Submillimeter spectroscopy of Venus atmosphere with ALMA: CO, HDO and sulfur species

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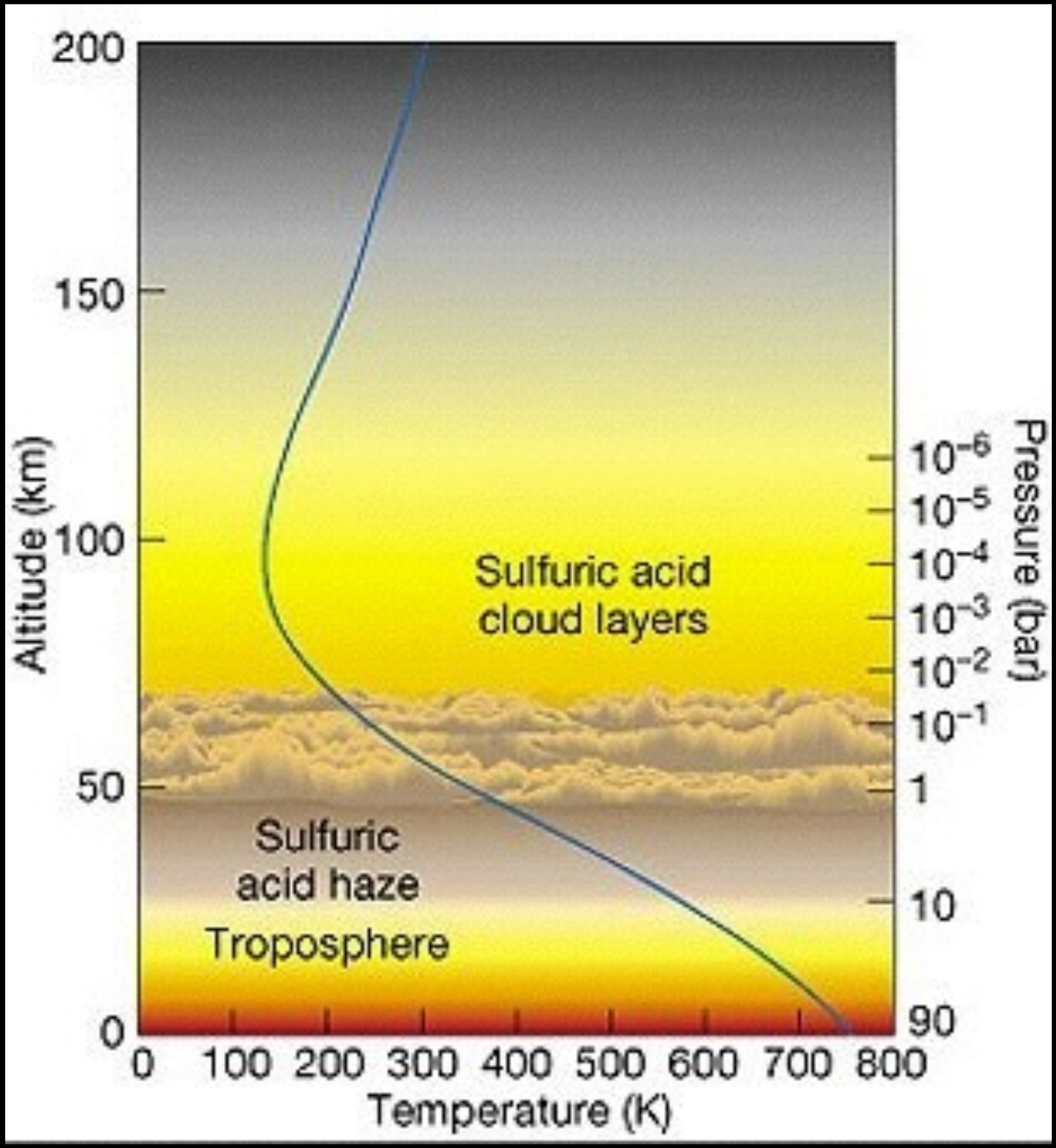
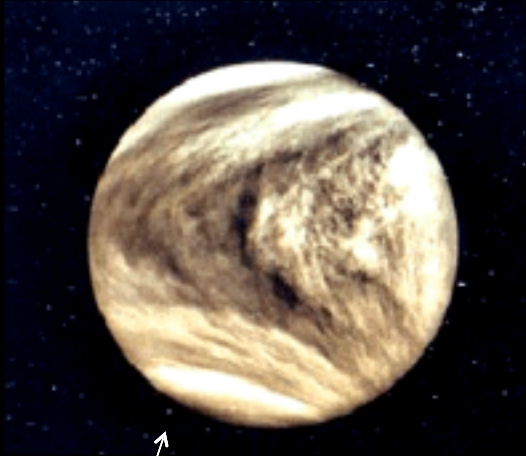
ALMA

Introduction to Venus' atmosphere

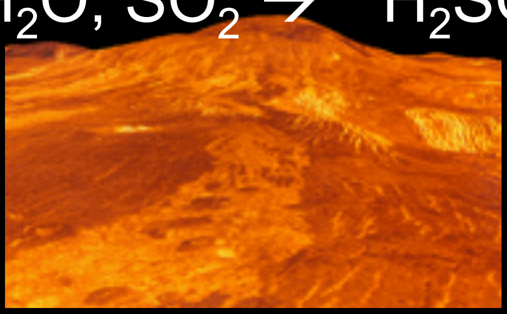




H_2SO_4 clouds (Z~55 km)

