Sub-mm Observations of Venus

Studying atmospheric temperature, dynamics and chemistry

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Venus observations with JCMT

- Since 2000, submm spectroscopic observations with JCMT have supported altitude-resolved (= distinguishing information from different altitudes in the atmosphere) measurement of **minor species abundances** (CO, SO, SO_2, HDO, HCl), as well as **temperature** and **Doppler winds** in the Venus mesosphere and lower thermosphere (70-110 km altitude).

Understanding planetary atmosphere is to study the physical/chemical interactions between…

Radiation	Dynamics	Chemistry
Thermal structure, Energy budget, Cloud microphysics	Material & momentum transport, Atmospheric escape	Composition, Atmospheric evolution, Cloud microphysics, Heterogeneous chem.

- Submm observations (including the ones we are doing with JCMT) are very powerful tool for planetary (atmospheric-)science!

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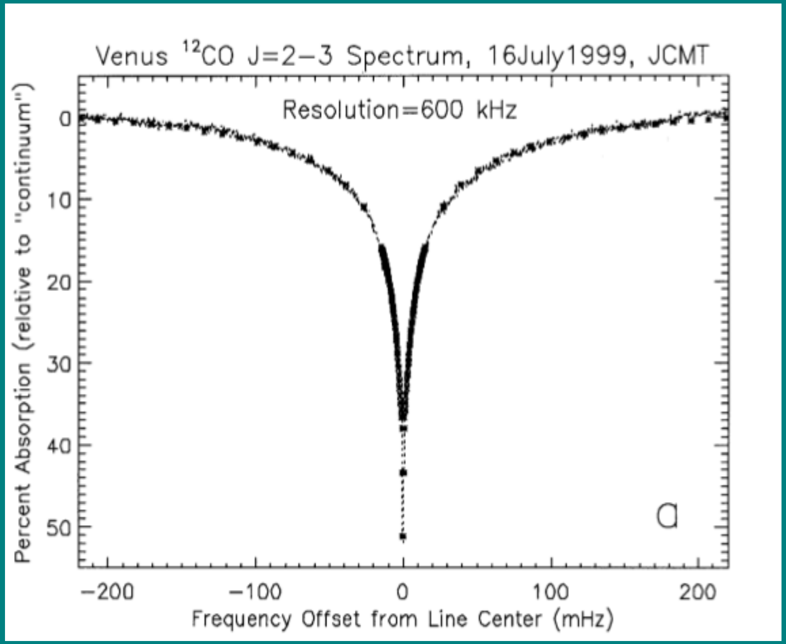
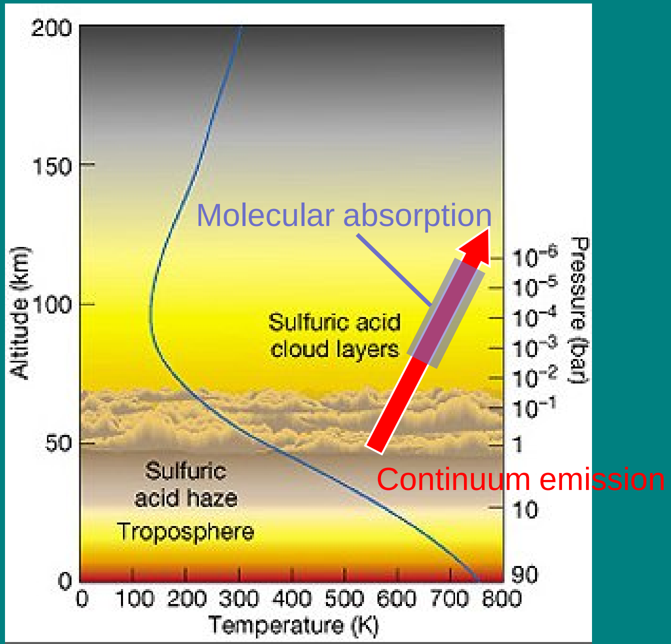
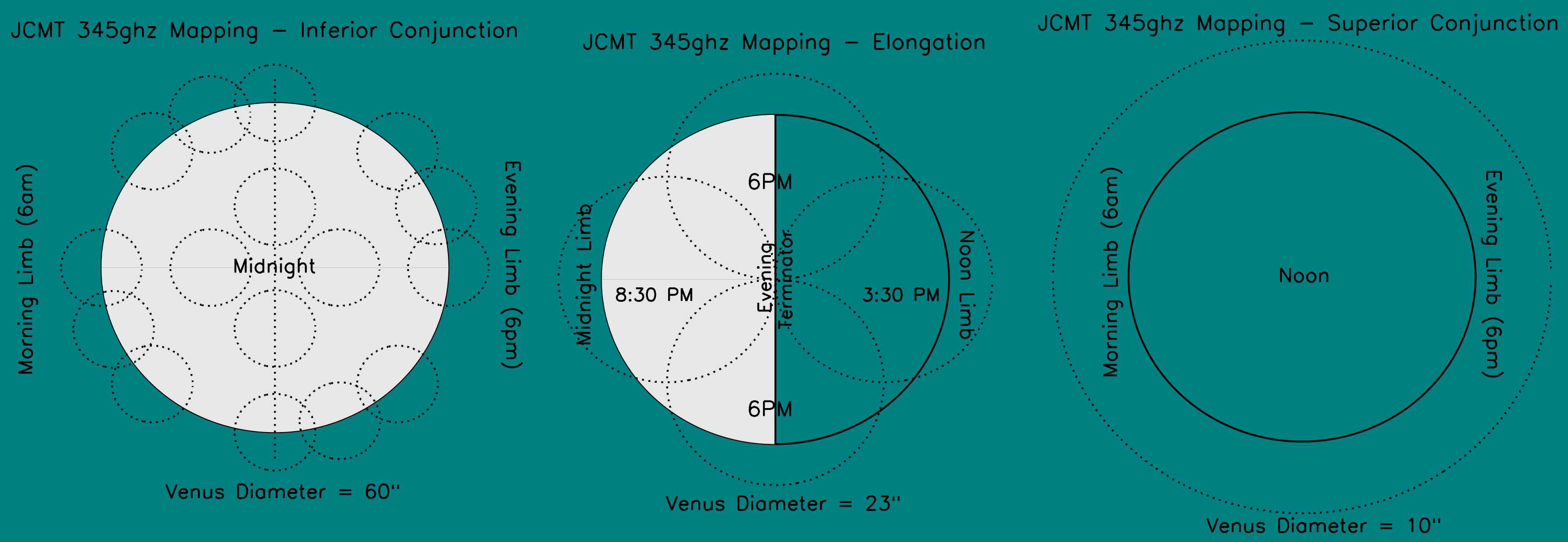
Shaped by the pressure-broadened (due to collisions of molecules in the atmosphere) line width.
→ Different line widths in a spectrally-resolved data represent the opacity and the Doppler shift information at different pressure levels (= different altitudes).



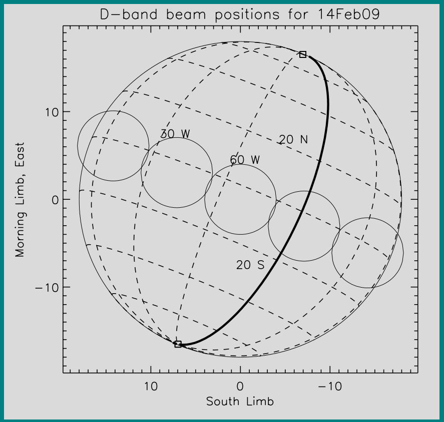


Spatial resolution (Venus disk = 10 – 60")



At 330-352 GHz, the 14" beam limits our capability to spatially resolve the Venus dayside. At inferior conjunction (full nightside), 20+ positions are observed on the 60" disk (*above left*). In contrast, at full dayside the 10" disk (*above right*) allows only disk-average data. Limited dayside resolution is obtained at half phase (25-35" disk, *above middle*).

Best resolution is obtained at 625-691 GHz (D-band), with corresponding 8" beam footprint. At quarter phase (*fig at right*), multiple dayside positions are observed independently, and cross-terminator behavior is characterized.



