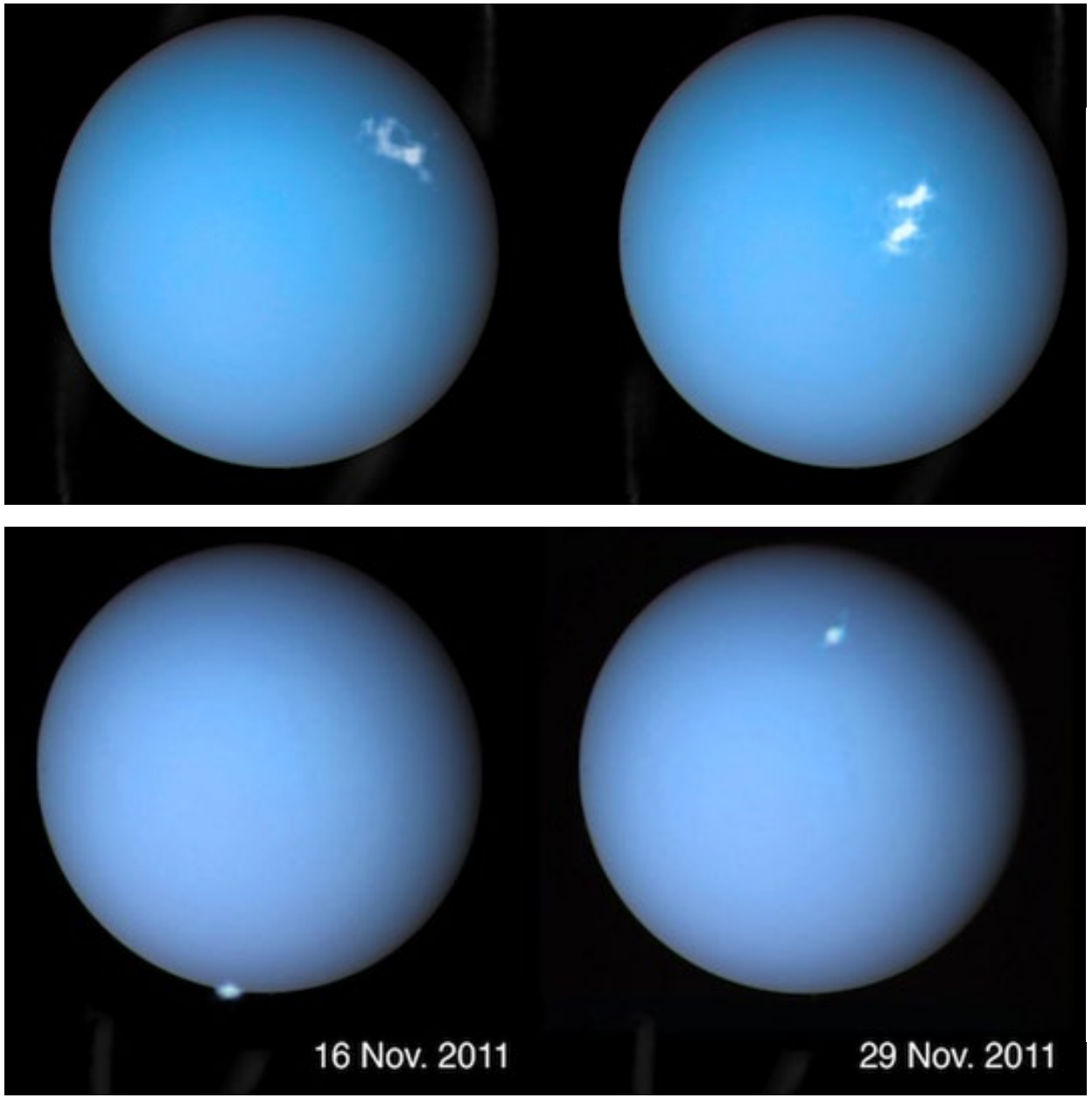


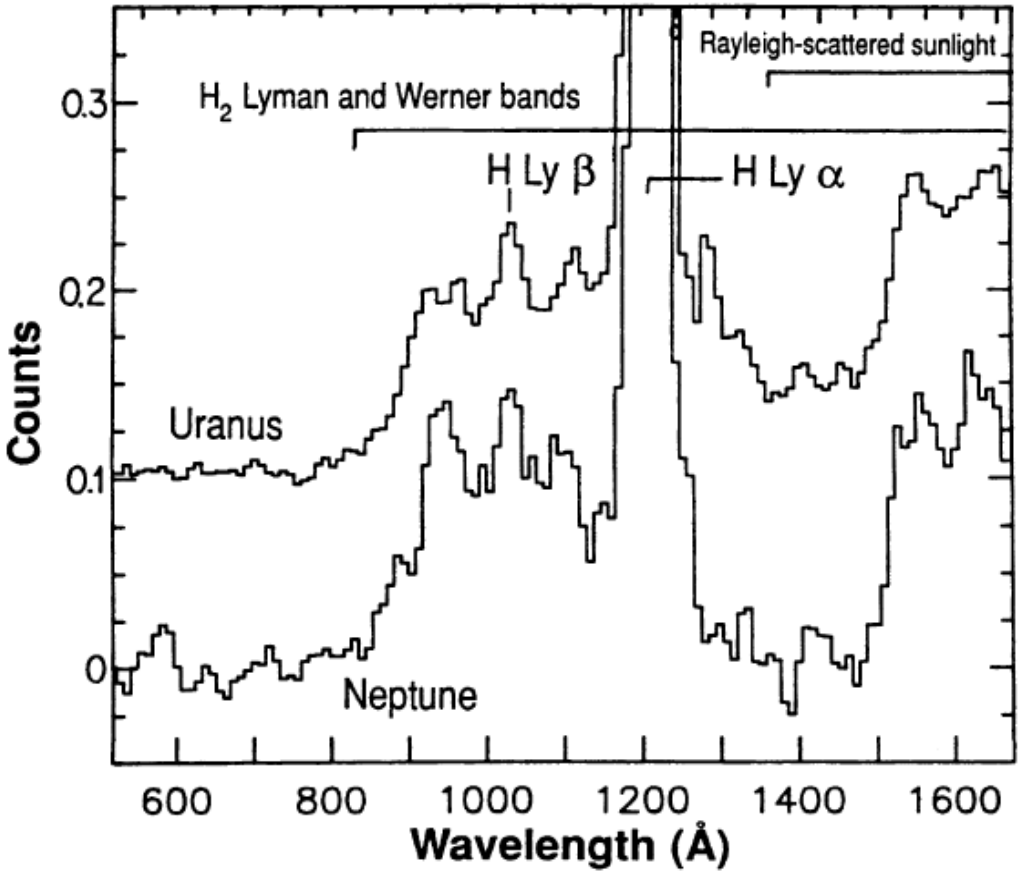


Titan's FUV spectrum
(*Cassini* UVIS)
Continuum reflected sunlight
Emission features due to electron dissociation and excitation of molecular and atomic Nitrogen (N, N_2)



Uranus aurora & airglow





ESA/Hubble & NASA, L. Lamy / Observatoire de Paris

Conclusions

Planetary Atmospheres in UV:

- High variability (daily, seasonal, dynamical events)
- Upper aerosols (cromophores) & dynamics
- Aurora phenomena
- Airglow & nightglow emissions

Other Solar System objects in UV:

- Asteroids: surface composition
- TNO: surface composition
- Dwarf planets: surface composition and exospheres
- Comets: composition of the coma, corona and tail

→ Application to **Exoplanet Atmospheres**