The History of Water on Venus and Mars

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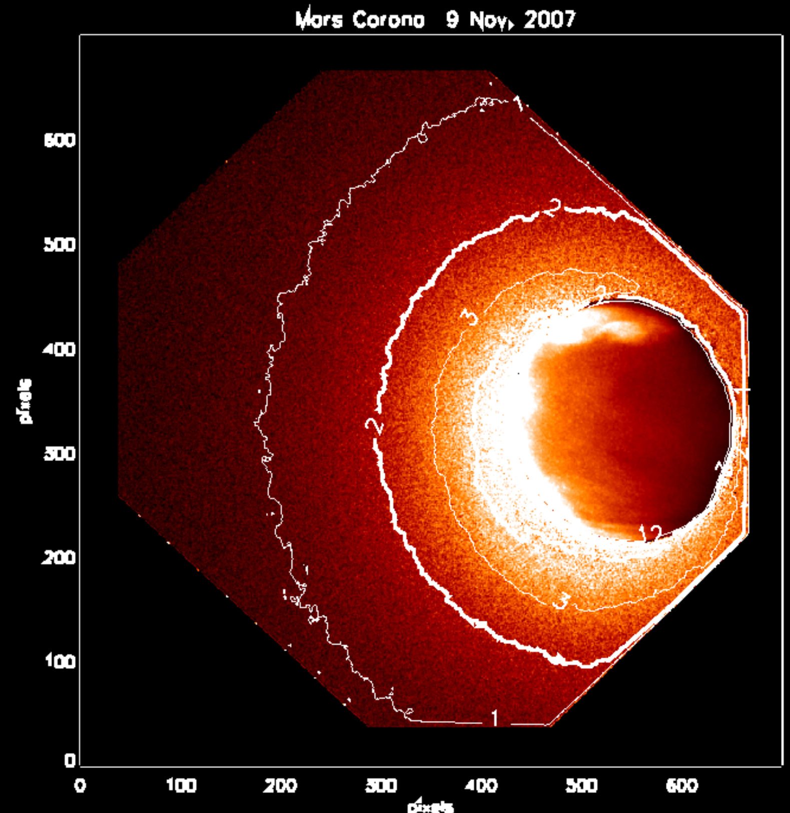

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The “Goldilocks” problem:

Venus is too hot, Mars too cold, but the Earth is just right for life to thrive - why?

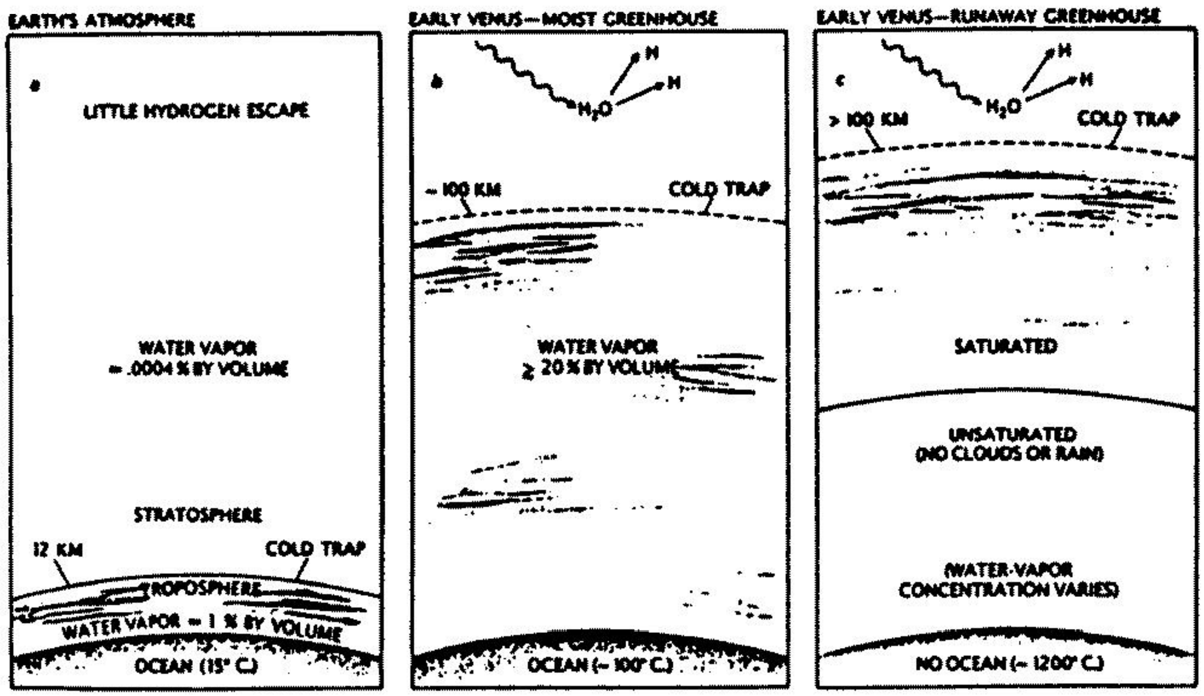
How did the three planets evolve to their present conditions?

What is the range of distance from the Sun in which an Earth-like planet could have evolved?

What are the conditions needed for life *as we know it* to evolve?

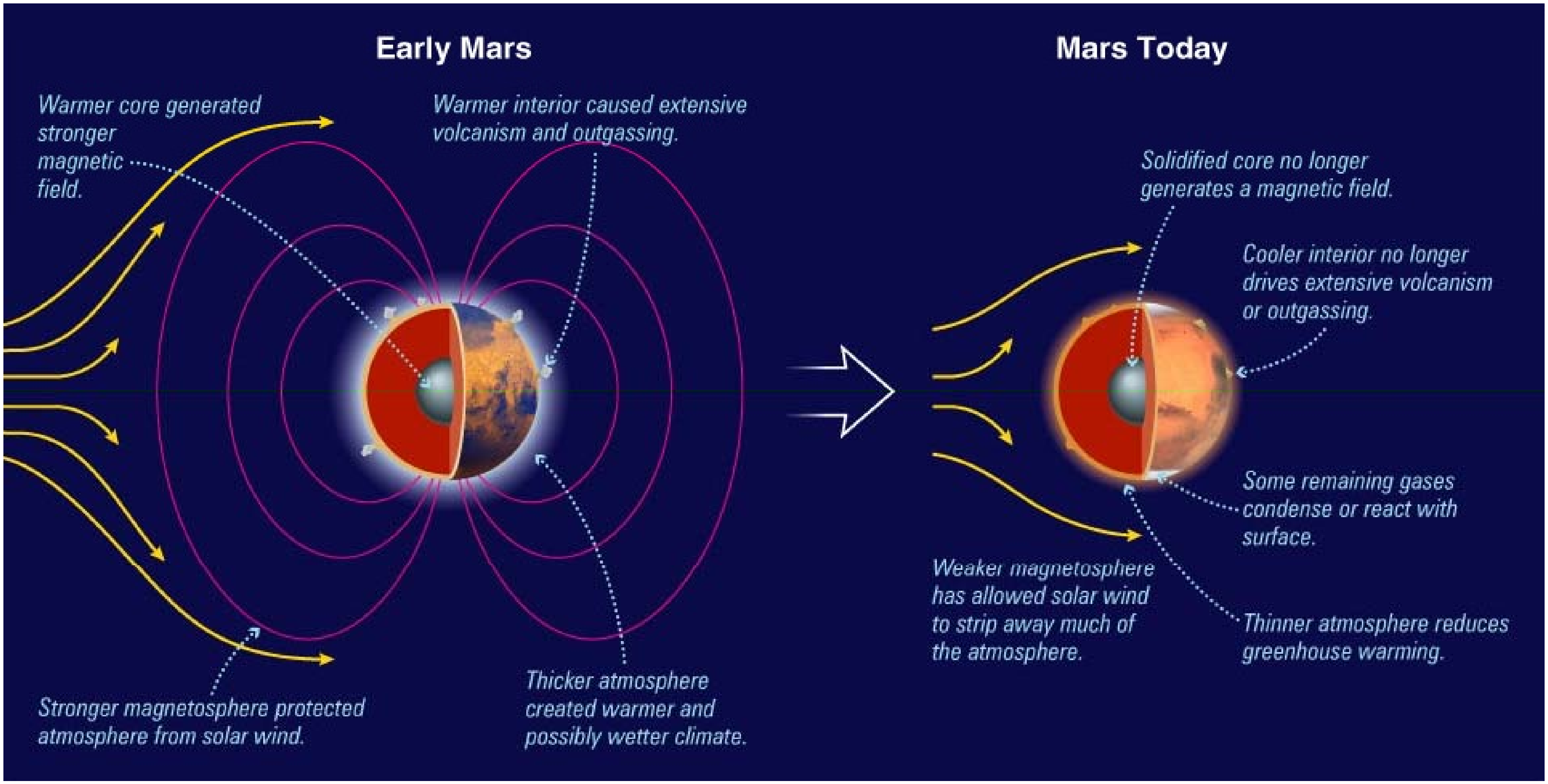
The history of water on the three planets is critical to understand the history of life *as we know it*. Many programs have undertaken the study of the evolution and loss of water into space as key goals.