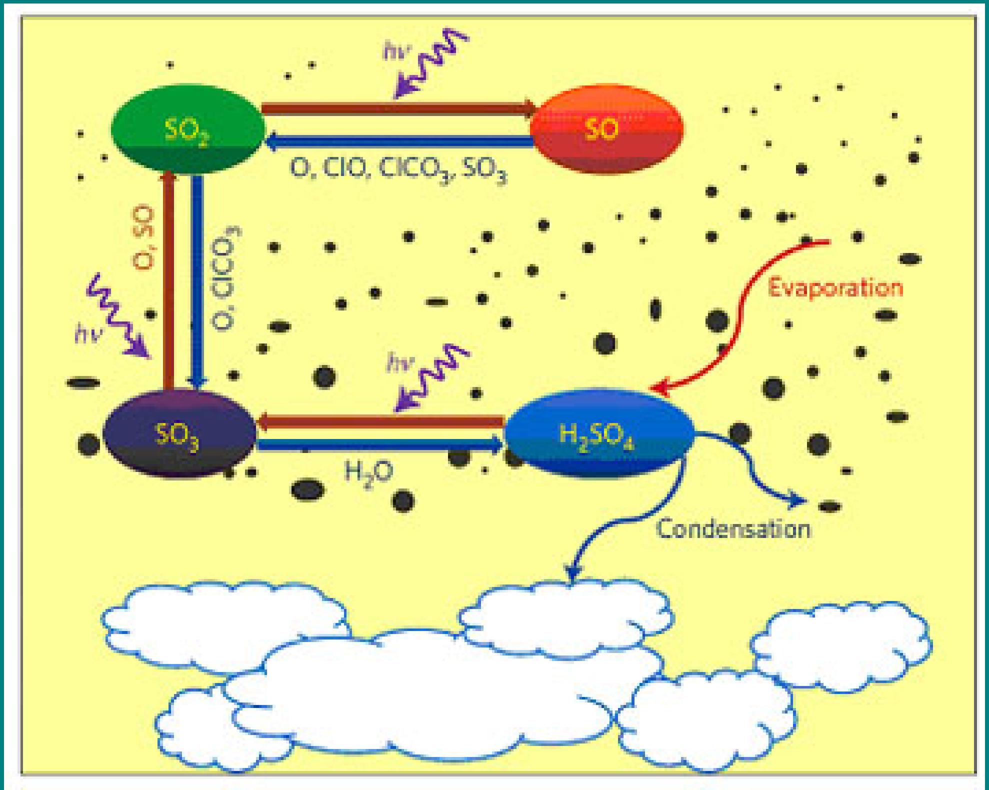
JCMT Discoveries on Venus atmosphere!

8 with B-band & 1 with D-band

1. SO and SO_2 (SO_x) abundances are altitude increasing - the reverse of prior model prediction that they would be altitude decreasing.
2. A photochemical mechanism subsequently proposed to explain the observed SO, SO_2 altitude dependence is not compatible with a strict observational upper limit for H_2SO_4 abundance.
3. Equatorial HCl abundance decreases rapidly above 80 km - contrary to model expectation of HCl to be the dominant Cl reservoir below 110 km.
4. Observations since 2004 show SO and SO_2 abundances each undergo strong (factor of 20) temporal variations, which exhibit diurnal influence, but not control.
5. Measured HCl shows strong variation on a 1-month timescale.
6. Observed spatial patterns of nightside temperature and CO change profoundly between consecutive inferior conjunctions.
7. At most times, nightside doppler winds in the lower thermosphere (100-110 km) are predominantly zonal, with a significant (smaller) SubSolar to AntiSolar (SSAS) axisymmetric component. In a small number of cases this is reversed, with SSAS-dominated flow.
8. Nightside hemispheric winds can change between zonal and SSAS dominance on a 1-week timescale.
9. Venus solar transit data reveal terminator winds to be supersonic, and time variable on a 1-2 hour timescale.

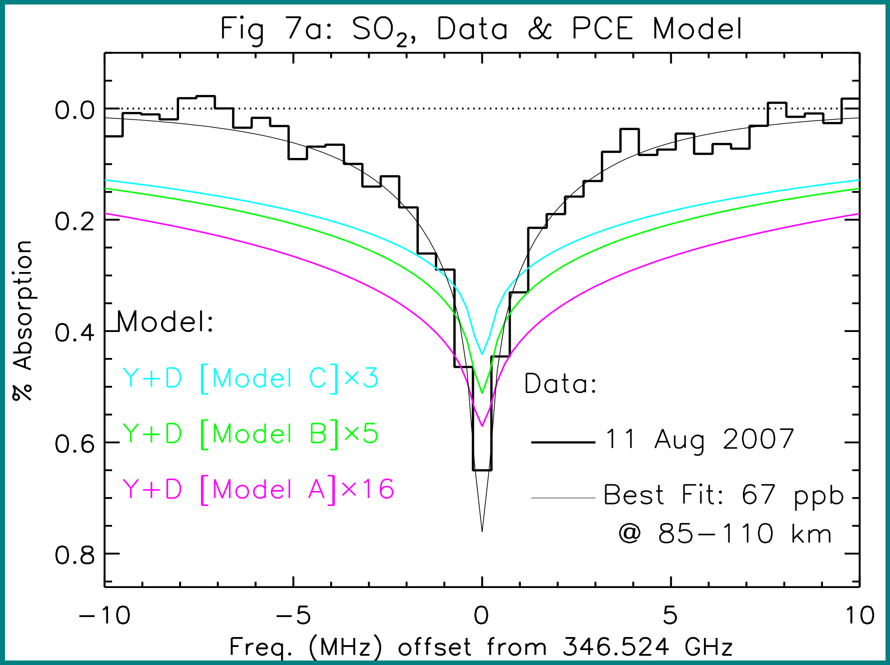
SO_2 and SO Altitude Dependence

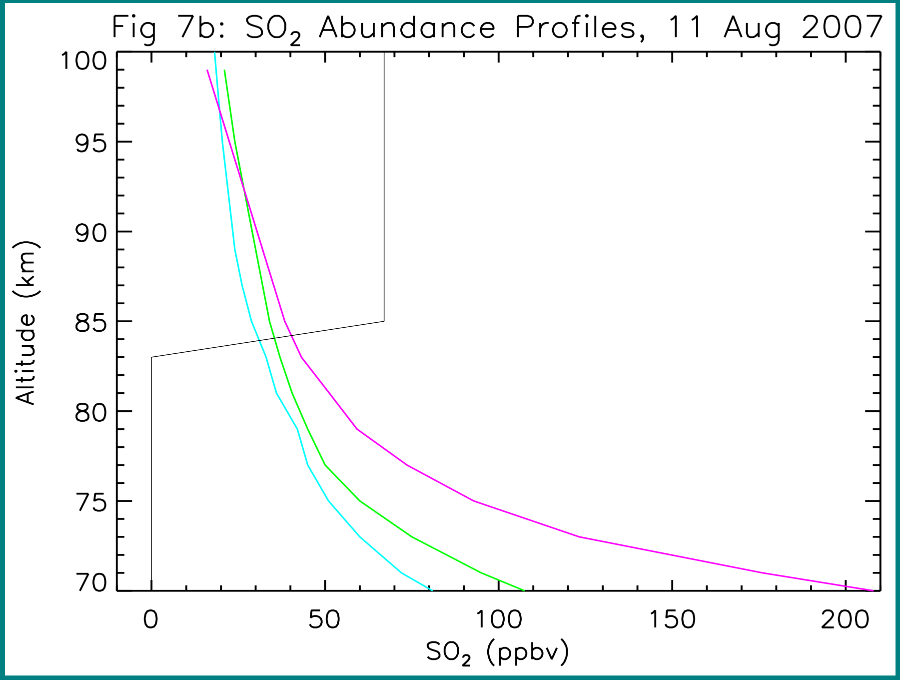
- SO2 is the major source (and also sink) of the thick H2SO4 cloud of Venus.
- Sulfur chemistry is one of the key reaction cycles in Venus atmospheric chemistry.