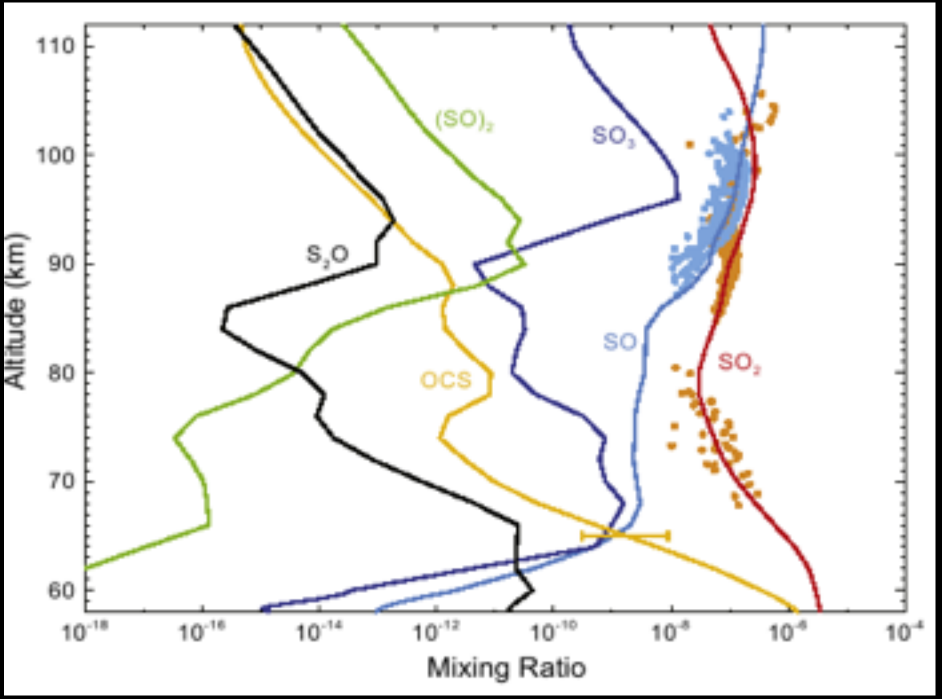
mm/submm observations

Volcano outgassing :
H_2O, SO_2 → H_2SO_4



Mesospheric chemistry

- Condensation/evaporation cycle:
  $H_2O + SO_3 \leftrightarrow H_2SO_4$
- UV-photochemistry
  → SO, SO_2, H_2O and SO_3
- Upward transport (SO_2)



Zhang et al., 2012 : Vertical profile models of S-species, no S_x aerosols

S- species display:
- large temporal variations
- strong depletion above clouds, then increase w altitude (Sandor et al., 2010)

Suggests a **supplemental mesospheric source** of sulfur species such as : H_2SO_4 / S_x aerosols ?

ALMA observations

Objective (chemistry) : accurate temporal and diurnal variations, horizontal and vertical distribution of **CO, SO, SO_2 and HDO in 70-100 km region of the day hemisphere**

l 4 observing dates through November 2011 (Cycle 0), near superior conjuction (~'full Venus' phase)

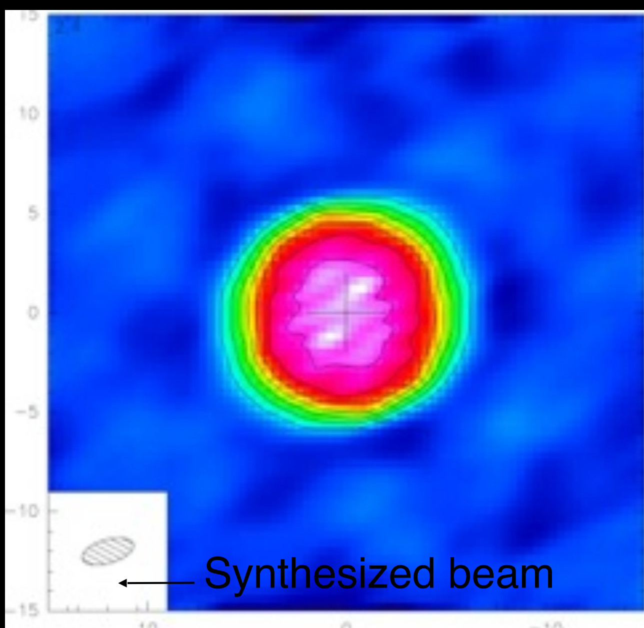
l All rotational lines observed in a single setup (band 7), High spectral resolution ~55 m/s

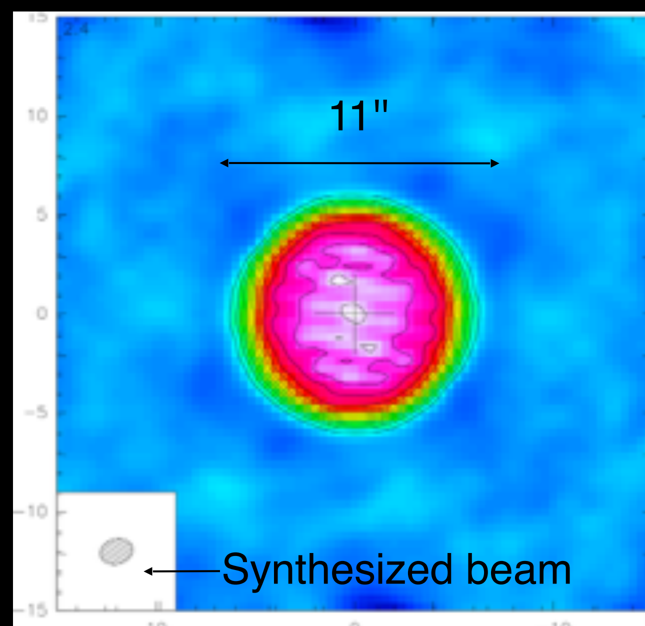
l 16 x 12-m dish array, high dry site (Atacama): **great sensitivity**

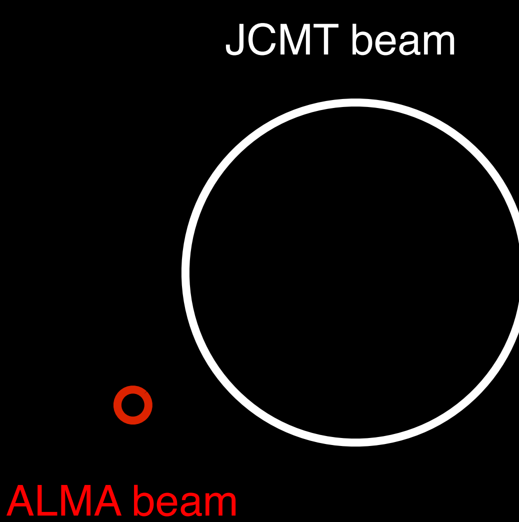
ALMA observations

Projected baselines up to 200 m (compact configuration) :
spatial resolution (synthetized beam) of 1-3" at 345 GHz