The runaway greenhouse on Venus:



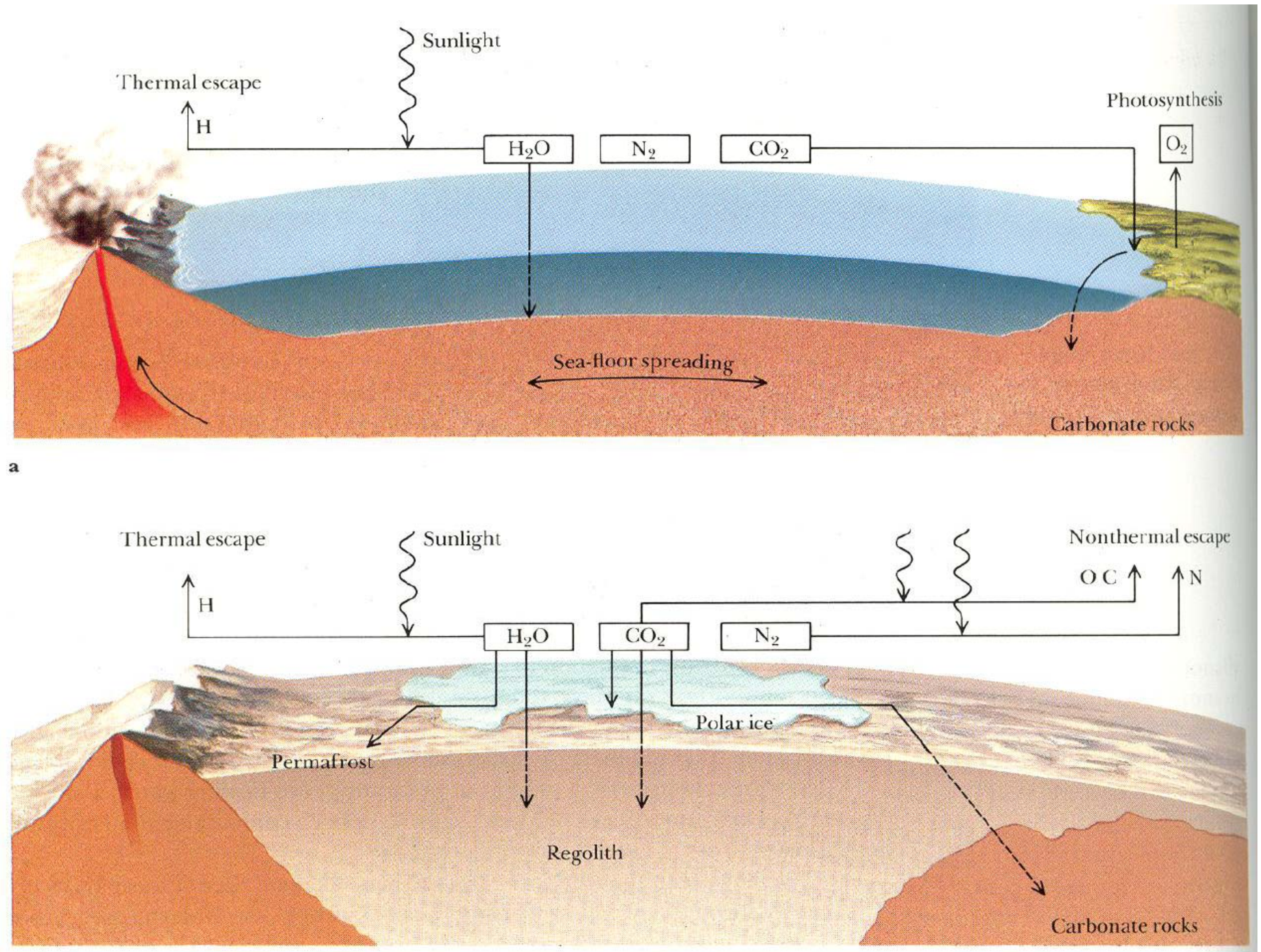
On the Earth (a) water in the troposphere is blocked from entering the stratosphere by a cold trap: the region where cold temperature and high ambient pressure combine to condense the water vapor. On the early Venus the lower atmosphere, although warm by the Earth's standards, may have been cool enough for water to condense and form an ocean. That ocean would in time have been lost to a "moist greenhouse", (b) a condition that arises when a high surface temperature enables water vapor to constitute more than about 20 % of the lower atmosphere. The cold trap then moves to a higher altitude and becomes inefficient at preventing water vapor from rising into the upper atmosphere. Although some vapor condenses out as rain, the steam at the top dissociates from UV sunlight, and its constituent hydrogen atoms escape into space. Venus might have been so hot that a runaway greenhouse (c) developed instead. All the water released by the planet turned to steam instantly, and no ocean formed, while the hydrogen atoms were lost into space.

The evolution of the martian atmosphere:



The lost atmosphere of Mars:

How much water may remain, frozen into the crust?



Science Background - Isotopic Ratios

First assume that Venus, the Earth, and Mars all started with similar conditions, the same amount of water and the same HDO / H_2O ratio

Water near the surface will rise until the temp/pressure lead to condensation (clouds) - above that level the air is dry, and little water is photo-dissociated by solar UV light:

$$H_2O + h\upsilon \text{ (UV)} \rightarrow OH + H \qquad \text{and same for HDO}$$

H and D diffuse as H_2 to the top of the atmosphere, and can "boil off" into space if their thermal speed exceeds the escape speed

H escapes faster than D due to mass difference, leading to increase in D/H ratio in the atmosphere if lots of water escapes into space

Today on Earth D/H ~ 1.6×10^{-4}, on Mars ~ 9.3×10^{-4}, on Venus ~ 0.05

Did Venus lose an ocean of water into space?

The present rate of H escape from Venus is insufficient to remove early H_2O, so early escape must have been rapid, in part enhanced by solar FUV radiation (a good reference is Pollack, *Icarus*, 91, 1991).

The surface T increases non-linearly due to IR trapping in the 8-12 μm H_2O bands. Rapid greenhouse heating places H_2O in the upper atmosphere leading to photodissociation, leading to H escape.

For a moderately enhanced solar EUV flux (x10), the H_2O would be gone in 10^8-10^9 years.

This rapid escape would drag heavier elements along leading to mass fractionation in the bulk atmosphere.

This will help deplete O as well as H, and the D/H ratio will increase more than the isotopic ratios of heavier species….