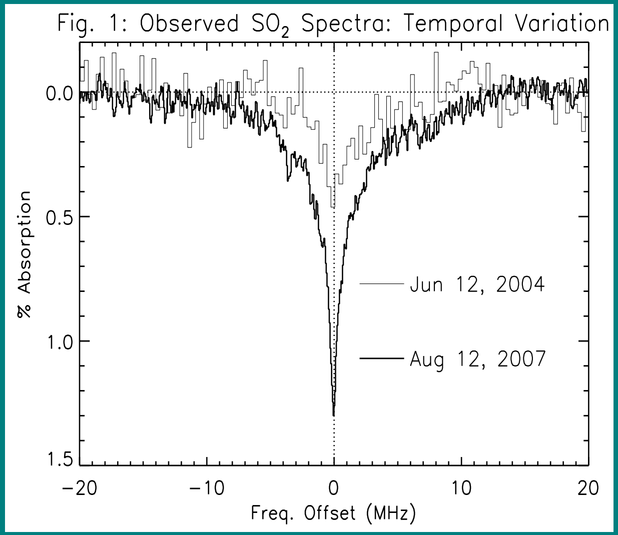
SO_2 and SO Altitude Dependence

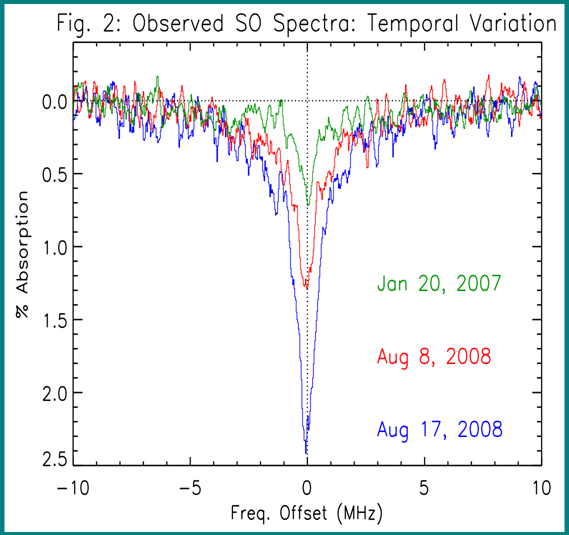
- Photochemical model SO_2 (*below right; blue, green, purple; Yung and Demore model, 1982*) decreases with altitude. Chemistry includes upward transport of SO_2, with no known chemical production mechanism in the mesosphere.
- Observed SO_2 submm spectra are <u>much narrower</u> than synthetic spectra corresponding to Y+D model SO_2, <u>indicating data are not consistent with theoretical altitude dependence</u>. The retrieved (measured) SO_2 abundance increases abruptly at 84±2 km.
- **Conclusion:** A presently unkown in-situ SO_2 production mechanism must exist in the upper mesosphere (*Sandor et al., 2007, 2010*).

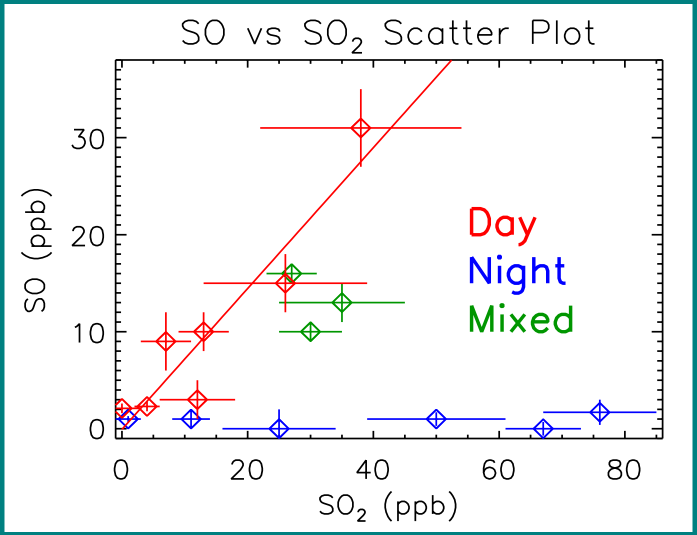




SO_2, SO Temporal Variation

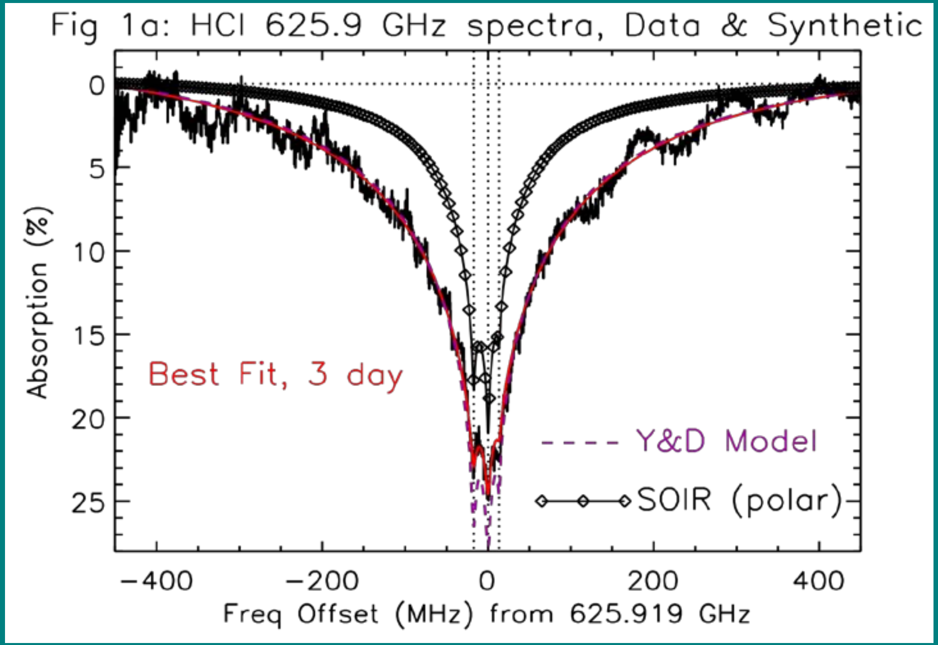


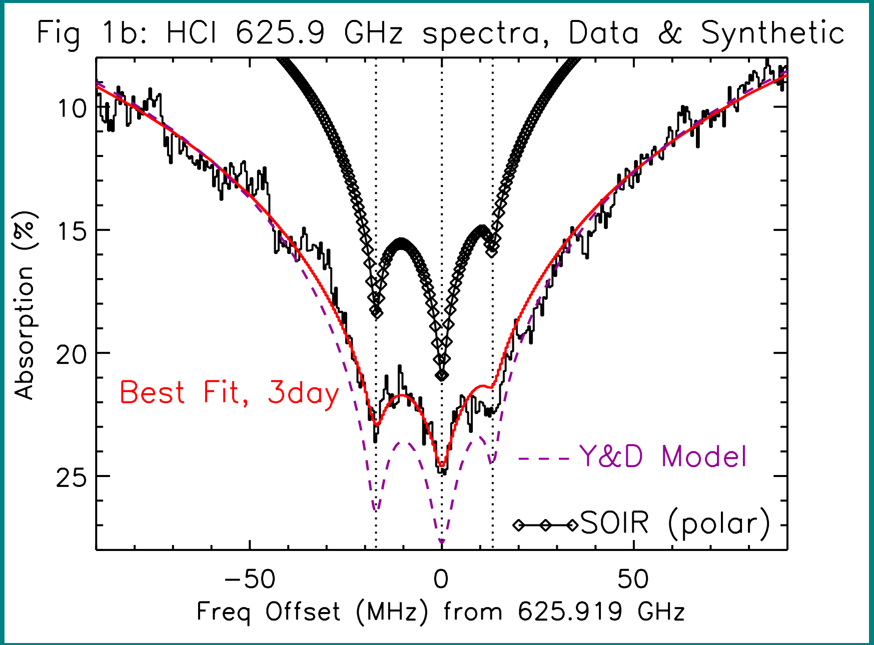




- ***Secular (non-diurnal) temporal variation is strong.*** Nightside SO_2 abundance changed by a factor of 2.5 between 2004 and 2007 (*above left*). Dayside SO abundance variation is evident among 3 dates in 2007-08 (*above middle*). Note SO abundance doubled over only 9 days in Aug 2008.
- ***Diurnal influence is also clear***. The scatter plot (*above right*) shows dayside SO and SO_2 are positively correlated, with abundance ratio 1:1. Nightside SO abundance is always small, with maximum nightside SO_2 roughly equal to maximum dayside total [SO_2+SO].