Necessary to instantaneously map the 11"-day-side disk
→ variability

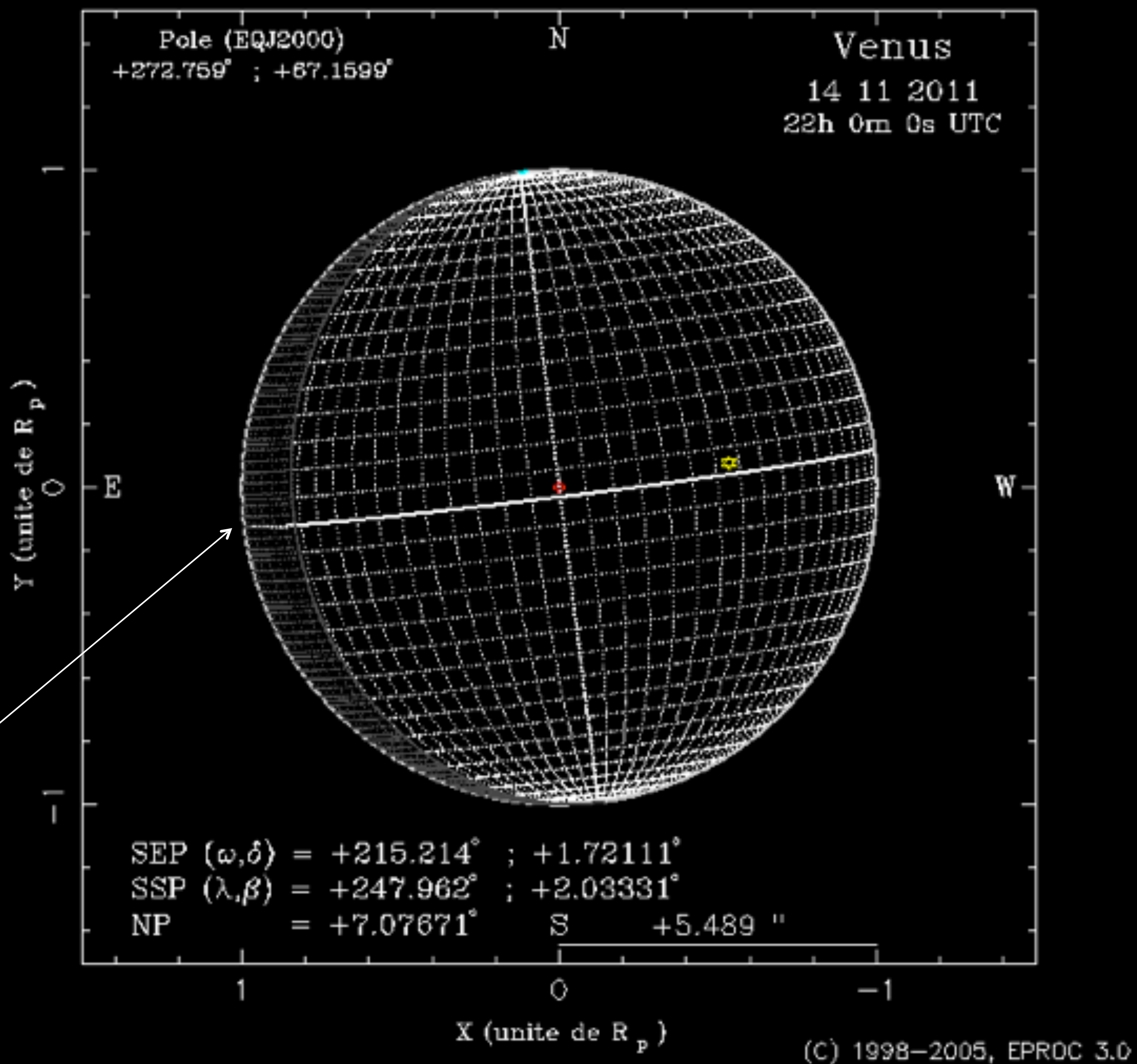






Observed continuum at 346 GHz, Nov 14th, 2011

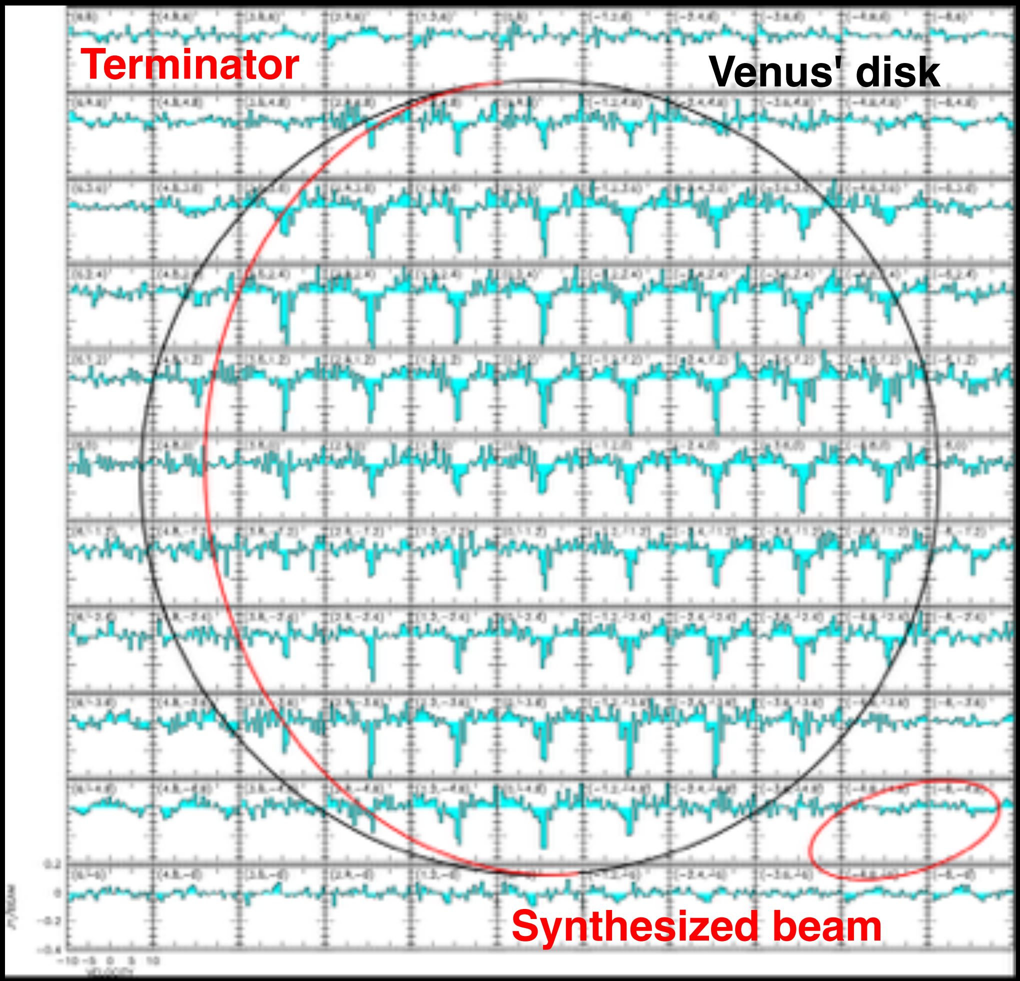
Observed continuum at 346 GHz, Nov 15th, 2011



Eastern limb :

Local time ~4 AM

SO mapping



346.528 GHz SO line map,
Nov. 14th, 2011

Variation of SO line depth with local hour: **steep decrease from day to night** (undetected at 6 pm)

Confirms diurnal variations suggested by disk-average observations
Sandor et al. (2010)