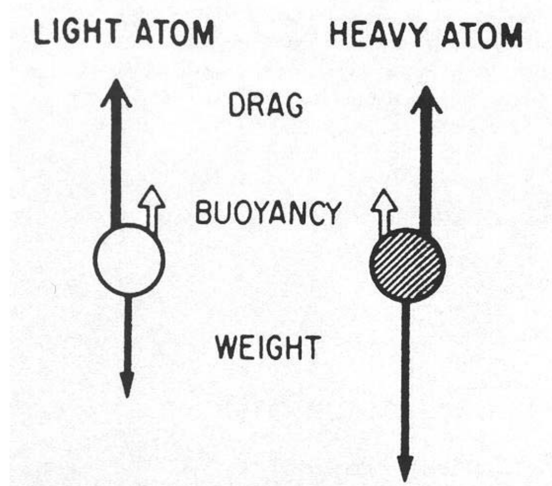
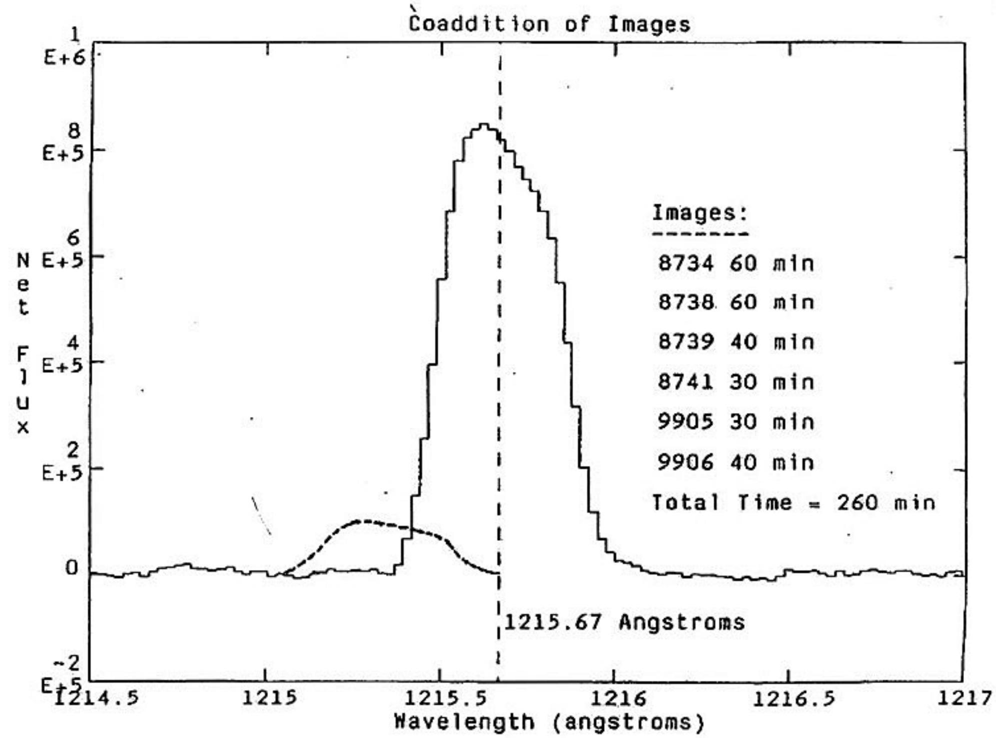


FIG. 5. The forces on an atom in the presence of an upward flow of hydrogen. Left, a light atom, net force upward; right, a heavy atom, net force downward.

Venus: Measurements of D/H on Venus from Pioneer Venus in orbit and IR spectra of deuterated water both gave D/H ~ 0.05



The present rate of escape depends on D/H at the top of the atmosphere, look at UV wavelengths and for H at H Ly α (reflected sunlight)

UV spectra of Venus taken by the International Ultraviolet Explorer (IUE) orbiting telescope in early 1980's were at high spectral resolution, could resolve D and H Ly α lines (0.33 Ångstrom separation from mass difference)

If D/H = 0.05, should see 2 kRayleighs of D Ly α emission, upper limit was 300 Rayleighs, indicated variation in altitude of D/H ratio and strong influence on escape today (Bertaux and Clarke 1989)

Elevated ratios of D/H in Atmospheres of Venus and Mars

Venus: 150 times SMOW

Mars: 5 times SMOW

(SMOW = standard mean ocean water)

Complications:

Rates of condensation are different for HDO and H_2O (well known from Earth atmosphere) - will act to remove more D than H in middle atmosphere, more H_2O subject to solar UV

Rates of photo-dissociation of HDO and H_2O are different - will also differentiate species mixed into upper atmosphere

Bertaux (2003) proposed "deuteropause" in atmosphere of Mars, limiting upward flux of D atoms compared with H atoms

Summary: Evidence for Escape of Water into Space

Present dry conditions on Venus and Mars compared with Earth

No evidence for recent (1 Gyr on Venus, 3.8 Gyr on Mars) surface geologic activity that could release new water into the atmosphere

Elevated ratio of D/H in atmospheres of Venus and Mars consistent with relatively faster escape of H from exobase

Elevated ratios of other isotopes of atmospheric species supporting general escape of atmospheric gases (on Venus ^{2}H, ^{36}Ar, and ^{38}Ar are strongly enriched compared with Earth)

Theory of evolution of atmospheres on Venus (runaway greenhouse) and Mars (elevated escape rates of gases due to weak gravity, solar wind sweeping?)

Coordinated Rocket, HST, and SPICAV Observations of Venus in Nov. 2013

A campaign of observations of the upper atmosphere of Venus has been organized for Oct/Nov 2013 to address:

- the loss of water into space
- the diffusion of hydrogen upward through the atmosphere
- the relative loss rates of D and H

The goal is to detect the D Lyman α line and thereby derive the D/H ratio in atomic hydrogen in the upper atmosphere (sounding rocket VeSpR and HST)

To measure the altitude profile of HDO and H_2O in the middle atmosphere (SPICAV).

The Venus Spectral Rocket Experiment (VeSpR)

Now scheduled for launch at WSMR on 25 Nov. 2013

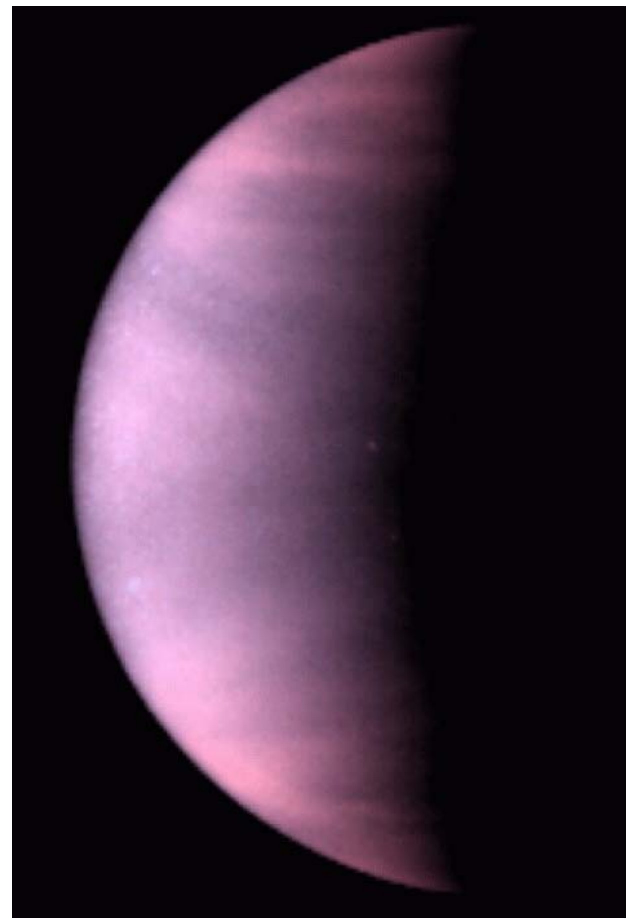
Investigators:

John T. Clarke Carol Carveth Nathan Darling	Boston U.
Jean-Loup Bertaux	LATMOS / BU
Jeff Hoffman	MIT

The Venus Spectral Rocket (VeSpR) sounding rocket experiment will measure D and H Ly α in Venus' upper atmosphere

Why not use HST? HST can only point within 50 deg. of the Sun, or sunlight will enter the telescope baffle structure - can in principle look at Venus before sunrise, then look away…

HST near-UV image of Venus from the one successful observation -> (L. Esposito *et al.*)