HCl: 70-95 km Altitude-Resolved Measurements





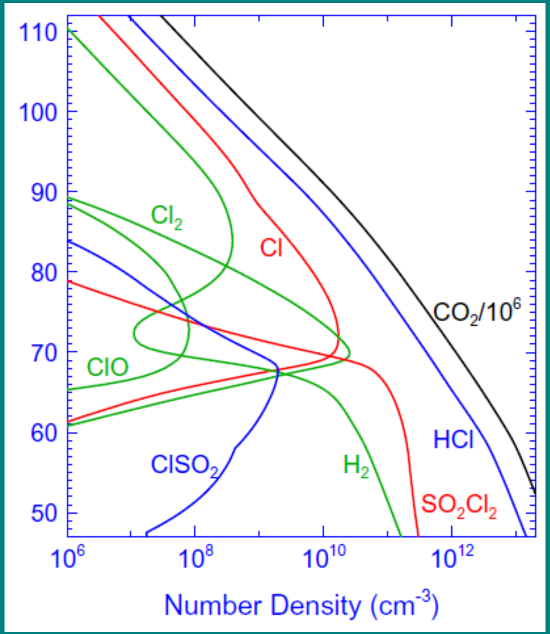
- The 625.9 GHz $H^{35}Cl$ absorption was observed at 1000 MHz bandwidth on 3 days in 2010 (*left fig, 3-day mean*). The left fig. presents only the middle 180 MHz of that spectrum.
- First measurements of equatorial HCl above 74 km were retrieved from these data (Sandor+Clancy, 2012). Width of ±500 MHz indicates large HCl abundance in the lower mesosphere. The absorption is formed by three HCl transitions (vertical dotted lines). Those lines are resolved in the data based upon absorption above ~80 km. Below 80 km, pressure broadening blends the three lines, such that they cannot be individually distinguished.

HCl: 70-95 km Altitude-Resolved Measurements

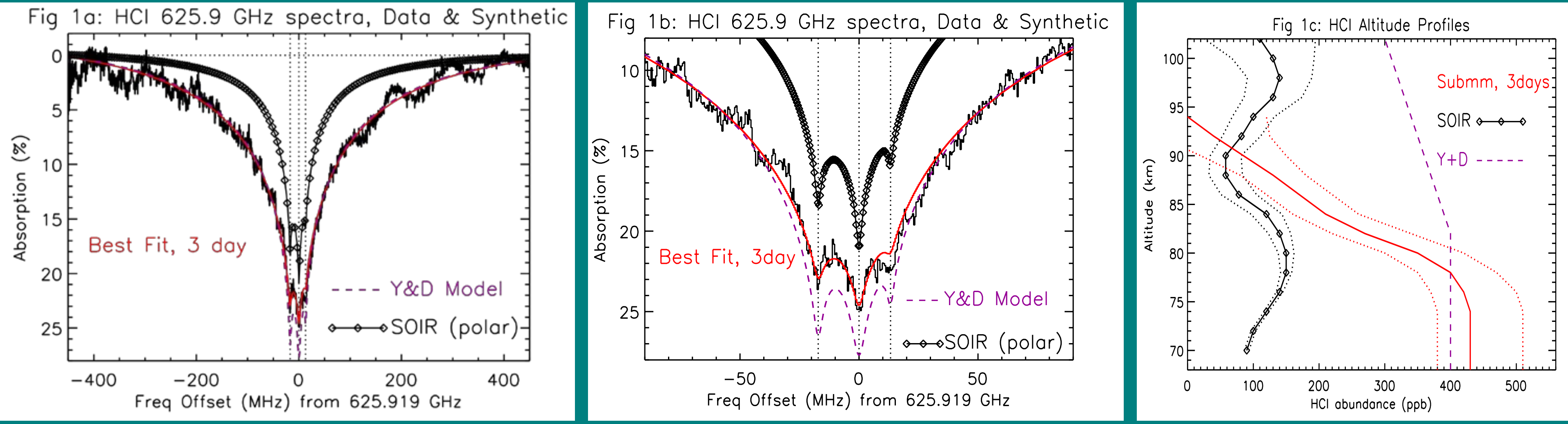
- Venus (and Martian) CO_2 atmosphere easily photo-dissociates into CO and O.
- Direct recombination of CO + O → CO_2 is spin-forbidden, therefore there should be certain mechanisms to recover CO_2 atmosphere; otherwise, all CO_2 can be changed into CO and O within a few thousands years [e.g., McElroy and Hunten, 1970]. (**"Stability of Venus atmosphere"**)

- It is suggested that **catalytic cycle (ClOx, HOx) should accelerate the recombination to CO_2**.
- HCl is the main reservoir of Cl.

  → Measuring HCl abundance is key to understand how much Cl exists in Venus atmosphere.