Consistent with **insolation control on SO abundance** (production from SO_2 photolysis)

SO and SO_2 abundance

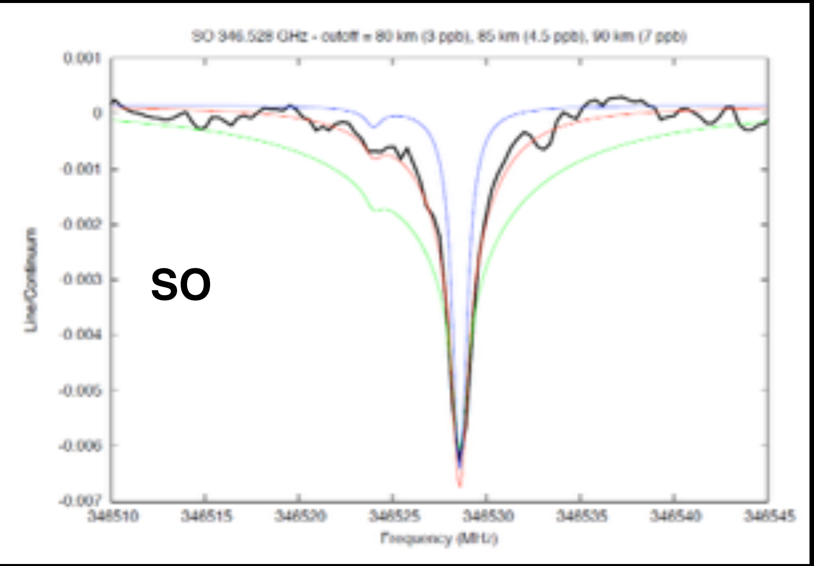
Modeling of disk-averaged lines on one date (Nov 14th, 2011) assuming typical thermal profile

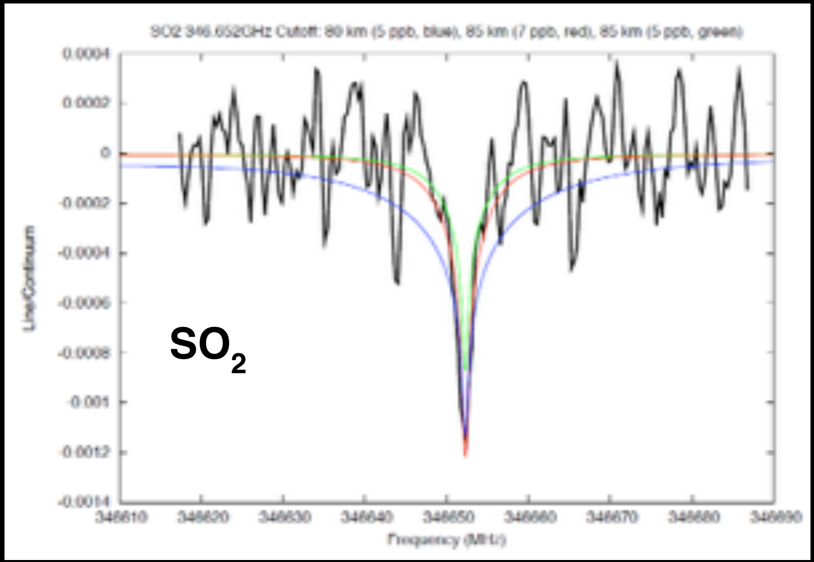
Line analysis indicates
- 6+/-1 ppb SO_2 > 85 km
- 4+/-1 ppb SO > 85 km

→ confirms sulfur-poor region in lower mesosphere (67-85 km)

→higher abundances than H_2SO_4 vapor upper limit (<3 ppb, Sandor et al., 2012)

→ ALMA allows detection of weak Line/continumm (<0.1%)