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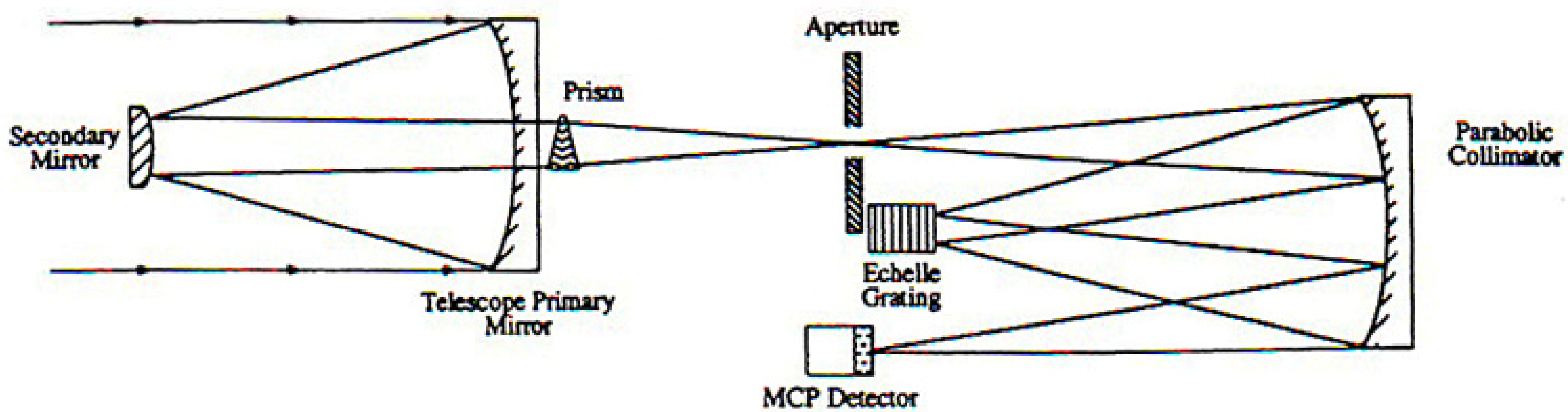
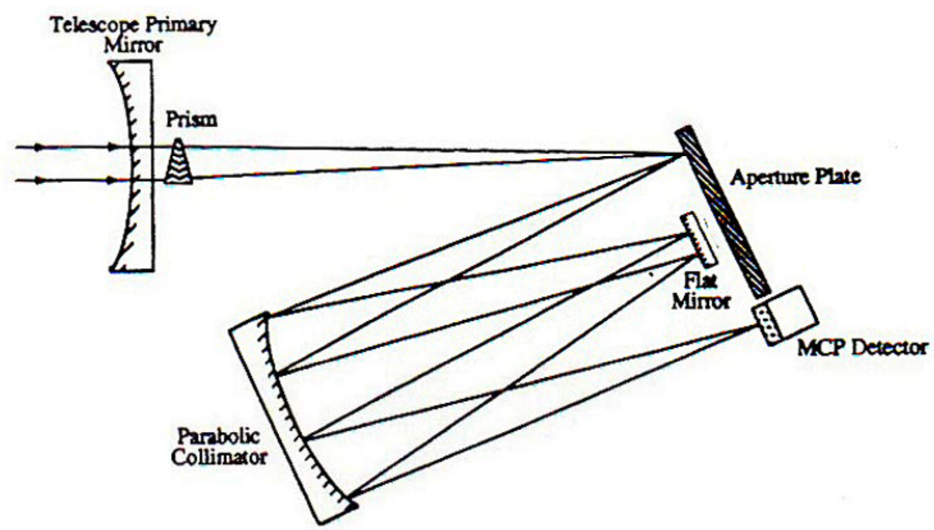
Jeff Hoffman	MIT

VeSpR:

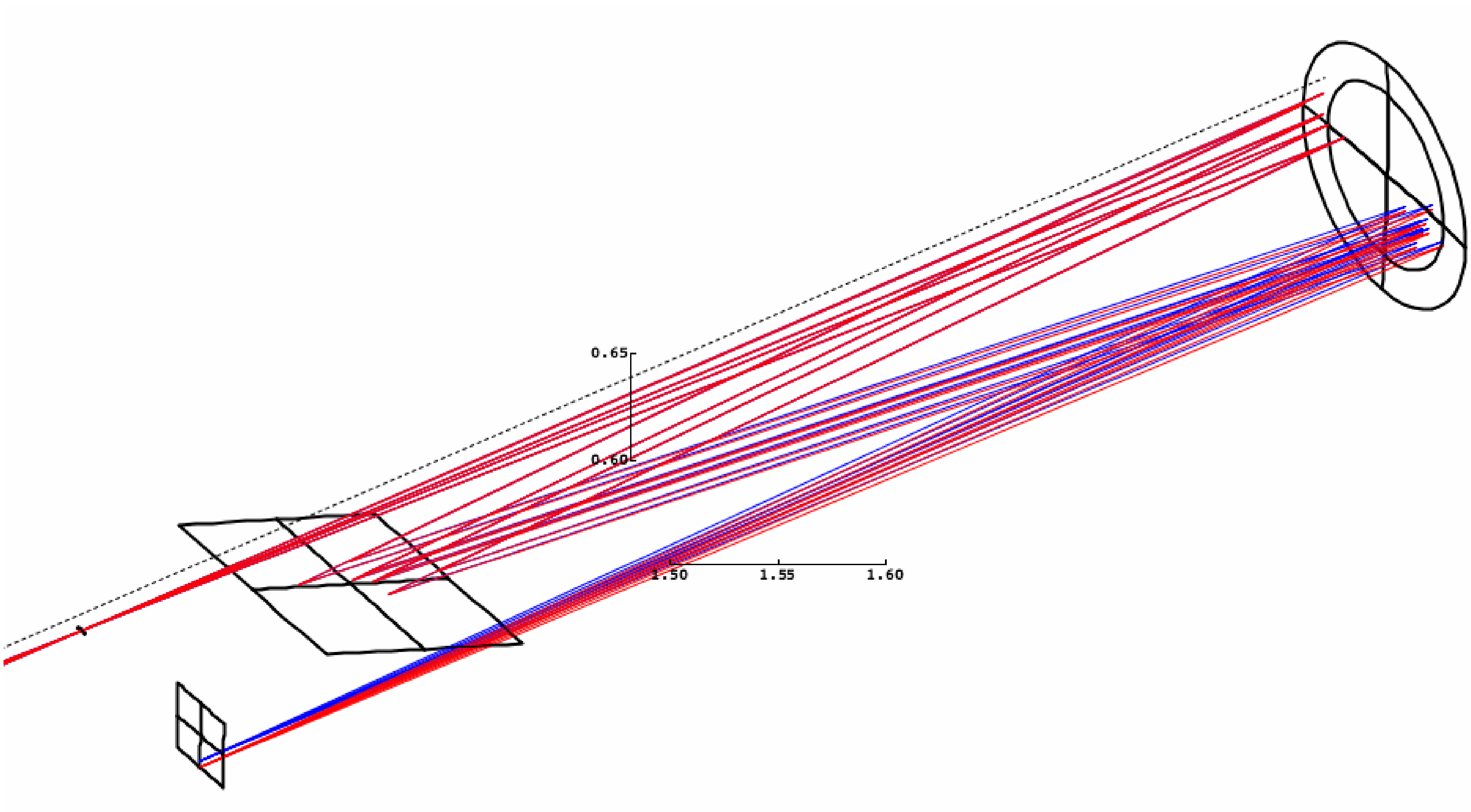
Layout of the telescope and echelle spectrograph:



Layout of the re-imaging camera:

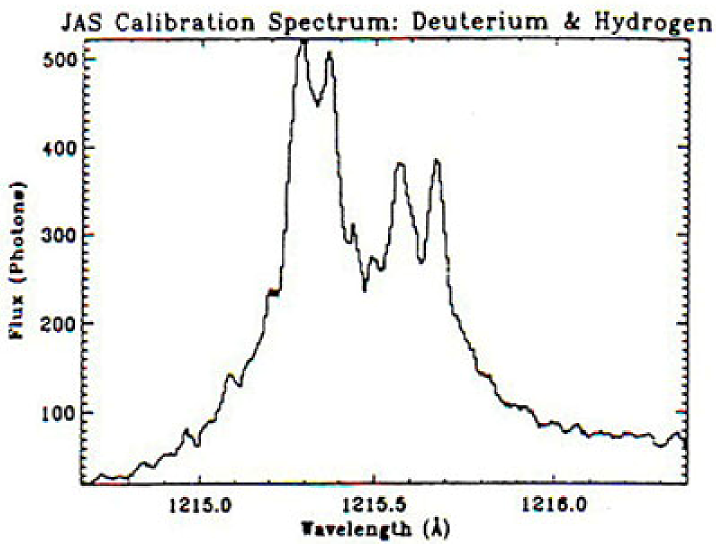


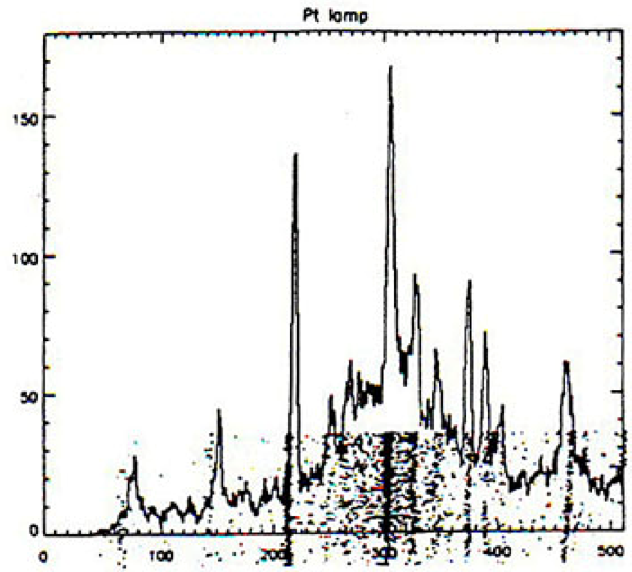
VeSpR: optical ray path in echelle spectrograph:

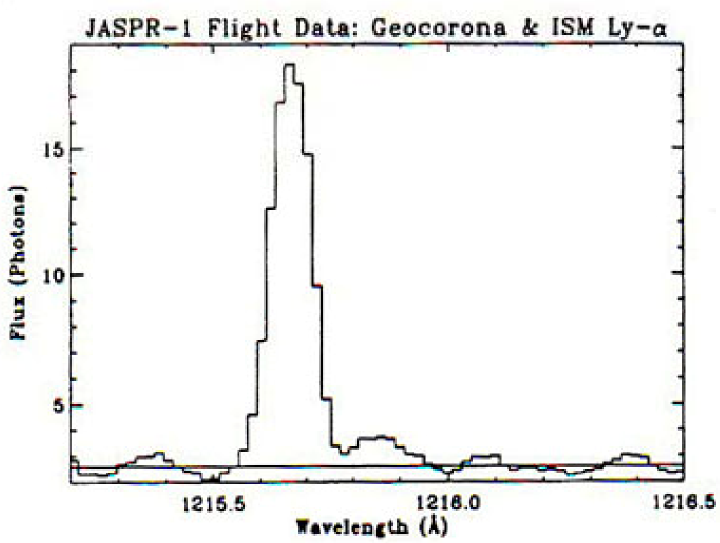


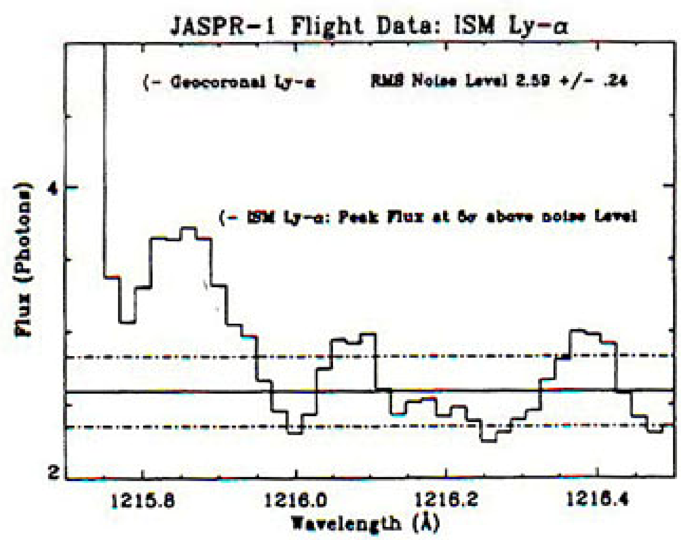
VeSpR uses 2 tricks: a) cross dispersion by prism, high throughput and allows use of long narrow aperture b) optical parameters set so that 5 arc sec aperture width corresponds to 0.04 Angstroms resolution

VeSpR: Examples of spectra from lab and first rocket flight:





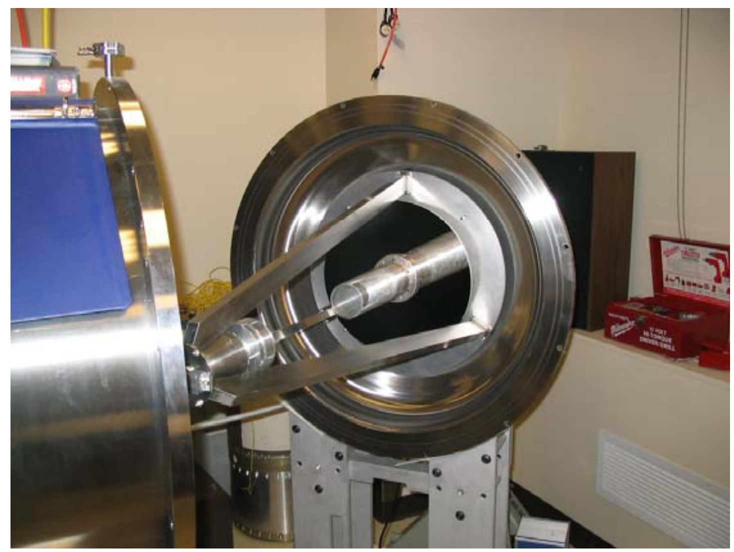




VeSpR: Protect UV optics from hydrocarbon contamination

Cleanliness program - No machine oil!

Measure throughput of whole
experiment in vacuum chamber:



HST Observations of Venus in Nov. 2013

Investigators:

John T. Clarke
Jean-Loup Bertaux
Jody K. Wilson
Jean-Yves Chaufray
Randy Gladstone
Carol Carveth
Ben Corbin

HST Observations of Venus accepted for Fall 2013:

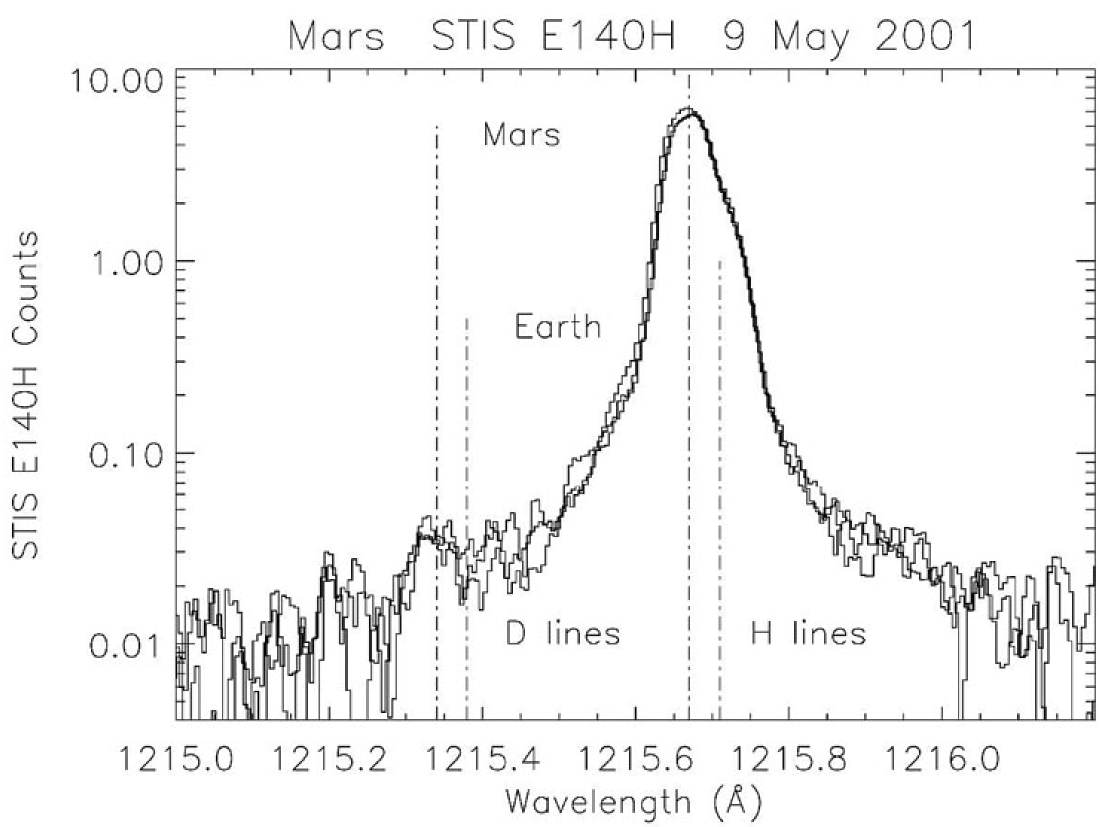
Technique of observing is to point at Venus before the Sun rises as seen from HST in orbit, then point away before the Sun rises.