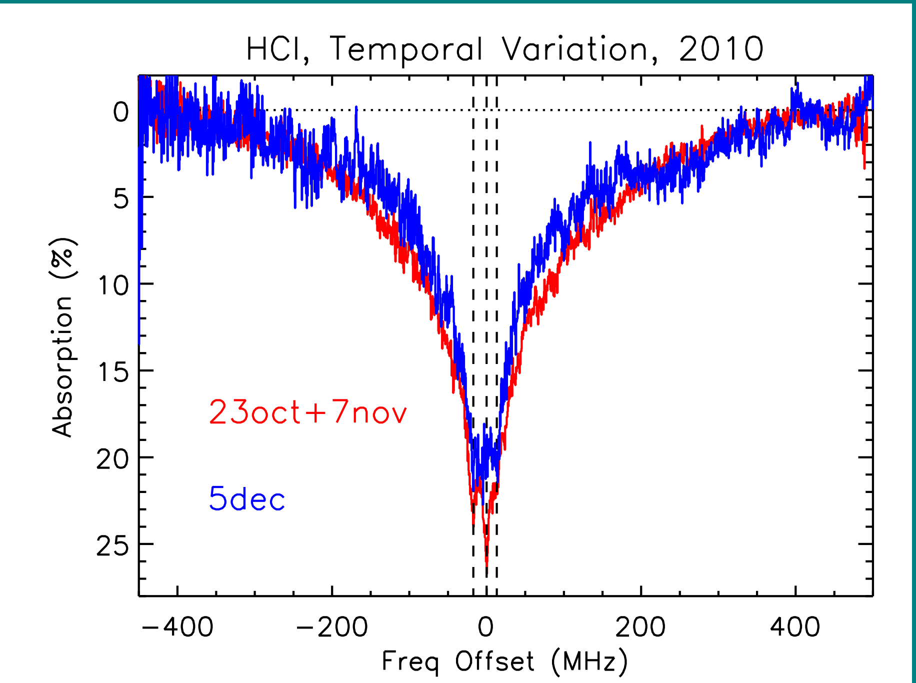
HCl Altitude Dependence

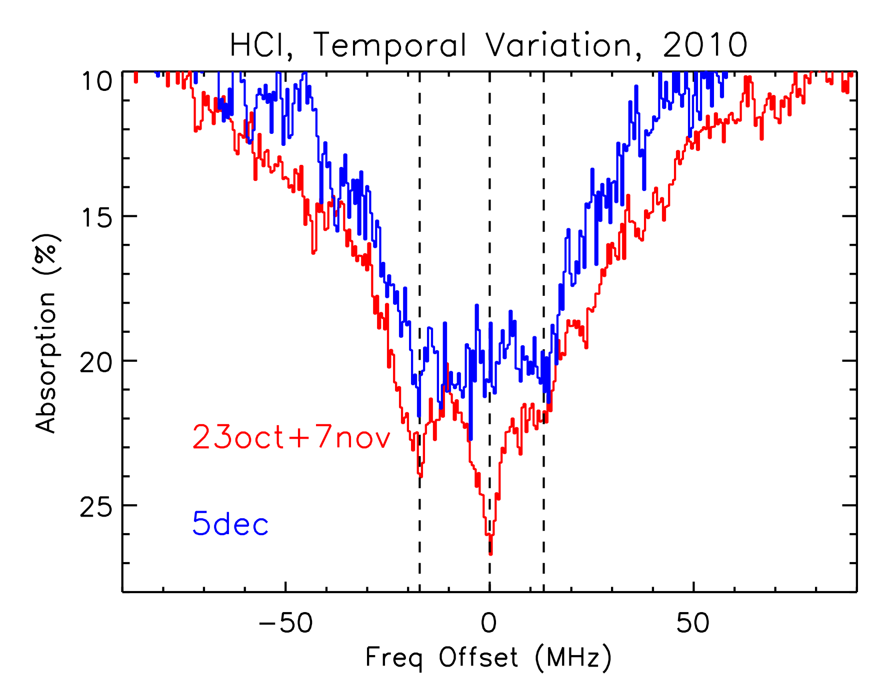


- The best-fit synthetic spectrum (red, *left and middle*) corresponds to the retrieved HCl altitude profile (red, *right fig*). Lower mesospheric values agree with the Krasnopolsky (2010) measurement at 74 km. The *right fig*. also shows model-predicted HCl dashed; (Yung+Demore, 1982), and SOIR-measured polar-latitude HCl (symbols; Vandaele et al., 2009). Corresponding synthetic spectra are also shown (*left; middle*).
- **Conclusion:** Theoretical expectation of HCl distribution is very likely wrong.
- **We suggest**: Downward transport of HCl-poor thermospheric air might drive the departure from theory seen in these nightside submm data. Consistent with this mechanism, stronger, deeper descent (to 70 km) over the North Pole could explain the low abundances seen with Venus Express/SOIR.

HCl Temporal Variation

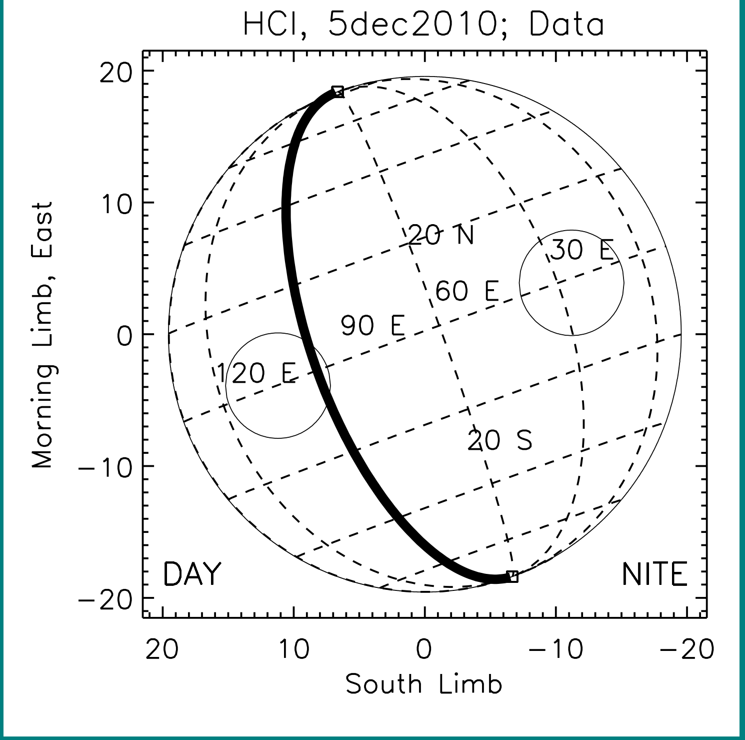
- HCl 626 GHz spectra observed Oct 23 & Nov 7, 2010 consistent, but the Dec 5 observation shows HCl decreased, especially above 80 km, in a 1 month period.
- Three individual line positions (right fig) are evident in Oct-Nov spectra (red), but not in the Dec data, indicating significant reduction of HCl abundance above 80 km.
- Difference in broad absorption (left fig) indicates a smaller HCl decrease in lower mesosphere.

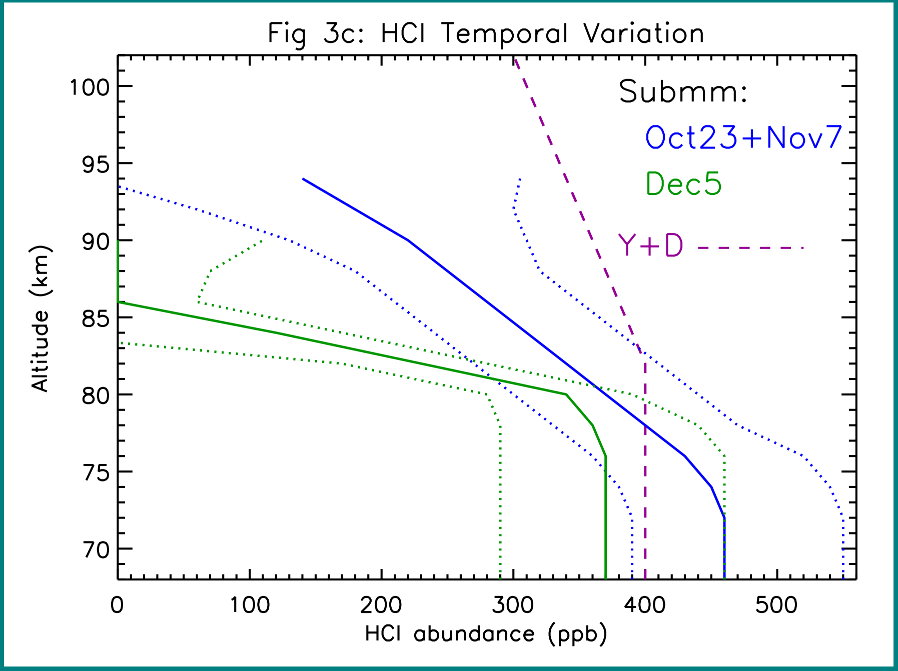


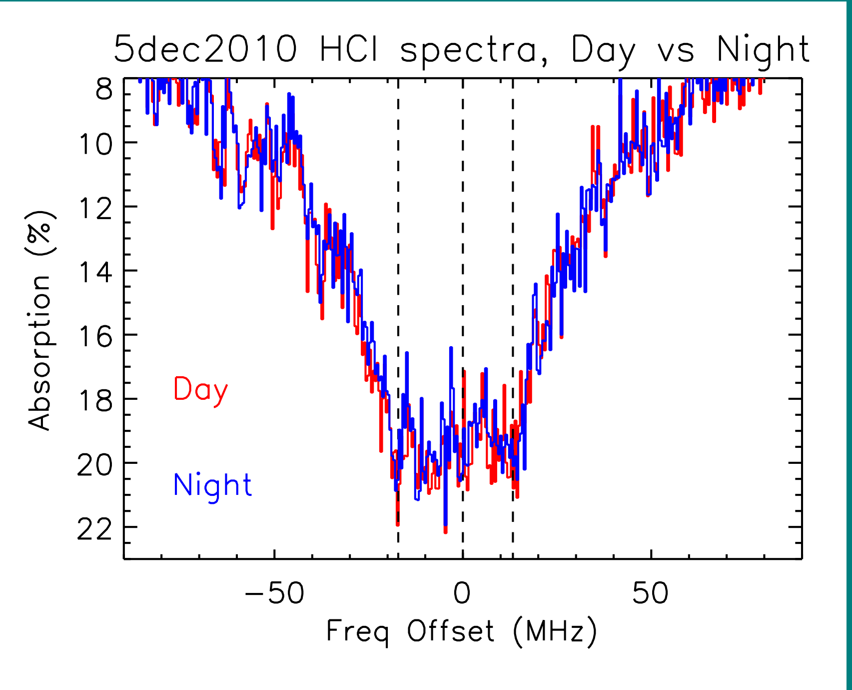


No Diurnal HCl Variation, 1am-7am

- Simultaneous 7am, 1am HCl observations were made on Dec 5, 2010. No diurnal variation is evident across this time range.
- Dec 5 post-dawn (7am) and night (1am) HCl altitude profiles are similar to each other, and each is much different than those observed Oct 23 and Nov 7 (midnight).