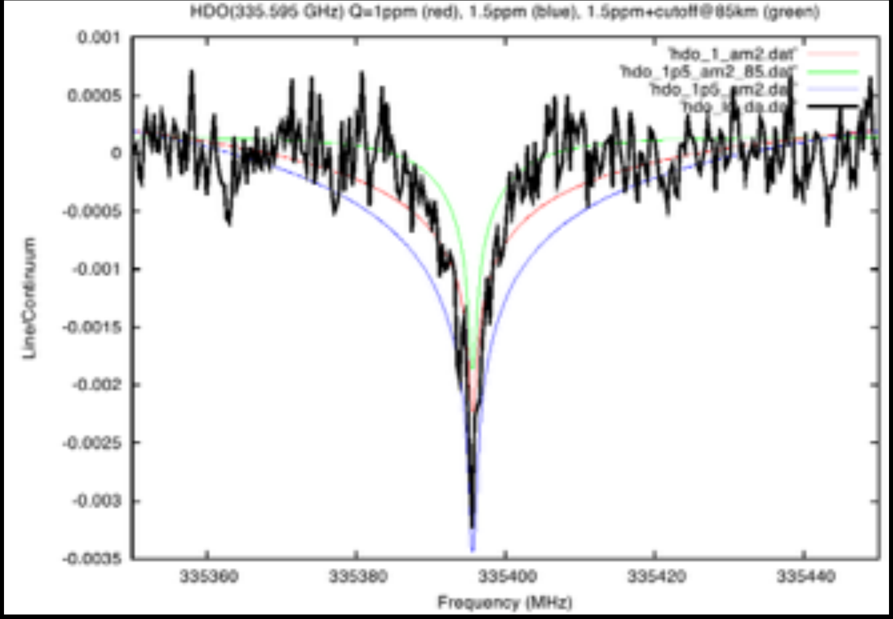


346.528 GHz and 346.652 GHz SO_2 disk-averaged lines

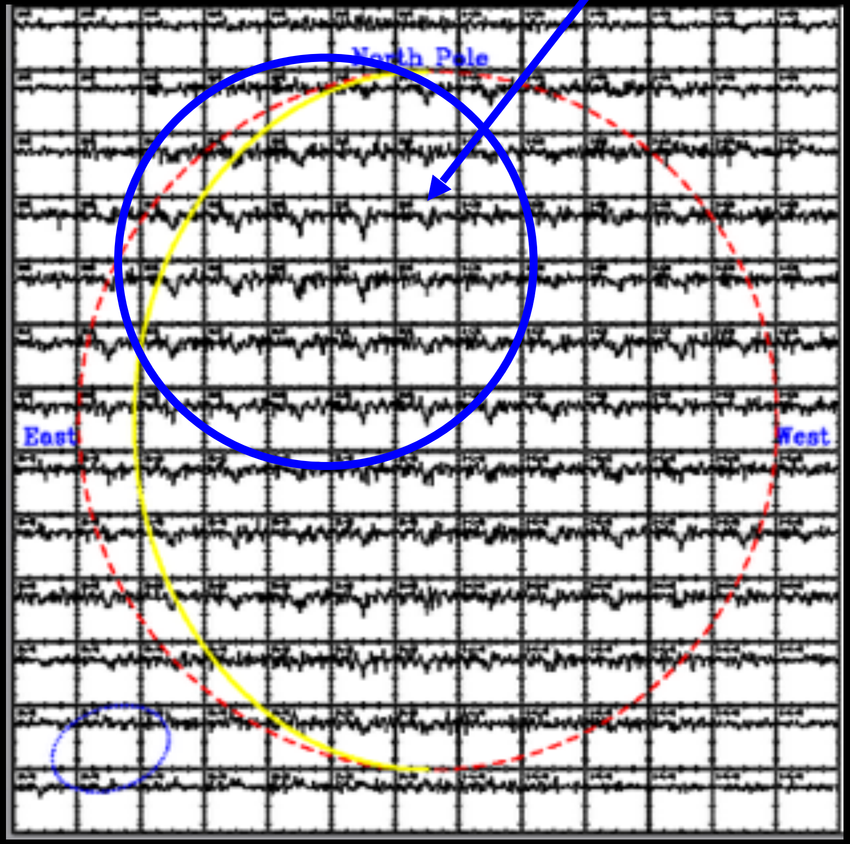
Water tracer : HDO

Modeling of disk-integrated line on one date (Nov 14th, 2011) assuming typical thermal profile

Abundance profile may indicate increase w altitude



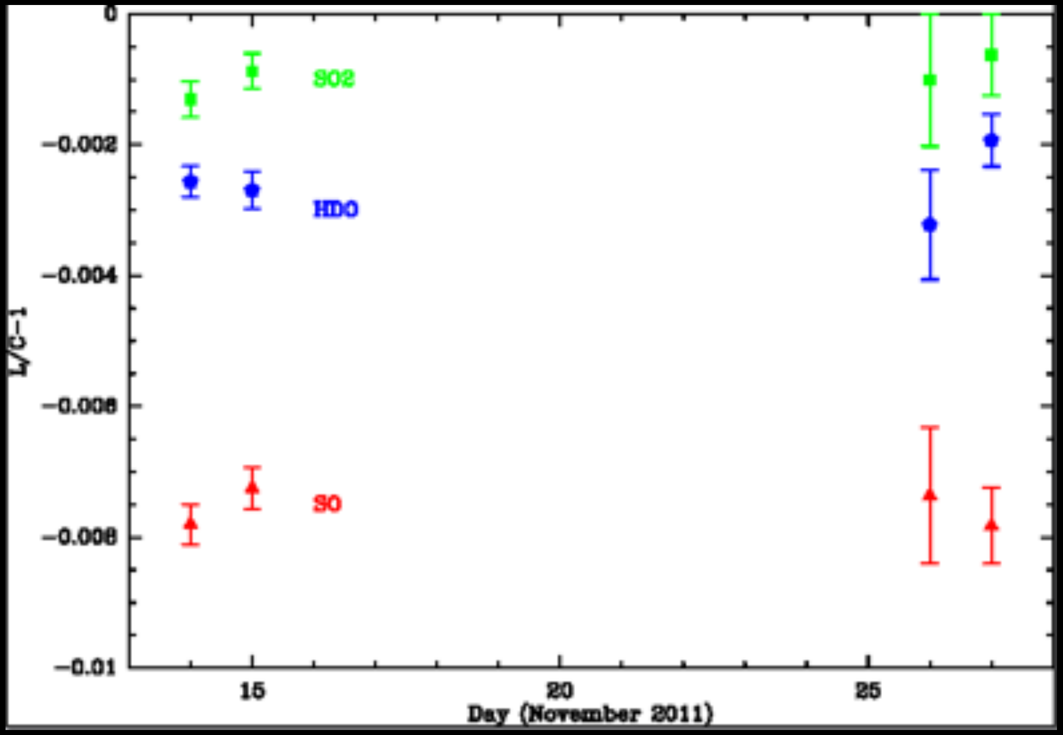
335.395 GHz HDO line map, Nov. 14th, 2011