Example of HST STIS echelle spectrum of Mars:

Use Doppler shift of earth and planet orbits to shift geocoronal lines from planet lines:

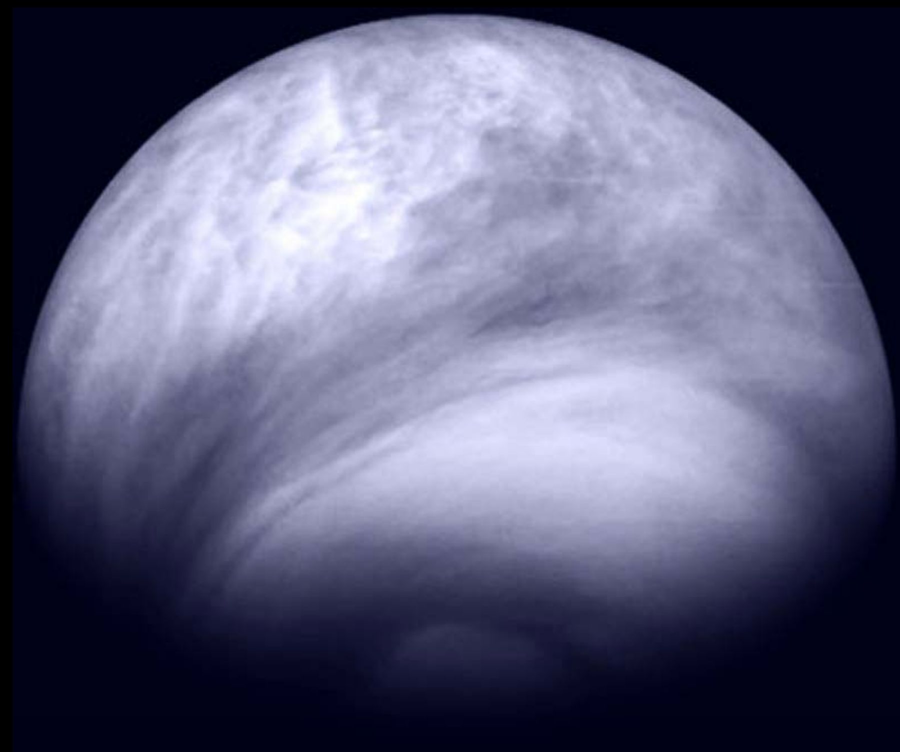
This observation will give high angular resolution, but limiting observing time

Key factor is grating scattered light profile…



SPICAV Observations of Venus Fall 2013

Investigators:



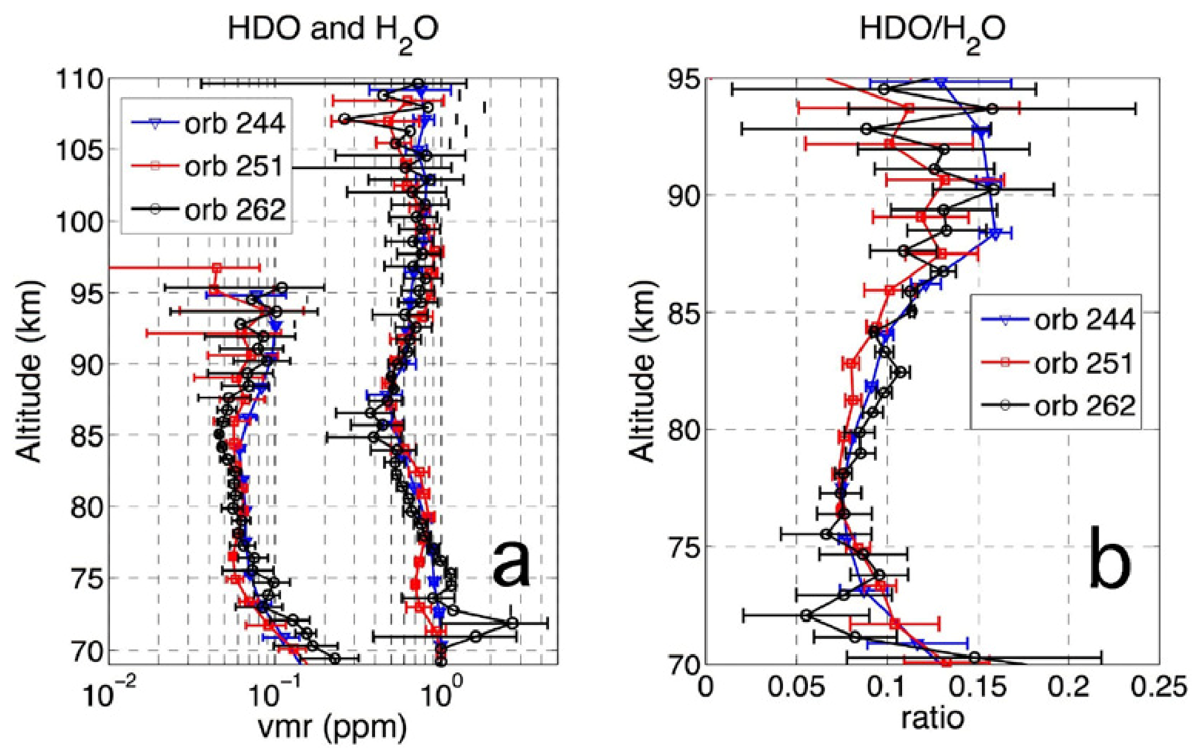
Jean-Loup Bertaux
Valerie Wilquet,
and the
SPICAV / SOIR
team

Venus' middle atmosphere has been measured by the SOIR experiment on Venus Express. IR occultations provide altitude profiles of densities of H_2O and HDO (Bertaux *et al.* 2007):

The decrease in HDO/H_2O between 70-85 km is unexpected and unexplained:

HDO/H_2O ratio is also higher than 0.05 for bulk atmosphere

These may reflect the differences in rates of condensation and dissociation of H_2O and HDO....



Summary of Venus Campaign:

VeSpR and HST will measure the D and H Ly α line emissions from the upper atmosphere, derive D/H ratio above the water

HST will have high angular resolution and may show profile across the disk, incl. limb brightening peak – gives altitude information about distribution of emission

VeSpR will have overall higher sensitivity to faint emission plus higher spectral resolution to cleanly separate H and D lines – gives best detection of faint D emission integrated over disc

Exact dates of HST and VeSpR observations are TBD, likely late Oct or early Nov for HST, late Nov. for VeSpR

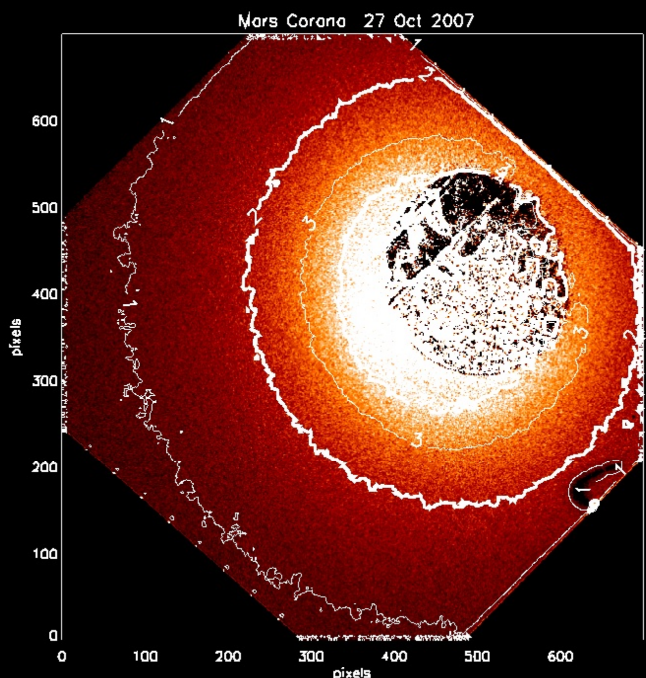
SPICAV observations are constrained by s/c geometry, will begin in mid to late Nov. and extend for several weeks

Mars: Background-subtracted HST images of H Ly α emission from Mars on the 3 days of observation. The pointing was offset in the direction toward the Sun on the latter 2 days to detect the more distant martian coronal emission profile.