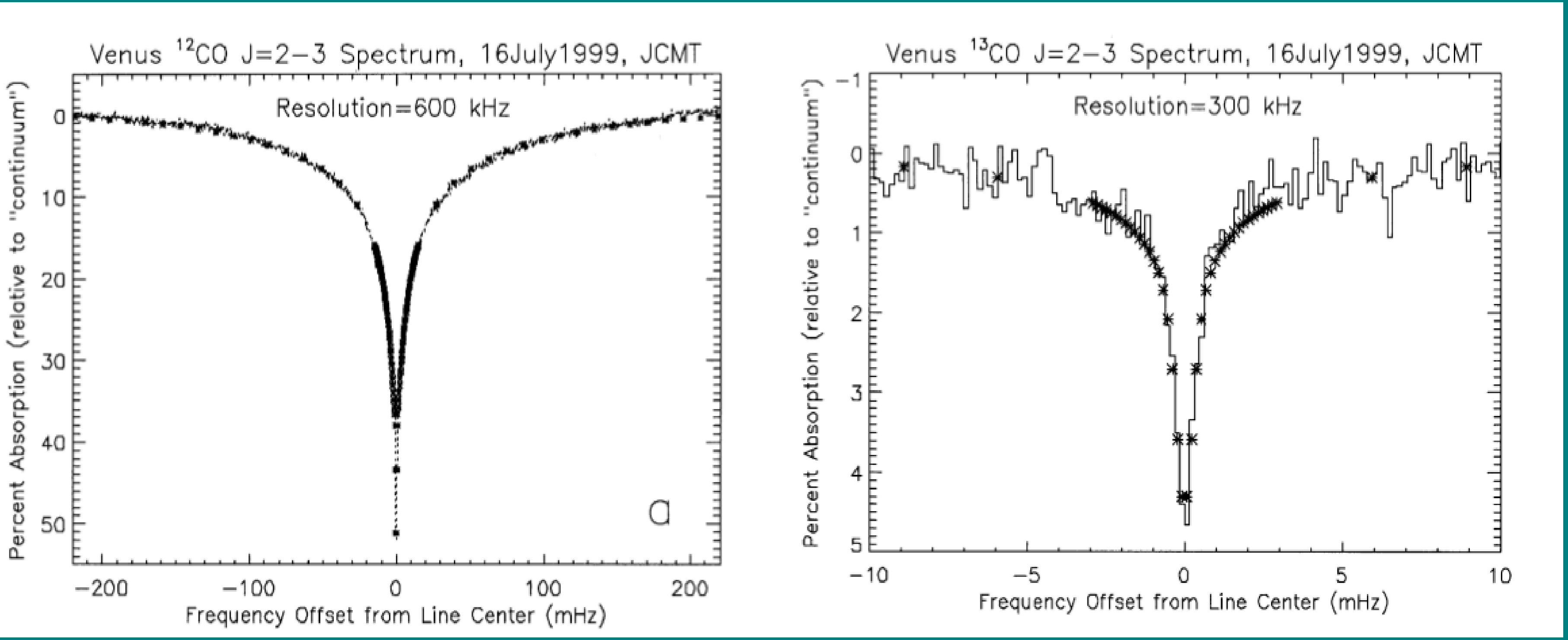






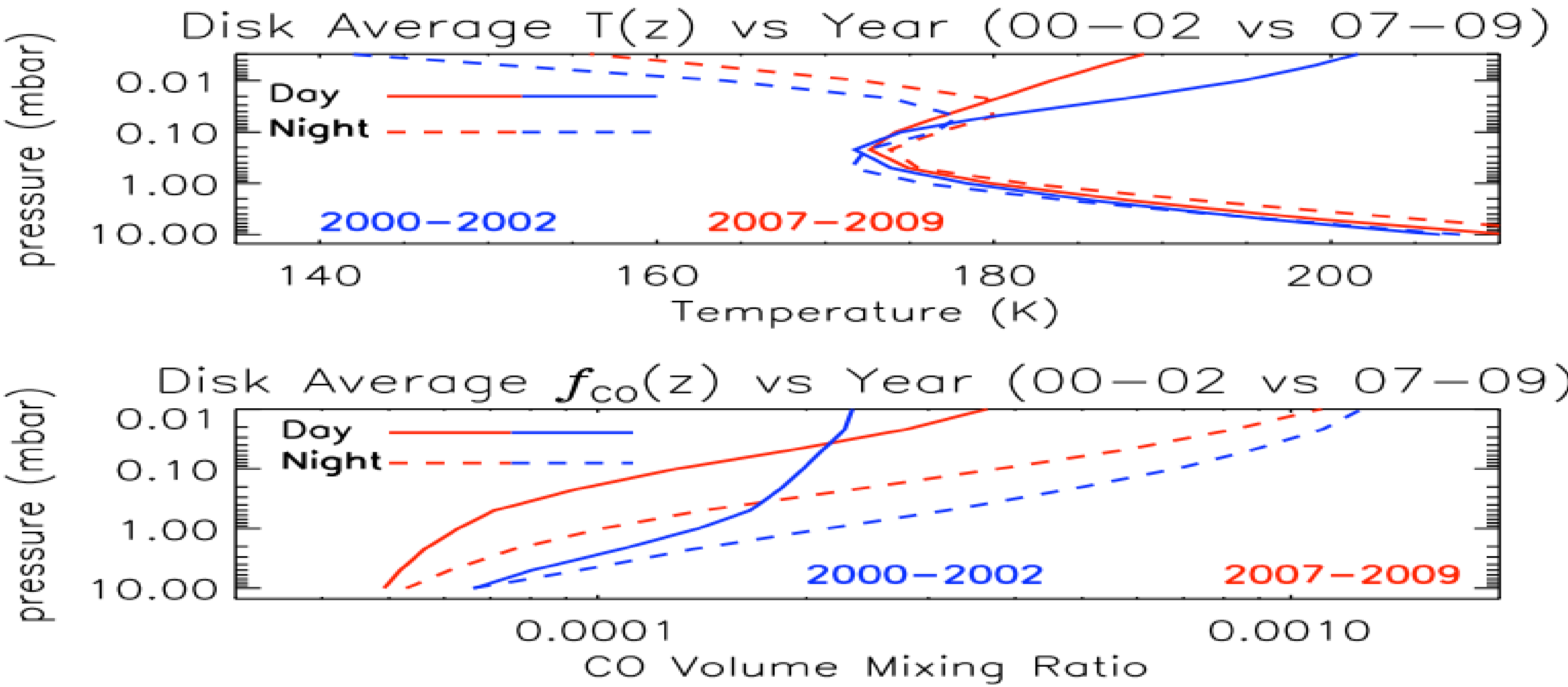
Temperature and CO Altitude Profiles

- Temperature and CO abundance altitude profiles are obtained by coordinated retrieval from simultaneous, co-located observations ^{12}CO (optically thick) and ^{13}CO (optically thin) spectra. Nightside spectra are shown below.
- Both lines are required, as use of only one (^{12}CO or ^{13}CO) does not allow separation of CO abundance from temperature.



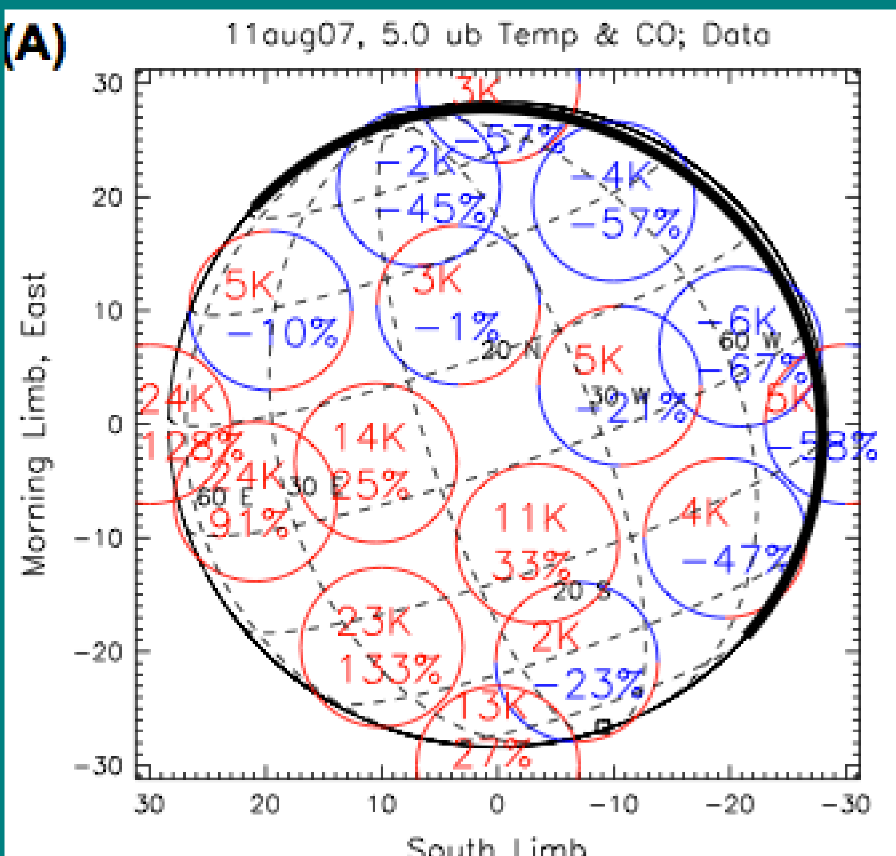
T, CO disk average day vs night : “climatology”