Consistent with H_2O ~1-1.5 ppm

(assuming typical [D/H])

Temporal abundance variations



Temporal variation of line depth on 346.528 GHz SO, 346.652 GHz SO_2 and 335.395 GHz HDO

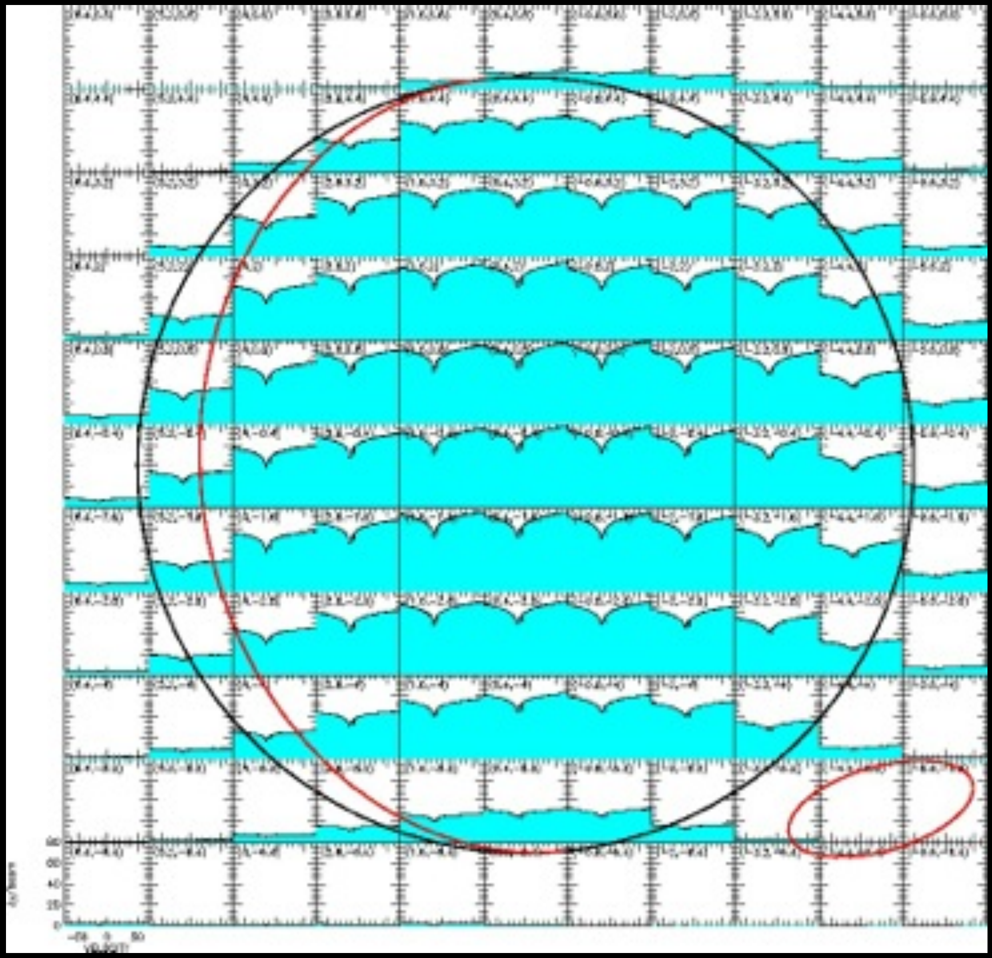
Variations on 24 hour and 11 days timescales

no significant HDO, SO and SO_2 abundance variations

Mesospheric Doppler-shift mapping

Line cores of CO(3-2) lines sound 95-105 km (sub-Earth point)

Gaussian-fit of line-cores indicate line-of-sight projected velocity



Subsolar-antisolar wind :
Increases with solar incidence up to $V_{terminator}$

Retrograde zonal wind :
~ solid rotation (constant w longitude)