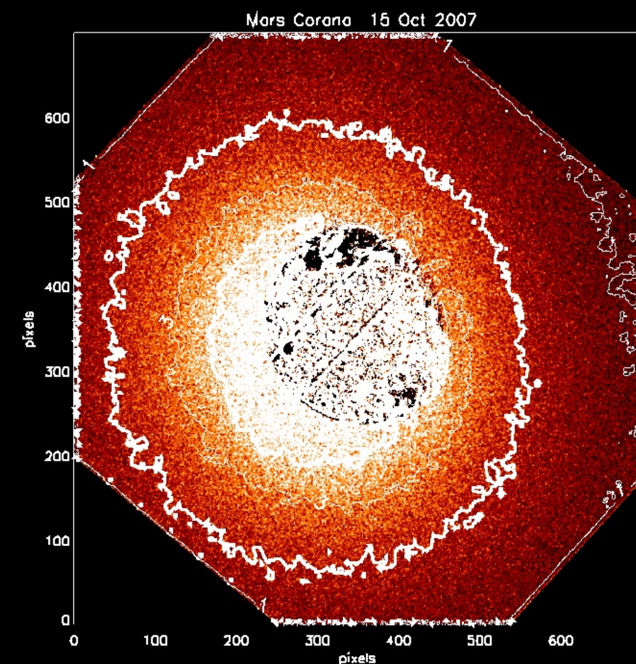
15 Oct

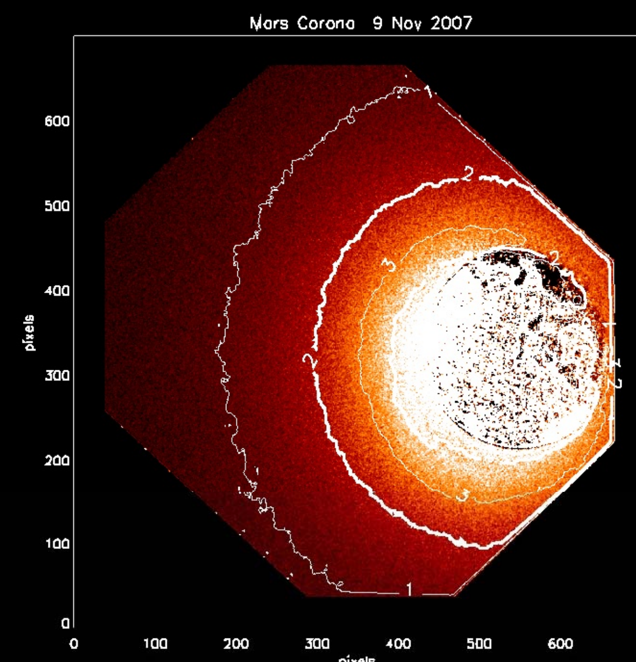
27 Oct

9 Nov



Contours at 1 kilo-Rayleigh intervals are overplotted. The disc of Mars appears noisy due to the high level of reflected UV sunlight from the surface. The general shape, but not the intensity level, repeats from day to day.

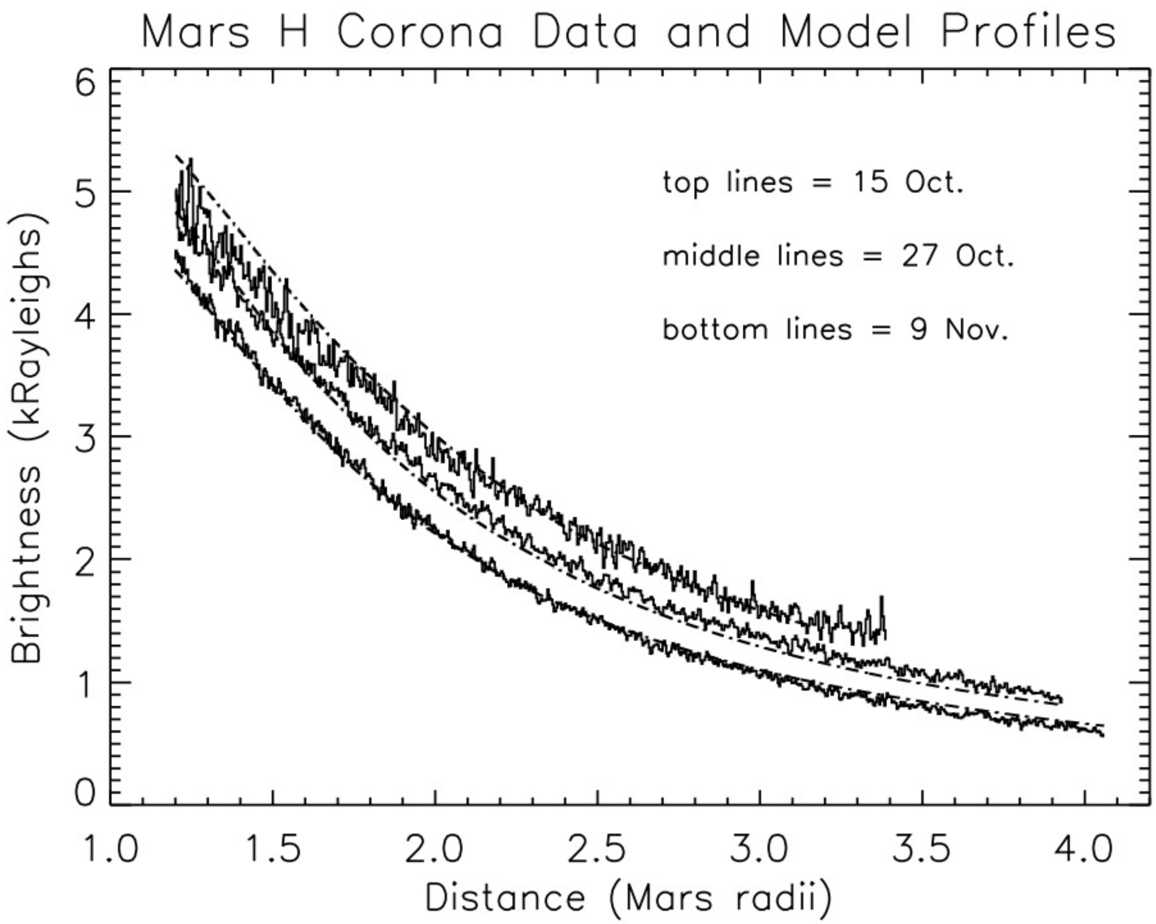




Comparison of HST intensity profiles with RT model profiles. The general shape of the profiles in the sub-solar direction are the same, but the levels of emission steadily decreased with time, with the observations separated by 12 days in both intervals.

The model profiles are consistent with a change mainly in n_H.

The solar Ly α emission was constant over this time to within a few percent, so that does not explain the decrease.