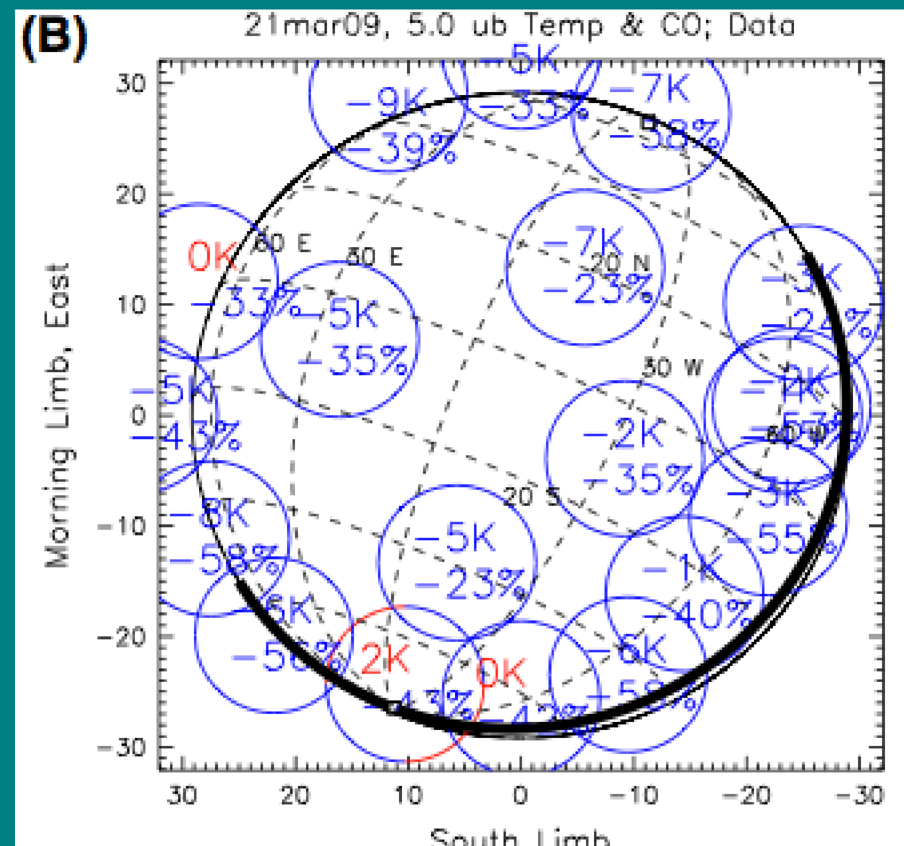
- Dayside exhibits a hot, Earth-like thermosphere, and less CO than nightside Clancy et al., 2003; 2012a).
- Nightside has cold cryosphere, and large CO abundance.
- Magnitude of the diurnal T, CO variations decreased over the seven year period 2001-2008.



T, CO **spatial distributions** in the Nightside Lower Thermosphere

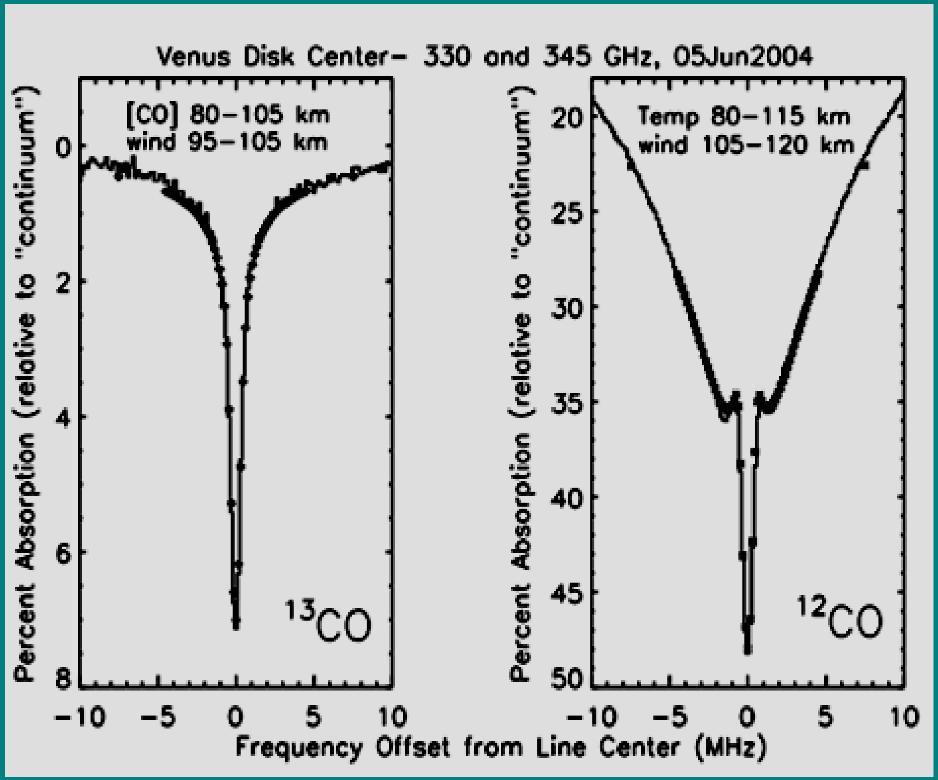
- T and CO are strongly correlated on the nightside. Downward transport both enhances CO abundance and drives compressional heating.
- Location of strongest downward flow varies among inferior conjunctions.
- At 105 km, strongest descent was at local time 2am, latitude 10-15° S in Aug 2007 (*fig A, left*), and at equatorial midnight in Mar 2009 (*fig B, right*).