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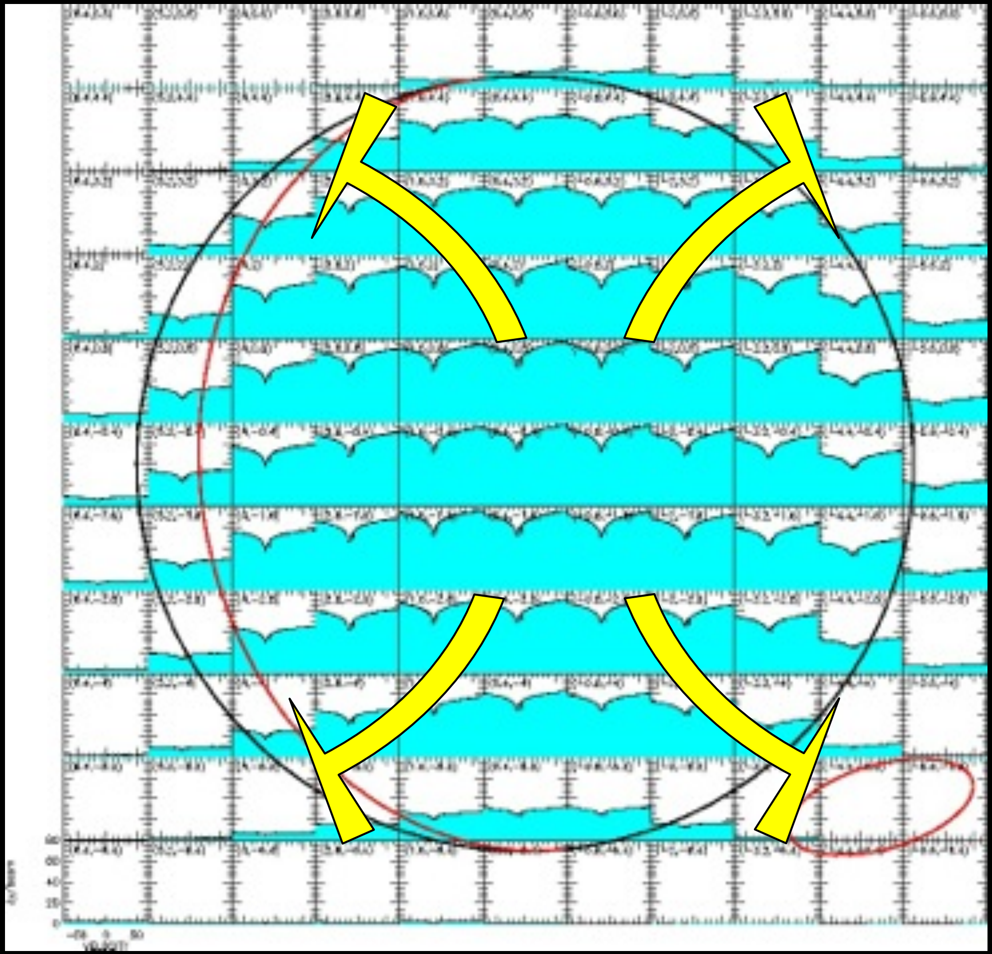

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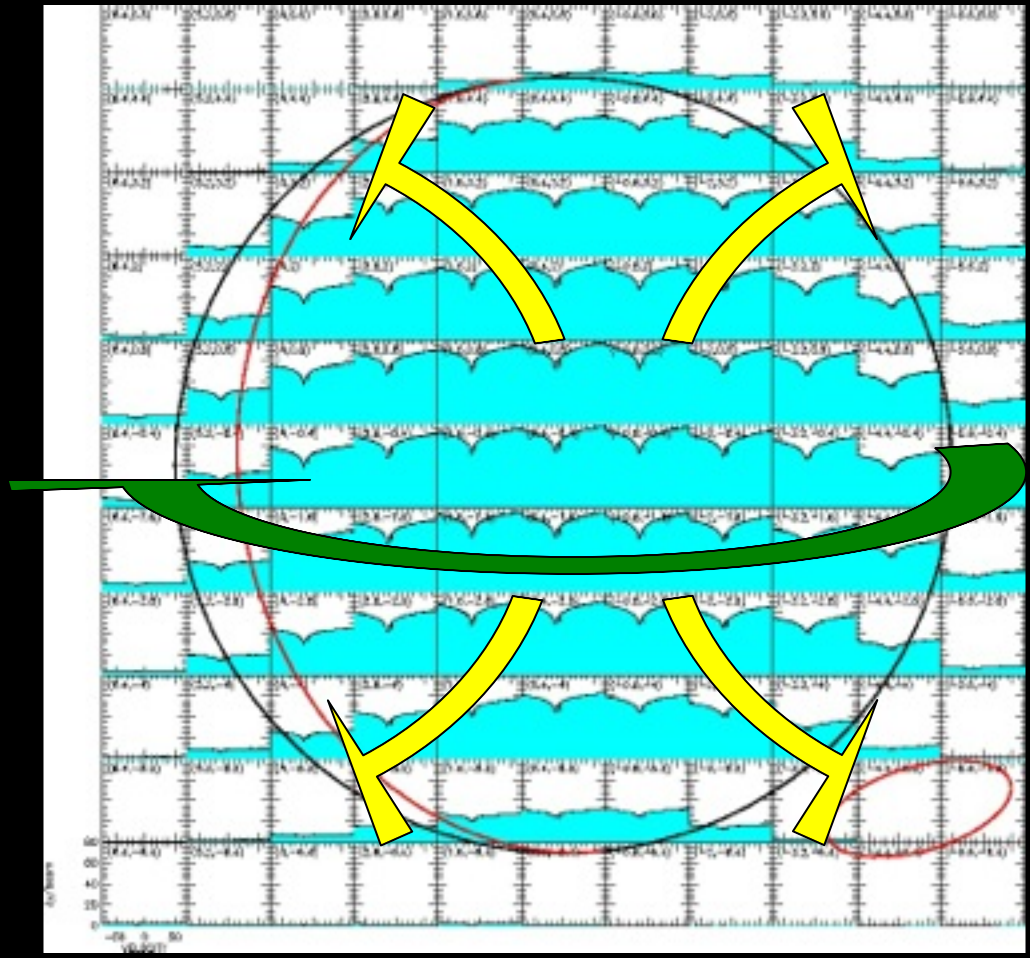