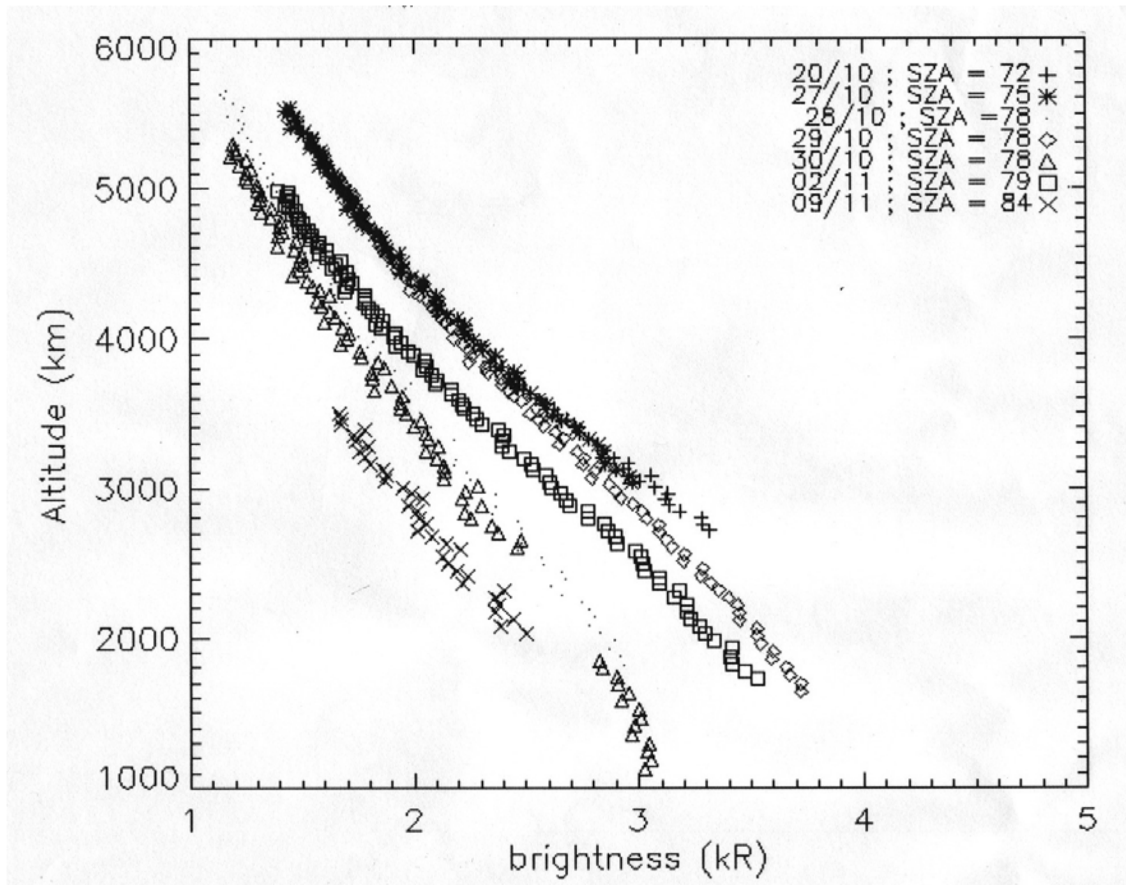


Spatial profiles of H Ly α intensity with distance from the SPICAM instrument on Mars Express. The 10/27 and 11/9 curves correspond to days of HST observations. The same constancy of fall-off and decrease in intensity with time are seen as in the HST data, confirming the trend in the data. Note that the SPICAM profiles were obtained from within the atmosphere, hence the different shape of the profiles showing line of sight brightnesses.

These look more like the scans that MAVEN will get within the atmosphere:

MEX apoapse 10000 km

MAVEN " ~ 4000 km



Mars Express SPICAM H Ly α

H Escape Scenario:

H atoms are launched from the exobase,
if they escape they must be replaced by flux from lower atmosphere

The path that hydrogen takes from the surface to the exobase is:

H_2O sublimates from the ground
H_2O gas dissociated by solar near-UV into H and O
recombination of H into H_2
H_2 diffuses into the upper atmosphere
H_2 is dissociated by solar far-UV into H

Time scales:

H_2O sublimation and photo-dissociation	~ hours
H recombination into H_2	~ hours
H_2 diffusion up to 120 km	weeks to months
H_2 dissociation into H	~ hours
H atom ballistic trajectory from exobase	~ hours
H atom charge exchange with solar wind p^+	~ 100 days

Interpretation:

In principle any one of these steps could decrease the supply of H atoms to the exobase, but the observations took place during a time when the the solar flux changed little (few % over 2 months).

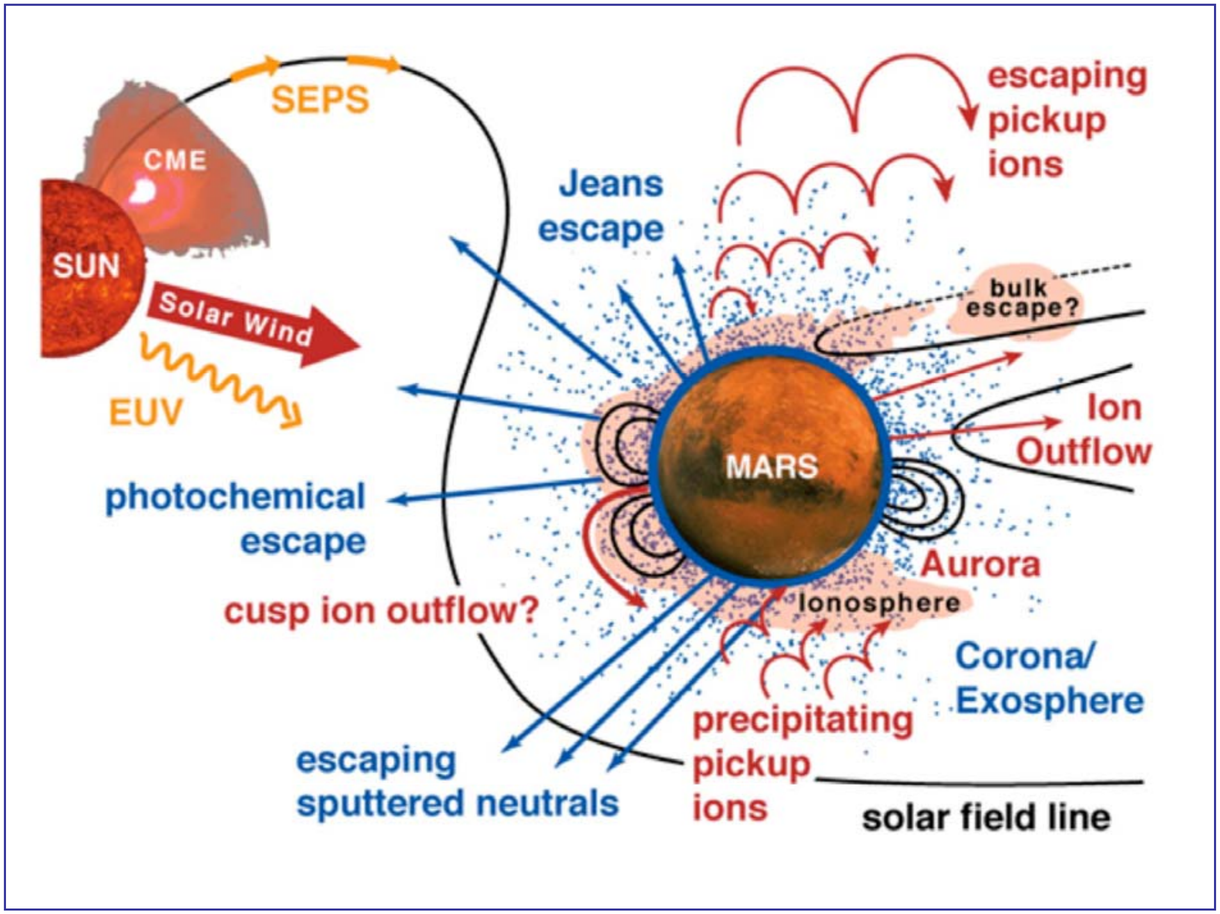
In the fall of 2007, Mars was moving from summer to winter (L_S ~ 300-320), with a global temperature decrease, decreased dust storm activity, and lower water vapor partial pressures.

The HST observations followed the largest dust storm in the prior 3 martian years (Smith 2009)

Mars Express observations show that water can rise much higher in the atmosphere than expected (super-saturation) (Maltagliati *et al.* 2011, 2013)

It appears that the loss rate of H into space is mainly limited by water vapor density and altitude distribution in the lower atmosphere, which has important implications for the rapid loss during past periods when Mars was wetter than today

MAVEN Will Allow Us To Understand Escape Of Atmospheric Gases To Space



- MAVEN will determine the present state of the upper atmosphere and today's rates of loss to space.
- Measurements will allow determination of the net integrated loss to space through time.

Backup Slides

Mars Upper Atmosphere: Diffusion and Escape

The main escaping species are H and O (Liu and Donahue, 1976; Ip, 1990).

The source of both H and O is $H_2O + h\nu \rightarrow OH + H$ ($\lambda < 242$ nm)

From Mariner 6/7 data, estimated H escape is ~1.2×10^8 cm^{-2}-sec^{-1}.

In one year, this is ~5×10^{-4} μm H_2O compared with the existing 15 μm precipitable H_2O in the atmosphere.

In the lower atmosphere:

$H + O_2 + M \rightarrow HO_2 + M$ then $H + HO_2 \rightarrow H_2 + O_2$

Then H_2 mixes into the upper atmosphere, produces H atoms in the upper atmosphere, and CO_2^+ recombines.

$$H_2 + CO_2^+ \;\; \text{->} \;\; H + CO_2H^+$$

$$CO_2H^+ + e^- \;\; \text{->} \;\; H + CO_2$$

The H atoms thereby produced have thermal energies at 200-400 K, and are lost by Jean's escape and nonthermal processes acting in the upper atmosphere (such as solar wind charge exchange and sweeping).

By contrast, O is produced "hot" by dissociative recombination of O_2^+: escape flux originally thought to be ~ 1/2 that of H (may be less).

If the total H_2O loss is ~ 10^{26} sec^{-1}, this is enough for Mars to lose 2-3 meters of water across the planet in 4.5 Gyr, if the rate has been maintained.

The vertical structure of the martian upper atmosphere:

homopause ~ 140 km   exobase ~ 200-250 km

superthermal atoms at z > 200 km can escape into space.