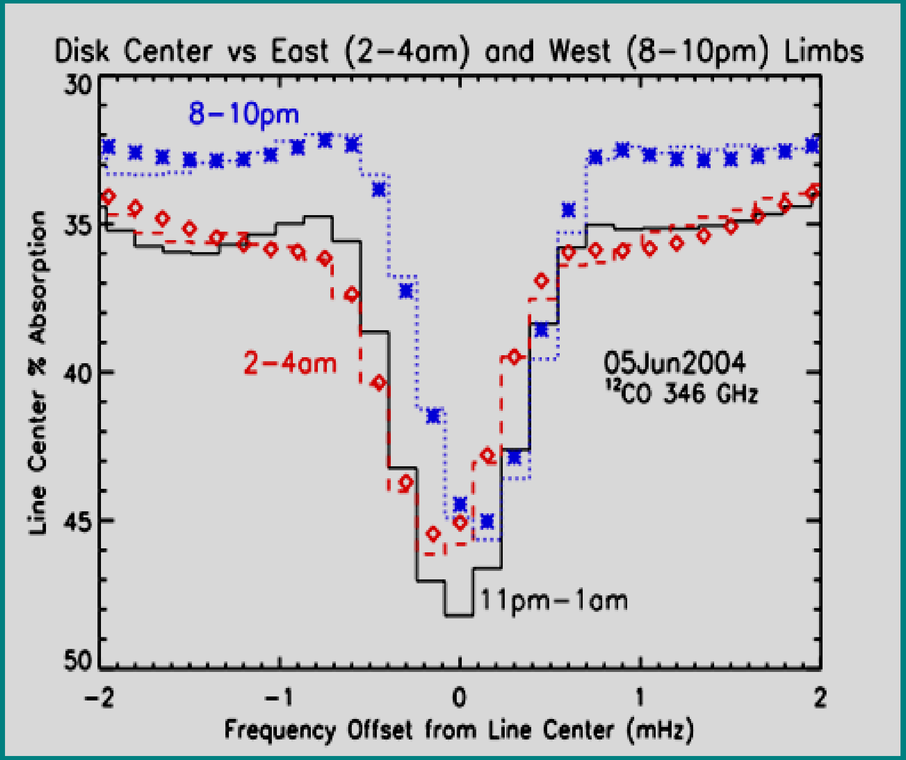




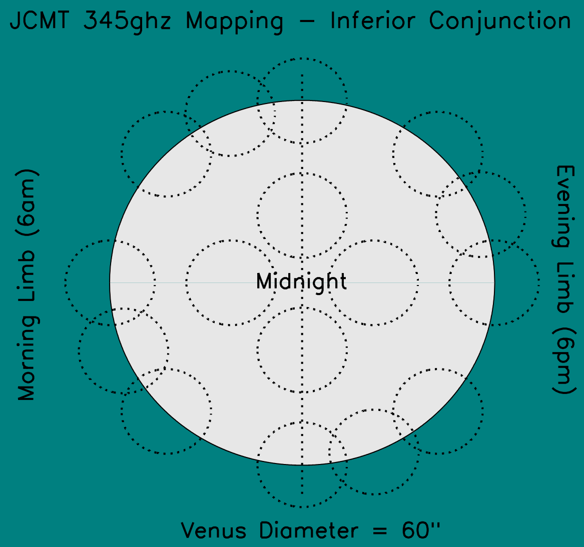
Nightside Doppler Winds

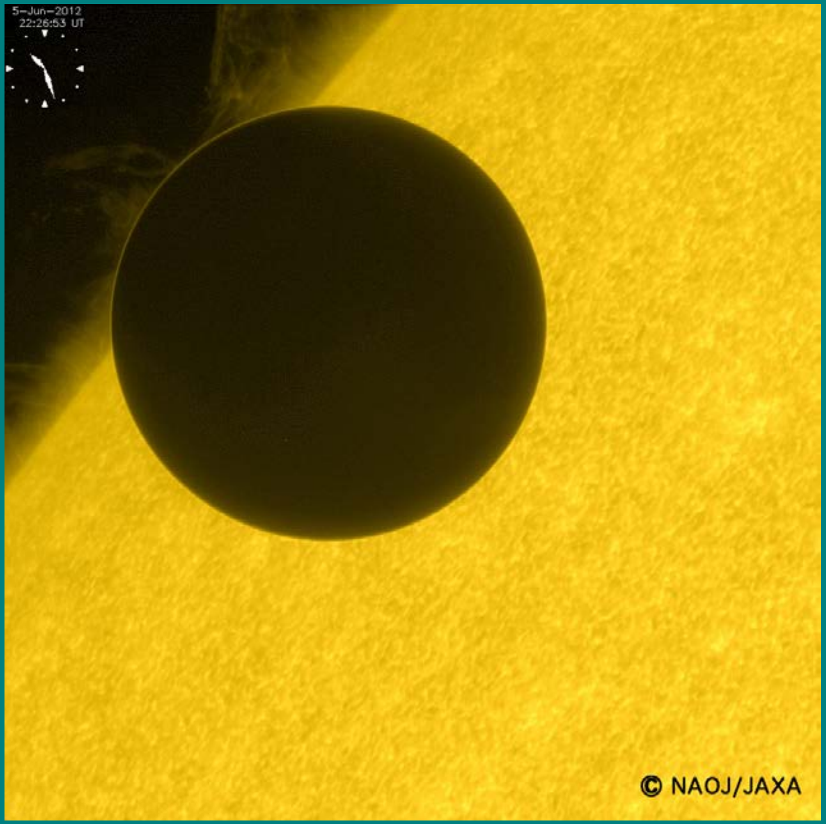
- Nightside lower thermospheric winds (100-110 km; Clancy et al., 2008; 2012b) are measured based upon doppler shift of the narrow ^{12}CO, ^{13}CO line cores (*left fig*).
- In the (*right fig*) example, winds are blue shifted (approaching) at 8-10 pm, and red shifted (receding) at 2-4 am, where the zero-wind reference is equatorial midnight (11pm-1am, black).





Venus solar transit observations of terminator wind





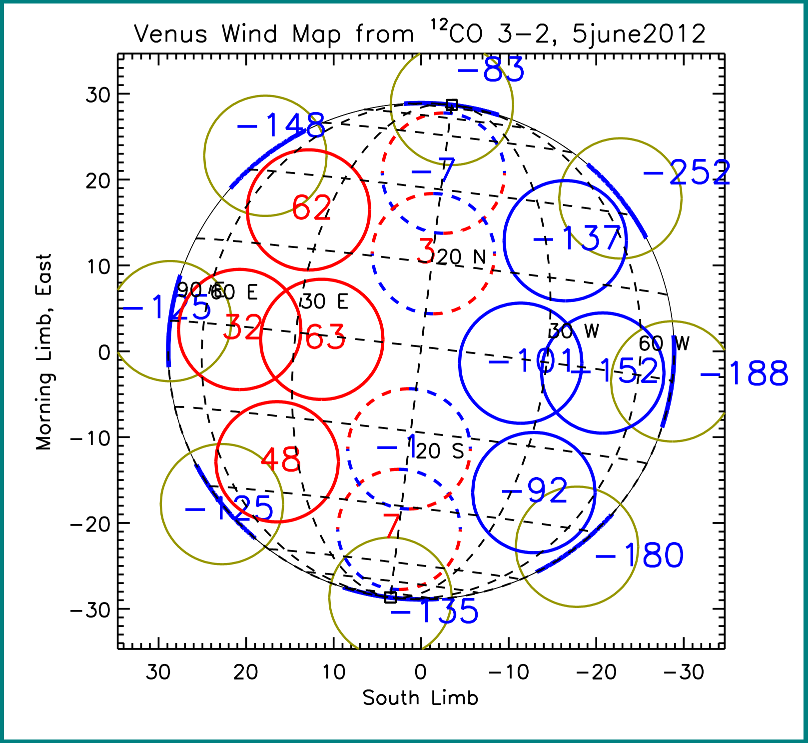
- Solar transit on 5-June 2012 afforded the best (and non-repeatable!) opportunity to study the cross-terminator wind (>90% weight on "only" terminator)!

Venus solar transit observations of terminator wind

- Zonal wind dominates the 110 km nightside. However, dayside measurements by other observers (Goldstein et al., 1991; Sornig et al., 2008, 2012), are more consistent with SSAS circulation.

  → **A transition region must be present at or near the terminator.**

The combined map (left fig) shows wind is primarily zonal on the nightside, but primarily SSAS across the terminator (Clancy et al., 2012; 2015).



Summary of Findings

- Ground-based submm observations of Venus with the JCMT reveal extreme temporal variability in its middle atmosphere. They are uncovering photochemistry far different from, and dynamics far more intricate than theoretical expectations.
- Sulfur and chlorine chemical cycles are fundamental to the state of the Venus atmosphere. Submm observations of SO, SO_2, HCl altitude and temporal behaviors both identify serious problems in our understanding of these cycles, and enable advancement of that understanding.
- Global submm observations of temperature, CO and winds support new investigations of atmospheric dynamics, research which previously had been hampered by absence of data.
- Basic laboratory work shows that sulfur, chlorine, and hydrogen compounds interact chemically, and with temperature dependence.
- *Hence spatial/temporal variability of any one of these observables (SO, SO_2, HCl, water, CO, temperature, wind) can only be understood through coordinated study of all of them.*

Ongoing Work

- Understanding the relationships among the temporal variations of individual molecules is critical to identifying the mechanism(s) that drive variation.
- As one example (among many): Sulfur gases both react with and dissolve in water, such that existence of some correlation between water, sulfur time variations is all but certain. However, neither the sign of the correlation, nor possible influences of diurnal and dynamical effects are known. ***Finding and characterizing such correlations is the focus of ongoing work.***
- The JCMT discovery and characterization of SO, SO_2 correlation through analysis of 5+ years of data (three Venus' diurnal cycles), illustrates both our approach and its viability.

JCMT is a very powerful observatory

for Solar system sciences!