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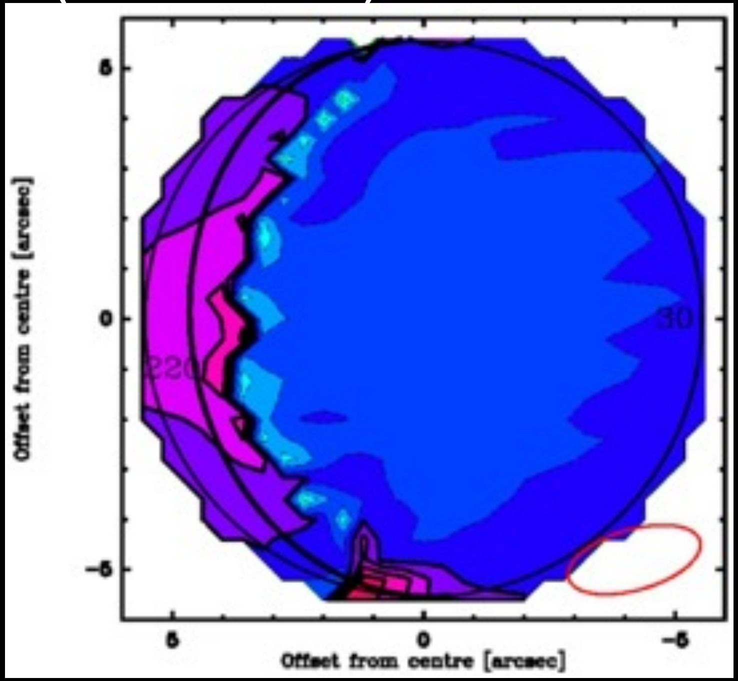
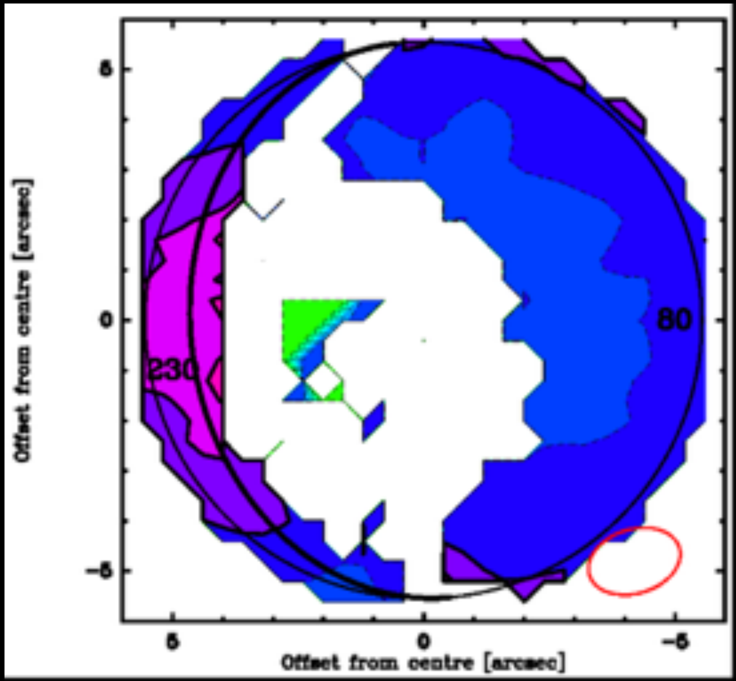
Doppler-shifts results

Similar wind pattern over ~ 24 hours. Errors ~ 10 m/s
- **all-over redshift**
- **East/ West asymmetry**
- >200 m/s Doppler-shifts on Eastern limb (terminator)



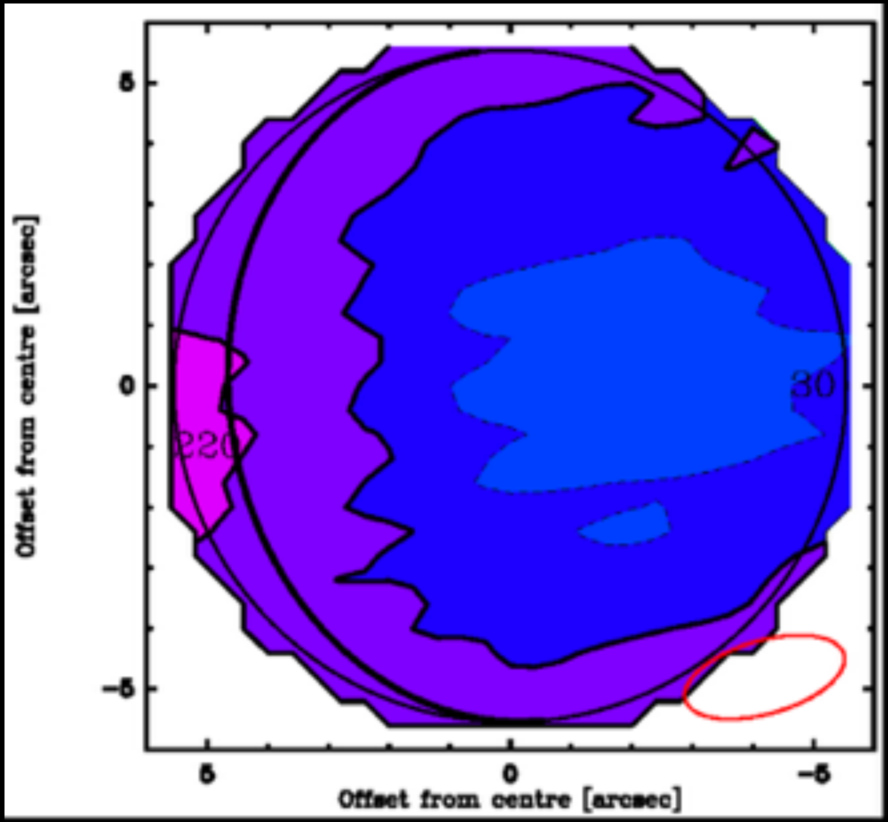
Doppler-shift map, Nov 14th



Doppler-shift map, Nov 15th

Wind modeling

Measured Doppler-shift assymetry can be partially explained by **limb insolation difference** in the context of SSAS wind (East limb: 4 AM, West limb: 8 PM)



Best Doppler-shift synthetic model
for Nov 14th, 2011

Best models combine :

- **dominant SSAS wind** (V_{ter}= 211/245 m/s)

- zonal retrograde wind in an equatorial band (V_{equ}= 50/30 m/s),

Temporal variations of
up to 35 m/s over 24 hours

Summary

• First **high-resolution mapping of day hemisphere** at (sub)mm wavelengths (line/continuum < 0.1%)

I Wealth of information to be analyzed on S-species and water distribution, mesospheric dynamics, on different timescales

I Vertical profile suggests **additional middle-mesospheric source** for S-species, photolysis source of SO

I Upper mesospheric wind consistent with **dominant sub-solar/anti-solar wind**, moderate equatorial zonal wind